



**PEARSON NEW INTERNATIONAL EDITION**

**Mineralogy**  
**Dexter Perkins**  
**Third Edition**

# Pearson New International Edition

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Mineralogy  
Dexter Perkins  
Third Edition

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# Table of Contents

<b>Glossary</b>	
Dexter Perkins	<b>1</b>
<b>1. Elements and Minerals</b>	
Dexter Perkins	<b>23</b>
<b>2. Crystallization and Classification of Minerals</b>	
Dexter Perkins	<b>47</b>
Crystallization and Classification of Minerals Color Plates	
Dexter Perkins	<b>67</b>
<b>3. Mineral Properties: Hand Specimen Mineralogy</b>	
Dexter Perkins	<b>69</b>
Mineral Properties: Hand Specimen Mineralogy Color Plates	
Dexter Perkins	<b>95</b>
<b>4. Optical Mineralogy</b>	
Dexter Perkins	<b>101</b>
Optical Mineralogy Color Plates	
Dexter Perkins	<b>129</b>
<b>5. Igneous Rocks and Silicate Minerals</b>	
Dexter Perkins	<b>133</b>
Igneous Rocks and Silicate Minerals Color Plates	
Dexter Perkins	<b>167</b>
<b>6. Sedimentary Minerals and Sedimentary Rocks</b>	
Dexter Perkins	<b>171</b>
Sedimentary Minerals and Sedimentary Rocks Color Plates	
Dexter Perkins	<b>189</b>
<b>7. Metamorphic Minerals and Metamorphic Rocks</b>	
Dexter Perkins	<b>191</b>

Metamorphic Minerals and Metamorphic Rocks Color Plates	
Dexter Perkins	<b>215</b>
<b>8. Ore Deposits and Economic Minerals</b>	
Dexter Perkins	<b>217</b>
Ore Deposits and Economic Minerals Color Plates	
Dexter Perkins	<b>237</b>
<b>9. Crystal Morphology and Symmetry</b>	
Dexter Perkins	<b>239</b>
<b>10. Crystallography</b>	
Dexter Perkins	<b>273</b>
<b>11. Unit Cells, Points, Lines, and Planes</b>	
Dexter Perkins	<b>305</b>
<b>12. X-ray Diffraction and Mineral Analysis</b>	
Dexter Perkins	<b>319</b>
<b>13. Atomic Structure</b>	
Dexter Perkins	<b>343</b>
Descriptions of Minerals	
Dexter Perkins	<b>367</b>
Descriptions of Minerals Color Plates	
Dexter Perkins	<b>479</b>
Appendix: Classified List of Minerals	
Dexter Perkins	<b>487</b>
Appendix: Mineral Identification Tables	
Dexter Perkins	<b>493</b>
Appendix: Minerals Separated by Optic System and Sign, and Ordered by Index of Refraction	
Dexter Perkins	<b>525</b>
Appendix: Minerals Ordered by Birefringence and Interference Colors in Thin Section	
Dexter Perkins	<b>529</b>
Appendix: Minerals Ordered by Hardness	
Dexter Perkins	<b>533</b>
Appendix: Minerals Ordered by Specific Gravity	
Dexter Perkins	<b>537</b>
Coordination Numbers and Effective Ionic Radii	
Dexter Perkins	<b>541</b>
List of Mineral Properties	
Dexter Perkins	<b>543</b>
Periodic Table of the Elements	
Dexter Perkins	<b>553</b>



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# GLOSSARY

**Absolute hardness.** A numerical measure of a mineral's hardness; typically determined by indentation measurements (*c.f.* relative hardness).

**Accessory mineral.** A mineral present in small amounts in a rock, unimportant for rock naming or classification.

**Accessory plate.** A plate that may be inserted in the tube of a polarizing light microscope to produce interference colors of known birefringence. Typically made of quartz, gypsum, or mica.

**Acicular.** Having a needle-like shape.

**Actinide.** Elements (such as Th, Pa, and U) with atomic numbers 90 through 103 and valence electrons in  $5f$  orbitals.

**Acute bisectrix.** A line bisecting the angle formed by the two optic axes in a biaxial mineral.

**Acute bisectrix figure (Bxa).** The interference figure seen when looking down an acute bisectrix.

**Adamantine.** A type of luster that is bright, sparkly, and shiny, similar to that of diamonds.

**Aggregate (of crystals).** A mass of crystals, of the same or different minerals, that may be physically separated, perhaps with some difficulty.

**Albite law.** A common twin law in triclinic feldspars, often resulting in polysynthetic twins.

**Alchemy.** Chemistry of the Middle Ages that combined science, magic, and philosophy.

**Alkali element.** Any element (such as Li, Na, or K) of the first group in the Periodic Table of the Elements; alkali elements typically ionize to form monovalent cations.

**Alkaline earth element.** Any element (such as Be, Mg, or Ca) of the second group in the Periodic Table of the Elements; alkaline earth elements typically ionize to form divalent cations.

**Allochromatic.** A term describing a mineral that gets its color from minor or trace elements (*see also* idiochromatic).

**Alloy.** A noncrystalline mixture of two or more metals.

**Alluvium.** Unconsolidated sediment deposited by a stream.

**Amorphous.** Having a random atomic structure (*see also* noncrystalline).

**Amphibolite (facies).** One of the principal metamorphic facies introduced by Eskola, corresponding to high-grade conditions of about 450 to 650 °C and 3 to 8 kbar.

**Amphibolite (rock).** A metamorphic rock containing primarily hornblende and plagioclase.

**Analyzer.** A polarizing filter that can be inserted in the upper column of a polarizing light microscope to view minerals under crossed-polarized light (*see also* upper polarizer).

**Anatexis.** Partial melting of preexisting rock, generally associated with high-grade metamorphism.

**Andesite.** An extrusive igneous rock of intermediate composition containing plagioclase as the only major feldspar; minor K-feldspar or quartz, pyroxene, biotite, and hornblende may be present.

**Angle of incidence.** The angle that an impinging ray makes with a normal to an interface.

**Angle of refraction.** The angle that a refracted ray makes with a normal to an interface.

**Anhedral.** A crystal that lacks well-developed crystal faces or that has rounded or irregular form due to crowding by adjacent crystals.

**Anion.** An ion having a negative charge.

**Anionic complex.** A tightly bonded, negatively charged molecular group; in mineral formulas, often surrounded by parentheses.

**Anisodesmic.** Describing an ionic compound in which the ionic bonds are not all of the same strength.

**Anisotropic.** Having different physical properties in different directions.

**Anomalous interference colors.** Interference colors that are not represented on the Michel Lévy Chart; typically associated with minerals of extremely low birefringence, such as chlorite.

**Aphanitic.** Having no mineral grains that are visible to the naked eye.

**Aqueous solution.** A water-rich solution, usually containing dissolved elements or complexes.

**Arborescent.** A term describing an aggregate of crystals having a tree-like appearance (*see also* dendritic).

**Arenite.** General term for detrital sedimentary rocks composed of sand-sized grains and lithic fragments; includes sandstone, graywacke, arkose, and others (*see also* psammite).

**Arkose.** A feldspar-rich sandstone.

**Asbestiform.** A crystal habit characterized by fine thread-like, fibrous, or acicular crystals; more specifically, sometimes defined as a crystal habit with a length:diameter ratio of more than 3:1.

**Asbestos.** A general term referring to minerals that have an asbestiform habit; chrysotile, amosite, and crocidolite are typical asbestos minerals.

**Association (mineral).** A group of minerals found together in a rock.

**Asterism.** The play of colors seen in some minerals that produces a rayed or star-shaped figure when viewed in direct light; a star sapphire is one example.

**Atmophile.** An element that tends to concentrate in the Earth's atmosphere.

**Atomic absorption spectrophotometer.** An analytical instrument in which composition is determined by measuring the absorption of characteristic wavelengths of light by an atomized and flamed sample.

## Glossary

**Atomic absorption spectroscopy (AAS).** A technique for determining the concentration of a particular element in a sample that is based on light absorption by an atomized sample.

**Atomic mass unit (amu).** Unit for expressing atomic mass, equal to approximately  $1.6610 \times 10^{-27}$  kg.

**Atomic number (Z).** The number of protons in the nucleus of an atom of an element.

**Atomic weight.** The weight of an atom or compound in atomic mass units; generally close to the total number of protons and neutrons.

**Aufbau principle.** The principle that states that electrons fill orbitals in a systematic way from the lowest energy orbitals to the highest.

**Augen.** Large lenticular mineral grains or mineral aggregates in a foliated metamorphic rock.

**Augen gneiss.** A gneiss containing augen.

**Aureole.** A contact metamorphic zone surrounding an igneous intrusion (*see also* contact aureole).

**Authigenic.** Formed or generated in place; used to describe minerals that form in a sediment or sedimentary rock after deposition of an original sediment.

**Avogadro's number.**  $6.022 \times 10^{23}$ , equivalent to the number of atoms or molecules in a mole.

**Axial ratio** The ratio of unit cell lengths along each crystallographic axis,  $a : b : c$ .

**Axis (crystallographic).** One of three axes used to describe the geometry of a crystal lattice and the locations of points and planes in a unit cell.

**Axis (rotational).** A symmetry element that relates identical crystal faces or other things by rotation of  $60^\circ$ ,  $90^\circ$ ,  $120^\circ$ ,  $180^\circ$ , or  $360^\circ$  about an axis.

**Backscatter electrons.** High-energy electrons that are essentially reflected by the surface of a sample.

**Banded iron formation (BIF).** A layered rock containing chert, silicate, carbonate, or oxide layers, giving a banded appearance.

**Barrovian facies series.** The “normal” metamorphic facies series described by George Barrow; the most common sequence of metamorphic rocks that forms at mid-crustal depths.

**Basal cleavage.** A term used to describe the cleavage in minerals such as micas that allows the mineral to break into plates or sheets.

**Basalt.** An extrusive igneous rock of mafic composition containing plagioclase as the only major feldspar; clinopyroxene  $\pm$  orthopyroxene  $\pm$  olivine are typically present (*see also* gabbro).

**Basement rock.** Metamorphic and igneous rocks that underlie sediments and sedimentary rocks observed at Earth’s surface; often, though not exclusively, of Precambrian age.

**Basis.** A sufficient set of symmetry operators for describing the symmetry of crystals (point symmetry) or of atomic structures (space symmetry).

**Batholith.** A large mass of intrusive igneous rock that solidified within the earth.

**Bauxite.** Name given to a rock or a mineral-like material composed primarily of a mixture of aluminum oxides and hydroxides such as boehmite and gibbsite; bauxite is the most significant aluminum ore.

**Baveno twin.** An uncommon twin law in feldspar.

**Becke line.** A bright line, visible under a microscope, that separates substances of different refractive indices.

**Bentonite.** A clay-rich, earthy material formed by devitrification and alteration of tuff or volcanic ash; sometimes used more generally to refer to any clay deposit rich in montmorillonite.

**Berman balance.** A type of balance scale used to determine specific gravity.

**Bertrand lens.** A lens that can be inserted in the tube of a polarizing light microscope to facilitate observation of interference figures.

**Biaxial.** Describing a crystal having two optic axes and three principal indices of refraction ( $\alpha$ ,  $\beta$ , and  $\gamma$ ). Such crystals belong to the orthorhombic, monoclinic, and triclinic crystal systems.

**Binary solution.** A solid solution series that can be characterized by two end members.

**Biogenic.** Produced by living organisms or biological processes.

**Birefringence (property).** The property of a crystal that causes double refraction.

**Birefringence (value).** The difference between the greatest and least indices of refraction of a crystalline substance.

**Bladed.** Having the appearance of blades.

**Blocky.** A term used to describe crystals that have a block-like appearance, generally with a nearly square cross section.

**Blueschist (facies).** One of the principal metamorphic facies introduced by Eskola, corresponding to high pressure–low temperature conditions.

**Blueschist facies series.** A facies series characterized by high pressures at relatively low temperatures; typical of subduction zone environments.

**Blueschist (rock).** A vague term used to describe fine-grained, bluish colored rocks diagnostic of the blueschist facies. Key minerals include blue amphiboles (glaucomophane and riebeckite), lawsonite, jadeite, and aragonite.

**Body centered.** Said of a unit cell that has an extra lattice point at its center.

**Body diagonal.** A line passing through the center of a cube or other three-dimensional geometric shape and connecting opposite corners.

**Bohr model of the atom.** A fundamental model of an atom that describes electrons orbiting atomic nuclei in orbits associated with specific energy levels.

**Bomb.** A laboratory reactor vessel used to conduct experiments and synthesize gems and minerals at high pressure and temperature.

**Bort.** Diamond of low quality that is unsuitable as a gem but useful in industrial applications.

## Glossary

**Botryoidal.** A term used to describe a mineral habit that appears like a bunch of grapes.

**Boule.** A oblong-shaped synthetic mineral crystal that is produced from the Verneuil technique.

**Bowen's reaction series.** A hypothetical series that describes the order of crystallization of minerals from a magma.

**Bragg law.** A mathematical law that describes the relationship between the angle of diffraction ( $\theta$ ), X-ray wavelength ( $\lambda$ ), and atomic plane spacing ( $d$ );  $n\lambda = 2d\sin\theta$ .

**Bravais lattices.** The fourteen possible three-dimensional lattices that can describe mineral structures.

**Brazil law.** A common type of twinning in quartz.

**Breccia.** A clastic sedimentary rock composed of large (> 2mm diameter) angular broken rock fragments in a finer grained matrix.

**Bridging oxygen.** An oxygen atom in a crystal structure that is shared by two or more equivalent coordinating polyhedra.

**Brittle.** A term used to describe minerals that shatter or break easily when struck.

**Buchan facies series.** A facies series characterized by similar temperatures but lower pressures than the Barrovian facies series, characterized by the presence of andalusite and sometimes cordierite.

**Brucite layer.** A sheet of  $Mg(OH)_6$  octahedra in a layered crystal structure.

**Burial metamorphism.** Metamorphism affecting a large region; caused by pressure related to depth in Earth and temperature related to geothermal gradient (*see also* regional metamorphism).

**Cabochon.** A gemstone that has been ground and polished into a domed shape.

**Calcine.** To heat material, such as limestone, to high temperature, breaking down minerals and driving off carbon dioxide or other volatiles.

**Capillary.** Having a hair-like or thread-like appearance (*see also* filiform).

**Carbonate (mineral).** A group of minerals with formulas characterized by  $(CO_3)^{2-}$  radicals.

**Carbonate (radical).** The  $(CO_3)^{2-}$  anionic group.

**Carbonate (rock).** A chemical sedimentary rock dominated by carbonate minerals; limestone or dolostone.

**Carbonation reaction.** Reaction of a mineral or minerals with  $CO_2$  to produce a product carbonate mineral.

**Carlsbad twin.** A common twin law in orthoclase, less common in other feldspars, often resulting in penetration twins.

**Cartesian coordinate system.** An  $X-Y-Z$  coordinate system in which all axes are at  $90^\circ$  and the unit distances along all axes are equal.

**Cataclastic metamorphism.** Metamorphism caused by a transient high-pressure condition such as a meteorite impact (*see also* shock metamorphism and dynamic metamorphism).

**Cathode ray tube.** Vacuum tube in which beams of high-energy electrons pass through magnetic fields and hit a fluorescent screen.

**Cation.** An ion having a positive charge.

**Cementation.** Lithification of clastic sediments resulting from the deposition or precipitation of minerals in the spaces between individual clastic grains; it may occur at the time of deposition or during diagenesis.

**Centered.** Said of a unit cell that has (an) extra lattice point(s) at its center, in the center of its faces, or in the center of two opposing faces.

**Chain silicates.** Silicate minerals characterized by  $SiO_4$  tetrahedra joining to form chains either one tetrahedron or two tetrahedra wide (*see also* inosilicates).

**Chalcophile.** An element that tends to concentrate in sulfide minerals and ores.

**Characteristic radiation.** High-intensity radiation of one or a few wavelengths emitted by the target of an X-ray tube; the wavelength(s) of characteristic radiation depend on the elements in the target.

**Chatoyancy.** The play of colors seen in some minerals in which a silky sheen is seen to form a narrow band that changes position as the mineral is turned; for example, cat's-eye chrysoberyl.

**Chemical precipitate.** A solid that precipitates from an aqueous solution, typically due to supersaturation.

**Chemical sedimentary rock.** A sedimentary rock composed primarily of material formed by precipitation from solution; for example, most limestones and all evaporites.

**Chemical sediments.** Sediments produced by dissolution and precipitation resulting from chemical weathering; they may precipitate where weathering occurs or at a different place.

**Chemical weathering.** Type of weathering involving chemical reactions that transform or decompose minerals and rock.

**Chert.** A hard sedimentary rock composed primarily of cryptocrystalline silica, generally in the form of fibrous chalcedony with lesser amounts of quartz and opal.

**Chromophores.** Elements that give minerals their color.

**Class.** *See* crystal class.

**Clast.** A mineral grain, lithic fragment, or organic remnant that is produced by mechanical weathering and becomes part of a clastic sediment or rock.

**Clastic.** Being composed of fragments (clasts) derived from preexisting rocks.

**Clastic rock.** Sedimentary rock formed by the lithification of clastic sediments; for example, sandstone, shale, and siltstone.

**Clausius-Clapeyron equation.** An equation relating the slope of a reaction on a pressure-temperature diagram to the entropy and volume change of the reaction:  $dP/dT = \Delta S/\Delta V$ .

**Clay (grain size).** A clastic fragment of any composition smaller than silt, having a diameter less than  $1/_{256}$  mm.

## Glossary

**Clay (mineral).** Member of a group of loosely defined hydrous sheet silicates formed primarily by alteration or weathering of primary silicates. The most common clays belong to the illite, kaolinite, or montmorillonite groups.

**Cleavage.** The breaking of a mineral along a set of parallel, identical atomic planes.

**Clinonet.** A two-dimensional lattice characterized by two translations of different magnitudes at nonspecial angles to each other.

**Clinopyroxene.** Monoclinic pyroxene subgroup dominated by end members diopside and hedenbergite. The most common of all pyroxenes.

**Closest packing.** The most efficient way to pack like atoms together in three dimensions; each atom is surrounded by 12 others.

**Colloform.** Appearing as spherical or hemispherical shapes made of radiating crystals (*see also* globular).

**Color.** A sensation produced by different wavelengths of light hitting the eye.

**Colorimetric analysis.** Quantitative chemical analysis by color using a colorimeter.

**Columnar.** Having the appearance of an aggregate of slender, elongated individual crystals, nearly parallel in arrangement.

**Complex twin.** A twin composed of more than two individual crystals.

**Compositional zoning.** Variation in the composition of a crystal, typically from core to margin (*see also* zoning).

**Composition plane.** A plane that divides two twin domains in a twinned crystal.

**Compound (chemical).** A substance of fixed atomic proportions made by the combination of two or more elements.

**Concentration factor.** The extent to which an element must be concentrated above normal crustal levels to make mining it profitable.

**Conchoidal fracture.** A type of fracturing that produces curved surfaces similar to when glass breaks; for example, quartz has a conchoidal fracture.

**Condenser.** A lens, or several lenses, that may be inserted in the substage of a polarizing light microscope to cause light rays to converge on a sample (*see also* condenser lens).

**Condenser lens.** *See* condenser.

**Conglomerate.** A coarse-grained clastic sedimentary rock with fragments larger than 2 mm in diameter in a fine-grained matrix; the equivalent of lithified gravel. The clasts are rounded in conglomerates in contrast with breccias.

**Conoscopic illumination.** Describing the strongly convergent light produced by the insertion of a condensing lens in a polarizing light microscope substage.

**Constructive interference.** The addition of two waves that are in phase with negligible or no loss of energy.

**Contact aureole.** A contact metamorphic zone surrounding an igneous intrusion (*see also* aureole).

**Contact metamorphism.** Metamorphism localized around an igneous rock body; primarily in response to heat and flowing fluids.

**Contact twin.** A twin in which two individuals are symmetrically arranged about a twin plane giving the appearance of two crystals in contact with each other.

**Continuous radiation.** The low-intensity radiation covering a range of wavelengths that is produced by an X-ray tube; continuous radiation provides the background for characteristic radiation.

**Continuous side (Bowen's reaction series).** The side of Bowen's reaction series characterized by plagioclase.

**Coordinating polyhedron.** Polyhedron formed around an atom or ion by connecting the centers of the coordinated atoms or ions.

**Coordination number.** Number of neighboring atoms to which an atom is bonded.

**Coquina.** A soft, whitish limestone made up of broken sea shells and corals.

**Country rock.** Rock intruded by and surrounding an igneous intrusion.

**Coupled substitution.** Simultaneous substitution of two or more different ions in a structure in such a way that charge balance is maintained; for example, the substitution of  $\text{Ca}^{2+}\text{Al}^{3+}$  for  $\text{Na}^{+}\text{Si}^{4+}$  in plagioclase.

**Covalent bond.** An ideal chemical bond that involves the sharing of orbital electrons between elements that have little or no difference in electronegativity.

**Cover slip.** A thin piece of glass that is placed over grains and liquid to make a grain mount.

**Critical angle.** The angle of incidence that yields an angle of refraction of 90°.

**Crossed polars (XP).** The condition caused when the upper polarizer is inserted in a polarizing light microscope.

**Cryptocrystalline.** A term describing a material containing generally submicroscopic grains whose crystalline nature is not easily determined.

**Crystal.** A homogeneous solid body of an element, compound, or solid solution having a regularly repeating atomic structure that may be outwardly expressed as planar faces.

**Crystal classes.** The 32 possible combinations of symmetry elements that a crystal may have; in modern usage, synonymous with the 32 possible point groups.

**Crystal morphology.** The shape and form(s) of a crystal.

**Crystal structure.** Spatial arrangement of atoms or ions, and their bonds, in a crystal.

**Crystal structure determination.** Determination of the spatial arrangement of atoms and their bonds in a crystal.

**Crystal system.** One of the six distinct coordinate systems used to describe minerals: cubic, orthorhombic, tetragonal, hexagonal, monoclinic, and triclinic. The trigonal subdivision

## Glossary

of the hexagonal system is sometimes counted as a separate crystal system.

**Crystalline.** Having a crystal structure; having a regular arrangement of atoms characterized by a space lattice.

**Crystallographic axis.** One of three axes used to describe the geometry of a crystal lattice and the locations of points and planes in a unit cell.

**Cube.** A closed form of six identical square faces at 90° to each other; a form of crystal class  $4/m\bar{3}2/m$ .

**Cubic.** Having a cube shape or belonging to the cubic system.

**Cubic (cleavage).** A term used to describe three equal cleavages at 90° to each other; for example, halite has cubic cleavage.

**Cubic (coordination).** The bonding of an ion to eight others arranged so that connecting their centers forms a cube.

**Cubic (system).** A crystal system characterized by lattice symmetry  $4/m\bar{3}2/m$ .

**Cubic closest packing.** Closest packing of atoms in a pattern similar to a face-centered cubic lattice; closest packing equivalent to stacking closest packed layers in an ABCABC sequence.

**Cumulate.** A layer of minerals accumulated by gravity settling of crystals as they form in a magma chamber.

**Cyanide method.** A method for extracting valuable metals from ore that involves hydrogen cyanide.

**Cycle.** One complete upward and downward motion by a wave.

**Cyclic twinning.** Repeated twinning of three or more individuals according to the same twin law but with the twin axes or twin planes not parallel, usually producing a twinned crystal in which twin domains are related by apparent rotational symmetry.

**Cyclosilicates.** Silicate minerals characterized by  $\text{SiO}_4$  tetrahedra joining to form rings (*see also* ring silicates).

**Czochralski process.** A method of making synthetic gems that involves a seed crystal drawing material out of a melt.

**D-value.** The distance between adjacent planes with the same Miller indices.

**Dacite.** An extrusive igneous rock of silicic composition that contains more plagioclase than K-feldspar; biotite and hornblende are typically present (*see also* granodiorite).

**Daughter element.** The product element of radioactive decay.

**Daughter isotope.** The product isotope of radioactive decay.

**Dauphiné law.** A common type of twinning in quartz.

**Decarbonation reaction.** A reaction that liberates  $\text{CO}_2$  from a mineral.

**Defect.** A flaw in an otherwise ideal crystal structure.

**Degrees of freedom.** The number of intensive variables that may be changed independently without causing a change in mineral assemblage or composition.

**Dehydration reaction.** A reaction that liberates  $\text{H}_2\text{O}$  from a carbonate mineral.

**Dendritic.** A term describing an aggregate of crystals having a tree-like appearance (*see also* arborescent).

**Density.** The quantity of matter in a unit volume; mineral densities are typically given in units of  $\text{gm}/\text{cm}^3$ .

**Destructive interference.** The addition of two out-of-phase waves resulting in a total, or significant, loss of energy.

**Detrital.** Referring to a product of mechanical weathering.

**Detrital sedimentary rock.** Rock formed by lithification of detrital sediments.

**Detritus.** Broken-up material resulting from mechanical weathering.

**Diagenesis.** Chemical, physical, and biological changes that affect sediment or sedimentary rocks after initial deposition, but excluding weathering or metamorphism.

**Diamagnetism.** A property of minerals that causes a small negative reaction (repulsion) to a magnet.

**Diamond (shape).** A parallelogram having four sides of equal length and no angles of 90°.

**Diamond lattice.** *See* diamond net.

**Diamond net.** A two-dimensional lattice characterized by two translations of the same magnitude at nonspecial angles to each other.

**Diaphaneity.** The ability of a mineral to transmit light; often described as transparent, translucent, or opaque.

**Diaphragm.** An adjustable opening used to control the size of a light beam in a polarizing light microscope.

**Diatomite.** To come.

**Dichroism.** Pleochroism of a mineral that is observed as two different colors.

**Diffraction.** Apparent bending of radiation by evenly spaced atoms, slits, or gratings.

**Diffraction grating.** A grating that causes diffraction.

**Diffraction slit.** A slit that causes diffraction.

**Diffractometer.** An instrument that records X-ray diffraction patterns.

**Dioctahedral.** Describing a layered mineral structure in which only two of three available octahedral sites are occupied.

**Diorite.** An intrusive igneous rock of intermediate composition containing plagioclase as the only major feldspar; minor K-feldspar or quartz, pyroxene, biotite, and hornblende may be present.

**Diploid.** A closed cubic form of 24 quadrilateral faces; a form of crystal class  $2/m\bar{3}$ .

**Dipyramid.** A closed crystal form of 6, 8, 12, 16, or 24 faces, comprising two pyramids related by a mirror plane of symmetry.

**Discontinuous side (Bowen's reaction series).** The side of Bowen's reaction series characterized by olivine-pyroxene-amphibole-biotite.

- Disequilibrium.** The state of being in the process of reacting so that the relative amounts of reactants and products are changing.
- Dispersion.** A difference in wave velocity for different wavelengths.
- Disphenoid.** A closed crystal form comprising two sphe-noids related by 222 symmetry.
- Disseminated deposit.** An ore deposit in which the ore mineral is scattered throughout a host rock.
- Dissolution.** The process of dissolving.
- Divalent.** Having a charge of  $\pm 2$ .
- Divariant field.** A region on a phase diagram characterized by two degrees of freedom.
- Divergent (crystals).** Slender crystals emanating from a common point (*see also* radiating).
- Dodecahedral (coordination).** 12-fold coordination.
- Dodecahedron.** A 3-dimensional geometric shape characterized by 12 identical faces; one of the common forms of the cubic system.
- Dolostone.** A chemical sedimentary rock composed primarily of dolomite.
- Domain.** A region within a crystal having an atomic orientation that differs from other regions within the crystal.
- Dome.** An open crystal form composed of two nonparallel faces related by a mirror.
- Dop.** A stick-like device that holds a gem crystal for grinding on a wheel.
- Double-chain silicates.** Silicate minerals (amphiboles) characterized by  $\text{SiO}_4$  tetrahedra joining to form chains two tetrahedra wide.
- Double refraction.** The ability of a mineral to split ordinary light into two waves of different velocities and polarization.
- Doubly primitive.** Term describing a unit cell containing a total of two lattice points.
- Drusy.** Having surfaces coated with fine crystals.
- Ductile.** A term used to describe the tenacity of minerals that are capable of being drawn into a wire-like shape.
- Dull.** A type of luster that does not reflect significant amounts of light or show any play of colors.
- Dunite.** An ultramafic intrusive rock in which the only major mineral is olivine; chromite is typically present as an accessory mineral.
- Dynamic metamorphism.** Metamorphism caused by a transient high-pressure condition such as a meteorite impact (*see also* shock metamorphism and cataclastic metamorphism).
- E ray.** *See* extraordinary ray.
- Eclogite (facies).** A high-pressure/high-temperature metamorphic facies characteristic of the mantle.
- Eclogite (rock).** A high-pressure/high-temperature rock containing Mg-rich garnet (pyrope) and Na-rich clinopyroxene (omphacite); mostly of mantle origin.
- Edge diagonal.** A line passing through the center of a cube or other three-dimensional geometric shape, and connecting the centers of opposite edges.
- Edge dislocation.** A kind of line defect caused by a terminated row of atoms.
- Edge sharing.** The sharing of two atoms or ions by two adjacent coordinating polyhedra; the coordinating polyhedra appear to be sharing an edge.
- Effective ionic radius.** Radius of a spherical volume effectively occupied by an ion in a particular structure.
- Effervescence.** A bubbling reaction; the term used to describe the reaction of calcite with dilute hydrochloric acid.
- Elastic.** A term used to describe minerals that return to their original shape after bending.
- Electromagnetic radiation.** Emission or transfer of energy in the form of waves; includes X rays, visible light, infrared light, radio waves, and television waves.
- Electron.** An extremely small atomic particle having little mass that is the smallest negative electric charge occurring in nature. Atoms have electrons orbiting around a nucleus.
- Electron cloud.** The space occupied by electrons surrounding an atomic nucleus.
- Electronegativity.** Measure of the tendency of elements to acquire electrons.
- Electron microprobe.** An analytical instrument in which a finely focused electron beam hits a sample, causing emission of elemental characteristic radiation.
- Electron microscope.** A microscope that is in some ways similar to a conventional light microscope but achieves much greater resolving power by using a beam of electrons to illuminate the sample instead of light.
- Electron probe micro analyzer (EPMA).** *See* electron microprobe.
- Electrostatic valency principle (Pauling's second rule).** The strength of ionic bonds to any ion is equal to the ion's charge divided by its coordination number.
- Element.** A basic chemical unit composed of atoms having the same atomic number; elements cannot be separated into simpler parts by chemical means.
- Elliptic.** A term describing crystals that are very small ellipsoids.
- Enantiomorphic pair.** A term describing two crystals whose atomic structures are mirror images of each other.
- End centered.** A term describing a unit cell with an extra lattice point in each of two opposing faces.
- End member.** An ideal chemical formula representing one limit of a solid solution.
- Energy dispersive X-ray spectroscopy (EDS).** An analytical technique that involves measuring the energy of X-rays emitted, in order to identify the elements present and their concentrations, in a sample.
- Energy level.** The energy associated with a particular electron orbit in an atom.

## Glossary

**Enthalpy (H).** A thermodynamic variable related to the Gibbs free energy.

**Entropy (S).** A thermodynamic variable representing the degree of randomness or disorder in a system, which are related to the system's ability to absorb energy without increasing its temperature.

**Epigenetic.** Refers to a mineral deposit that is emplaced after its host rocks already exist.

**Equant.** Having approximately the same dimensions in all directions.

**Equilibrium.** A static state of a chemical system in which the relative amounts and compositions of phases present do not undergo changes with time.

**Essential mineral.** A mineral in a rock that is necessary for the rock to be classified or named as it is.

**Euhedral.** A crystal that is completely bounded by well-developed crystal faces and whose growth was not restrained by adjacent crystals.

**Evaporite (mineral).** Minerals that may form by precipitation from aqueous solution under normal Earth surface conditions; for example, halite, sylvite, and gypsum.

**Evaporite (rock).** A chemical sedimentary rock formed by evaporation of water; for example, massive gypsum or salt beds.

**Evaporite deposit.** Mineral deposit formed by evaporation of water.

**Even (fracture).** A fracture that produces smooth planar surfaces.

**Exhalitive.** A hydrothermal deposit created at the Earth's surface; generally one that forms on the ocean floor from springs.

**Expandable clay.** One of a group of clay minerals (smectites) that can expand their structure to accommodate excess water or other chemical components.

**Exsolution.** The separating of an initially homogeneous mineral solid solution into two (or more) zones of distinct mineral phases; for example, the formation of perthite from a homogeneous feldspar during cooling.

**Exsolution lamellae.** Fine parallel zones of different compositions resulting from exsolution.

**Extinct (mineral grain).** A term describing a birefringent mineral grain oriented so that it appears dark when viewed under crossed polars.

**Extinct (X-ray peak).** A term describing an X-ray peak missing from a diffraction pattern due to destructive interference.

**Extinction (X-ray).** The systematic absence of a related group of X-ray peaks in a diffraction pattern.

**Extinction angle.** The angle, measured under crossed polars, between the position of extinction and a cleavage, long dimension, or other direction in a crystal.

**Extraordinary ray (E ray).** In a uniaxial crystal, the ray of light that vibrates in a plane containing the optic axis.

**Extrusive rock.** An igneous rock that crystallizes at or very near Earth's surface, typically characterized by relatively coarse crystal size (*see also* volcanic rock).

**Face centered.** A term describing a unit cell with an extra lattice point in the center of each of its faces.

**Face sharing.** The sharing of three atoms or ions by two adjacent coordinating polyhedra; the coordinating polyhedra appear to be sharing a face.

**Facet.** A polished face on a gemstone.

**Facies (metamorphic).** A range of pressure-temperature conditions characterized by one or more specific mineral assemblages.

**Family of planes.** An infinite number of planes, parallel and spaced equally, all characterized by the same Miller index.

**Fast ray.** The fastest of the two rays produced by double refraction.

**Feldspar.** Any of a group of common framework silicates that are found in rocks of many kinds and are characterized by Al- and Si-tetrahedra connected by bonds to Ca, Na, or K.

**Feldspathic.** An adjective describing a mineral aggregate that contains feldspar.

**Feldspathoid.** A mineral group containing framework silicates, closely related to the feldspar group but containing less silica.

**Felsic.** A general adjective referring to igneous rocks having light colored minerals in their mode.

**Ferromagnetism.** A type of magnetic order, characteristic of iron, that causes a mineral to respond strongly to a magnetic field.

**Fibrous (cleavage).** A term describing a cleavage that allows a crystal to be broken into fibers.

**Fibrous (crystals).** Having the appearance of being composed of fibers.

**Filiform.** Having a hair-like or thread-like appearance (*see also* capillary).

**Fissility.** The rock property of breaking easily along closely spaced planes; often used to describe shale or schist.

**Flash figure.** The interference figure observed when the optic axis (uniaxial mineral) or the optic plane (biaxial mineral) are oriented parallel to the stage of a polarizing light microscope.

**Flexible.** A term used to describe the tenacity of minerals that are bendable.

**Flood basalt.** A laterally extensive and thick lava flow of basaltic composition.

**Fluorescence.** A type of luminescence that occurs when minerals are exposed to ultraviolet light, X rays, or cathode rays, but ceases when the exposure ceases.

**Flux.** A substance added to promote a chemical reaction or to lower the melting temperature of a material without changing the chemistry of the important phases that are present.

**Flux method.** A method of synthesizing gems or other minerals by growing them in an inert flux.

**Foliated.** Having planar or sheet-like properties.

**Foliation.** A planar fabric or texture.

**Fool's gold.** Common name for pyrite.

## Glossary

**Form.** A set of identically shaped crystal faces related by symmetry.

**Fractional crystallization.** Separation of a crystallizing magma into compositionally different parts by the successive crystallization of different minerals (*see also* partial crystallization).

**Fracture.** Breaking of a mineral other than along planes of cleavage.

**Framework silicates.** Silicate minerals characterized by  $\text{SiO}_4$  tetrahedra joining to form three-dimensional networks (*see also* tectosilicates and network silicates).

**Frenkel defect.** A defect caused when an atom in a crystal structure is displaced from its normal position to a different position.

**Gabbro.** An intrusive igneous rock of mafic composition containing plagioclase as the only major feldspar; clinopyroxene  $\pm$  orthopyroxene  $\pm$  olivine are typically present (*see also* basalt).

**Gamma rays.** Electromagnetic radiation of higher energy and shorter wavelength than X-rays; emitted by atomic nuclei.

**Gangue.** The waste minerals in an ore deposit.

**Gem.** An especially fine or superlative specimen, often of mineralogical origin, usually having superb color, light properties, or shape; often a cut-and-polished stone that has value due to beauty, durability, rarity, or size; generally for use in jewelry or for ornamentation.

**Gemmy.** Having a gem-like appearance; typically having a bright color, an attractive luster, or geometric shape.

**Gemstone.** A gem of mineralogical origin.

**General angle.** A nonspecial angle between crystal faces or symmetry elements.

**General form.** For a given point group, a form that has the maximum possible number of faces and whose faces and face normals do not intersect at special angles.

**General point.** On a stereo diagram, a point that is located at a general position, not coincident with an inversion center, a rotational axis, or a mirror plane.

**Geode.** A hollow or partly hollow rock cavity lined by mineral material.

**Geothermometer.** A mineral or mineral system with compositional variations that reflect the temperature at which it formed.

**Gibbs free energy.** A thermodynamic variable that describes the relative stability of a mineral or a mineral assemblage; also refers to the energy change associated with a chemical reaction.

**Gibbs phase rule.** A consequence of the laws of thermodynamics: for any chemical system in equilibrium, the number of chemical components plus two is equivalent to the number of stable phases plus the number of degrees of freedom:  $C + 2 = P + F$  (*see also* phase rule).

**Gibbsite layer.** A sheet of  $\text{Al}(\text{OH})_6$  octahedra in a layered crystal structure.

**Glass.** An amorphous solid material; in most cases, a metastable supercooled liquid.

**Glide plane.** A compound symmetry operation that repeats a motif or other entity after a reflection and translation are combined.

**Globular.** Appearing as spherical or hemispherical shapes, often made of radiating crystals *see also* colloform.

**Gneiss.** A foliated metamorphic rock showing contrasting bands of light- and dark-colored minerals.

**Goldich's weathering series.** A hypothetical series that describes the order of weathering of minerals in outcrop; the series is essentially the opposite of Bowen's reaction series.

**Goniometer.** A calibrated instrument used to measure the angles between crystal faces, cleavages, or other planar features in crystals.

**Grade (metamorphic).** The degree of metamorphism; generally equivalent to the temperature of metamorphism (*see also* metamorphic grade).

**Grade (ore).** The concentration of ore minerals or elements in ore rock.

**Grain mount.** Fine mineral grains on a glass slide surrounded by a liquid and covered with a cover slip.

**Granite.** An intrusive igneous rock of silicic composition containing 10% to 50% quartz and K-feldspar as the major feldspar; plagioclase, biotite, and hornblende may be present (*see also* rhyolite).

**Granitic.** A general adjective applied to any light-colored intrusive igneous rock or to any rock composition that generally resembles that of a granite.

**Granitoid.** A general term for any coarse-grained light-colored igneous rock composed primarily of feldspar, quartz, mica, and hornblende.

**Granodiorite.** An intrusive igneous rock of silicic composition that contains more plagioclase than K-feldspar; biotite and hornblende are typically present (*see also* dacite).

**Granular.** Composed of many small grains.

**Granulite (facies).** The metamorphic facies corresponding to the highest grades of regional metamorphism.

**Granulite (rock).** A high-grade metamorphic rock containing orthopyroxene.

**Gravel.** Clastic material with grains greater than 2 mm in diameter; may include boulders, cobbles, pebbles, or granules.

**Gravimetric analysis.** An analytical technique that is based on the measurement of mass.

**Graywacke.** General term used for clastic sedimentary rocks similar to sandstones but containing an inordinate amount of clays, rock fragments, or other material in addition to quartz and feldspar.

**Greasy (luster).** A type of luster describing crystal faces or other surfaces that reflect light to give a play of colors similar to oil on water.

**Greenschist (rock).** A medium-grade metamorphic rock characterized by schistosity and green minerals including actinolite, chlorite, and epidote.

**Greenschist (facies).** A medium-grade metamorphic facies characterized by conditions of about 300 to 500 °C and 2 to 8 kbar.

## Glossary

**Greenstone.** A vague term used to describe any fine-grained, low-grade green metamorphic rock; generally of basaltic composition.

**Greenstone belt.** A metamorphic terrane characterized by the presence of low-grade metamorphosed volcanics and volcanogenic sediments and silicic to intermediate plutons.

**Ground mass.** The fine-grained or glassy material that surround larger crystals in an igneous rock.

**Group (of elements).** The elements of one column in the Periodic Table of the Elements.

**Group (of minerals).** Minerals within a class or subclass that share major chemical or structural features.

**Gypsum plate.** An accessory plate, made of gypsum, for a polarizing light microscope.

**Gyroid.** A 3-dimensional geometric shape characterized by 24 identical faces; one of the common forms of the cubic system; a form of crystal class 432.

**Habit.** The characteristic appearance of a mineral due to crystal form or combinations of forms, crystal intergrowths, aggregates, and any other irregular physical characteristics.

**Hackly.** A term describing fracturing that produces jagged edges.

**Halide.** Mineral compound with composition that includes a halogen such as F, Cl, or I as an anion.

**Halogen.** Elements (such as F, Cl, and Br) in the seventeenth group of the Periodic Table of the Elements; halogens typically ionize to become monovalent anions.

**Hanawalt method.** A systematic method for matching an “unknown” X-ray pattern with one in a reference data set such as the Powder Diffraction File.

**Hand specimen.** A piece of rock or mineral, convenient for studying macroscopic properties, that can be picked up in the hand.

**Hard radiation.** X-rays of extremely high energy; used in industry and manufacturing but generally not by crystallographers.

**Hardness.** The resistance of a mineral to scratching.

**Haüy's law.** A law that states that crystal faces make simple rational intercepts with crystallographic axes; a corollary is that crystal faces have rational and generally small Miller indices (*see also* law of rational indices).

**Heavy liquid.** A liquid of greater density than water that may be used to separate minerals of different densities.

**Heft.** An estimation of a mineral's density obtained by picking up the mineral and holding it in your hand.

**Heisenberg uncertainty principle.** A principle stated by Werner Heisenberg that says it is impossible to know the location and motion of an electron in an atom without some uncertainty.

**Hermann-Mauguin symbol.** A shorthand notation for the symmetry of a point group.

**Hexagonal.** Of or related to the hexagonal system.

**Hexagonal (system).** A crystal system characterized by lattice symmetry  $6/m\bar{2}/m\bar{2}/m$ .

**Hexagonal closest packing.** Closest packing of spheres in an arrangement similar to a hexagonal prism with three extra spheres in its interior; equivalent to stacking closest packed layers in an ABABAB sequence.

**Hexagonal packing.** Packing of identical spheres in a plane so that each is surrounded by six others.

**Hexahedron.** A 3-dimensional geometric shape composed of six equivalent faces related by symmetry; for example, a cube or rhombohedron.

**Hexanet.** A two-dimensional lattice characterized by two translations of equal magnitude at  $60^\circ$  to each other.

**Hexoctahedron.** A 3-dimensional geometric shape composed of 48 identical triangular faces; a form of crystal class  $4/m\bar{3}2/m$ .

**High symmetry.** Refers to a crystal or other object with shape characterized by a relatively large number of axes and mirror planes of symmetry.

**Hornfels.** A fine-grained metamorphic rock lacking foliation or lineation.

**Host rock.** The rock that hosts ore minerals or an ore deposit.

**Hydration reaction.** A reaction between a mineral, or minerals, and water that results in a product hydrous mineral.

**Hydrogen bond.** A type of electrostatic bond that is generally insignificant in minerals, but is prominent in ice and, to a lesser extent, in micas and hydroxides.

**Hydrolysate.** The material that goes into solution during chemical weathering.

**Hydrolysis reaction.** A type of weathering reaction that simultaneously produces dissolved material and secondary minerals.

**Hydrothermal.** Having to do with warm water-rich fluids.

**Hydrothermal fluids.** Hot water-rich fluids that circulate through Earth.

**Hydrothermal ore deposit.** An ore deposit precipitated by hydrothermal fluids.

**Hydroxide.** A chemical group, or group of minerals, with formulas characterized by the radical  $(OH)^-$ ; for example, gibbsite,  $Al(OH)_3$ .

**Hypothesis.** A proposed explanation for an observed set of facts.

**Idiochromatic.** Term describing a mineral that gets its color from its major elements (*see also* allochromatic).

**Igneous.** An adjective describing a rock or mineral that solidified from a magma or describing the process that forms such a rock or mineral.

**Immersion method.** A method for determining index of refraction by immersing a grain in liquid of known index of refraction.

**Immiscibility.** An inability of two or more phases to mix completely and uniformly.

**Impurity defect.** A defect caused when a foreign atom is present in a crystal structure.

- Inclined extinction.** Extinction when a principal cleavage or length of a crystal is at an angle to the crosshairs of a polarizing light microscope.
- Incompatible element.** An element that does not readily enter a crystal structure.
- Index (indices).** Number (numbers) used to describe the location of points, the orientation of lines, or the orientation of planes in space.
- Index (X-ray pattern).** To assign appropriate ( $hkl$ ) values to X-ray diffraction peaks.
- Index mineral.** A mineral characteristic of a particular set of pressure-temperature conditions for rocks of a given composition.
- Index of refraction.** The ratio of the velocity of light in a vacuum to the velocity of light in a crystal, glass, liquid, or other medium (see also refractive index).
- Inductively coupled plasma (ICP).** A type of plasma produced by electromagnetic induction (by time-varying magnetic fields).
- Inductively coupled plasma mass spectrometry (ICP-MS).** A type of mass spectrometry that uses an inductively coupled plasma to produce ions analyzed with a mass spectrometer.
- Inert gas.** Any of the generally unreactive elements (such as Ne, Ar, or Kr) in the eighteenth group of the Periodic Table of the Elements (see also noble gas).
- Infrared light.** Electromagnetic radiation with wavelengths slightly greater than visible light.
- Infrared spectroscopy.** A type of spectroscopy that deals with the infrared region of the electromagnetic spectrum, typically involving measuring the absorption of infrared light by a sample.
- Inorganic.** A general term used to refer to compounds that contain no carbon bonded to hydrogen as essential components.
- Inosilicates.** Chain silicates; either pyroxenes, pyroxenoids, or amphiboles.
- Integral molecules.** The fundamental and indivisible building blocks making up crystals, according to Haüy; now known not to exist as Haüy envisioned them.
- Intensive variable.** A thermodynamic variable, generally pressure or temperature, that is controlled from outside a chemical system.
- Interfacial angle.** The angle between two faces of a crystal.
- Interference.** The interaction of two waves traveling in the same direction.
- Interference colors.** The colors displayed by a birefringent crystal when viewed under crossed polars.
- Intergranular fluid.** A fluid between grains in a rock.
- Intergrowth.** Two or more crystals grown together.
- Intermediate igneous rock.** An igneous rock of composition intermediate between mafic and silicic.
- Internal energy (E).** A thermodynamic variable related to Gibbs free energy.
- Internal reflection.** The reflection of a light ray back into the interior of a crystal when it reaches a crystal boundary from within.
- Interstice.** A space between grains in a rock or between closest packed atoms in a structure.
- Intrusive rock.** An igneous rock that crystallizes at depth in the earth (see also plutonic rock).
- Invariant point.** A point on a phase diagram at which two or more reactions intersect.
- Inversion.** A term describing the operation that relates two crystal faces or other entities that are equal distant from a central point and have upside-down and backward orientations with respect to each other.
- Inversion center.** A point at the center of a crystal (and its atomic structure) through which every aspect of the crystal (and its atomic structure) is repeated by inversion.
- Ion.** An atom with a negative or positive charge as a result of having lost or gained one or more electrons.
- Ionic bond.** An ideal chemical bond between ions of opposite charge, electrostatic in nature and formed between elements that have large differences in electronegativity.
- Ionic charge.** The number of electrons lost or gained when an atom becomes ionized.
- Ionic crystal.** A crystal in which the predominant bonding is ionic.
- Ionic radius.** Radius of a spherical volume effectively occupied by an ion in a particular environment.
- Ion microprobe.** An analytical instrument that involves making a small amount of sample into a plasma and analyzing it using mass spectrometry (see also secondary ion mass spectrometry).
- Iridescence.** The display of rainbow-like colors in the interior or on the surface of a mineral.
- Iron formation.** General name given to chemical sedimentary rocks dominated by iron oxides, hydroxides, carbonates, sulfides, or silicates.
- Irregular (fracture).** A fracture that produces rough and irregular surfaces (see also uneven fracture).
- Island silicate.** A kind of silicate with atomic arrangement based on individual  $(\text{SiO}_4)$  tetrahedra linked by bonds to cations.
- Isochemical.** Refers to a process involving no significant change in chemical composition.
- Isochrome.** Color bands that wrap around the trace of the optic axis (uniaxial mineral) or the optic axes (biaxial mineral) in an interference figure.
- Isodesmic.** Describing a crystal in which all bonds are ionic and of equal strength.
- Isogonal.** A term describing space groups that contain the same rotation axes; also used to describe space groups that have the same symmetry when translation is ignored.
- Isograd.** Any line based on mineral or mineral-assemblage occurrences that can be mapped in a metamorphic terrane.

## Glossary

**Isogyre.** A band of extinction in an interference figure that appears where light vibration directions are parallel and perpendicular to the lower and upper polarizers.

**Isolated tetrahedral silicates.** Silicate minerals characterized by individual  $\text{SiO}_4$  tetrahedra linked by bonding to common cations.

**Isomorphous series.** A solid solution series in which the crystal structure is the same throughout the series.

**Isostructural.** A term describing two minerals that have different, but identically arranged, atoms in their crystal structures.

**Isotope.** One of two or more species of the same chemical element; different isotopes of an element have the same number of protons but vary in their number of neutrons.

**Isotropic.** Having the same properties in all directions.

**Join (phase diagram).** A line that connects two end member compositions on a ternary phase diagram.

**Jolly balance.** A type of balance scale used to determine specific gravity.

**$K_\alpha$  radiation.** The most intense of the various kinds of characteristic radiation associated with a particular element.

**Kimberlite.** An alkalic peridotite associated with diatremes, typically containing phenocrysts of olivine and phlogopite or their alteration products.

**Komatiite.** A general name given to a lava of ultramafic composition.

**Labradorecence.** A flashing and laminated iridescence, generally of a single bright hue, similar to that displayed by labradorite, a plagioclase feldspar.

**Lamellar.** Having a tab-like appearance; being thin in one dimension compared to the other two (*see also* platy and tabular).

**Lanthanide.** Elements (such as Ce, Pr, and Nd) with atomic numbers 58 through 71 and valence electrons in  $4f$  orbitals (*see also* rare earth elements).

**Laterite.** A highly weathered and leached soil or subsoil rich in aluminum, iron, or other insoluble elements; often rich in quartz and clay minerals.

**Latite.** An extrusive igneous rock of intermediate composition containing approximately equal amounts of plagioclase and K-feldspar; minor quartz, clinopyroxene, biotite, and hornblende may be present.

**Lattice.** A three-dimensional representation of the translational symmetry of a crystal structure.

**Lattice point.** Translationally equivalent points in space; in a crystal, lattice points are surrounded by identical and indistinguishable atomic arrangements.

**Laue equations.** Equations derived by von Laue that describe the angular relationship between an incident beam and a diffracted beam in three-dimensional space.

**Laue method.** X-raying a single crystal by placing it in the path of a polychromatic X-ray beam and positioning a flat piece of film behind it.

**Lava.** Molten extrusive magma.

**Lava flow.** A horizontal outpouring of lava from a vent or fissure.

**Law of definite proportions.** A general law that says compounds are made of elements combined in specific proportions.

**Law of Bravais.** An observational law that states faces on crystals tend to be parallel to planes having a high lattice point density.

**Law of rational indices.** A law that states that crystal faces make simple rational intercepts with crystallographic axes; a corollary is that crystal faces have rational and generally small Miller indices (*see also* Haüy's law).

**Laws of thermodynamics.** Scientific laws that describe the transport of heat and work in thermodynamic processes.

**Lawsonite-albite (facies).** One of the principal metamorphic facies, corresponding to medium-high pressure-low temperature conditions.

**Laws (scientific).** A formal statement of general scientific observations that have never been found to be violated.

**Layer silicates.** Silicate minerals characterized by  $\text{SiO}_4$  tetrahedra joining to form sheets; includes micas and clays (*see also* sheet silicates and phyllosilicates).

**Leach.** To dissolve and remove soluble components from a rock or soil.

**Left handed.** A relative phrase, referring to objects that rotate or point to the left.

**Length fast.** A term describing a birefringent mineral in which the fast ray vibrates more or less parallel to the length of an elongate crystal.

**Length slow.** A term describing a birefringent mineral in which the slow ray vibrates more or less parallel to the length of an elongate crystal.

**Lime kiln.** Long horizontal cylindrical furnace used to heat limestone in order to make lime ( $\text{CaO}$ ).

**Limestone.** A chemical sedimentary rock composed primarily of calcite; in a more general sense the term is sometimes used to refer to any chemical sedimentary rock composed mostly of carbonates.

**Line defect.** A kind of defect that occurs along a line in a crystal structure.

**Lineage structure.** A plane within a crystal separating slightly misoriented portions of a crystal structure.

**Linear (coordination).** Refers to bonding of a small ion or atom to only two others.

**Lineation.** Any linear feature that may be observed in a rock.

**Liquidus.** The line on a temperature-composition diagram that shows the temperatures above which a system is completely liquid.

**Lithic fragment.** Clastic fragment of a preexisting rock.

**Lithification.** Process of a sediment being converted to a rock; it often involves compaction, desiccation, cementation, and recrystallization.

**Lithophile.** An element that tends to concentrate in silicates rather than in metals or sulfides.

- Lode deposit.** An ore deposit comprising many small veins.
- Low symmetry.** Refers to a crystal or other object with shape characterized by few or no axes and mirror planes of symmetry.
- Lower polarizer.** A fixed polarizing lens located in the substage of a polarizing light microscope.
- Luminescence.** The emission of energy of a different wavelength from a mineral or other substance that has been stimulated by an external energy source of some wavelength(s).
- Luster.** The reflection of light from the surface of something, described by its quality and intensity.
- Macroscopic property.** A mineral property seen or measured in a hand specimen.
- Mafic.** Having a composition that is relatively poor in silicon and rich iron and magnesium; also a general term used to refer to any dark-colored mineral or rock.
- Magma.** Naturally occurring molten rock material.
- Major element.** An element that is a key and essential part of a mineral (*see also* minor element and trace element).
- Malleable.** A term used to describe the tenacity of minerals that are capable of being hammered into shapes.
- Mammillary.** Having a breast-like appearance.
- Mannebach twin.** An uncommon twin law in feldspar.
- Marble.** A metamorphic rock containing primarily calcite or dolomite.
- Marl.** A calcareous rock containing significant amounts of clay and other detrital material.
- Mass number.** Symbolized by  $A$ , the total number of protons and neutrons in an atom.
- Massive.** A term describing a mineral or mineral aggregate lacking in individual grains and internal structure or other distinguishable physical characteristics.
- Mass spectrometry.** An analytical technique for determining elemental and isotopic composition of samples based on measuring mass/charge ratios of ions emitted by the sample.
- Matte.** An impure metallic sulfide mixture produced by smelting.
- Matrix.** Small or fine-grained material that encloses larger grains or crystals.
- Mechanical weathering.** Type of weathering involving the physical decomposition of minerals and rock to produce smaller pieces.
- Melatope.** The trace of the optic axis (uniaxial mineral) or the optic axes (biaxial mineral) in an interference figure; the point where the isogyes cross in a uniaxial interference figure; the points on the isogyes closest to the center of a Bxa or Bxo interference figure.
- Mesodesmic.** Describing a crystal in which the strength of all bonds from a cation to its coordinating anions is equal to exactly one-half the charge of the anions.
- Metabasite.** A metamorphosed mafic rock.
- Metal (element).** A general term often applied to any element that ionizes easily to become a cation; alternatively used to mean any of a class of elements that, when in pure form, usually have a shiny surface, and are good conductors of heat and electricity.
- Metallic bond.** An ideal chemical bond in which electrons are highly delocalized and free to move from one atom to another.
- Metallic element.** *See* metal.
- Metallic luster.** A mineral luster characterized by brightness and shininess and the ability to reflect light.
- Metamorphic.** An adjective referring to the process of metamorphism.
- Metamorphic facies.** A range of pressure-temperature conditions characterized by one or more specific mineral assemblages.
- Metamorphic grade.** The degree of metamorphism; generally equivalent to the temperature of metamorphism.
- Metamorphic series.** An idealized sequence of metamorphic facies typical of a specific geological setting.
- Metamorphic zone.** A region in a metamorphic terrane that is characterized by a specific mineral or mineral assemblage.
- Metamorphism.** Mineralogical or textural changes in rocks in response to changes in physical or chemical conditions.
- Metapelite.** A metamorphic rock equivalent in composition to a clay-rich sediment.
- Metapsammite.** A metamorphic rock equivalent in composition to a sandstone or feldspathic sandstone with minor amounts of clay.
- Metasomatism.** A change in rock composition due to the movement of pore fluids associated with metamorphism.
- Metastable (thermodynamics).** An adjective describing a mineral or mineral assemblage that is not undergoing change but does not have the minimum possible Gibbs free energy.
- Metastable equilibrium.** Equilibrium not representative of the minimal possible Gibbs energy of a system; a chemical system at metastable equilibrium is not reacting but may eventually do so to attain stable equilibrium.
- Micaceous.** Having the properties of a mica, the ability to be split into thin sheets.
- Micrite.** Fine-grained microcrystalline calcite; the term is sometimes used to refer to a chemical sedimentary rock composed of microcrystalline calcite.
- Microcrystalline.** Having crystals that can only be seen with the aid of a microscope.
- Microscopic property.** A mineral property not generally seen or measured without a microscope.
- Migmatite.** A mixed rock composed of different colored bands, often associated with partial melting under high-grade metamorphic conditions.

## Glossary

**Miller index (indices).** Numbers used to describe the orientation of a plane with respect to crystal axes; Miller indices are generally enclosed in parentheses.

**Mineral.** A naturally occurring crystalline substance with composition that is fixed (or varies within limits).

**Mineral class.** A broad category of minerals generally based on commonality of anions or anionic complexes; for example, carbonates and sulfates are mineral classes.

**Mineral formula.** An expression that uses chemical symbols, parentheses, and subscripts to show the composition of a mineral.

**Mineral group.** A group of minerals within a class that are distinguished by common properties.

**Mineralogy.** The study of minerals, their formation, occurrence, properties, composition, and classification.

**Minor element.** An element that substitutes for a major element in a mineral, generally present at the 1% to 5% level (*see also* major element and trace element).

**Mirror plane.** A basic symmetry operator across which a mirror image is created.

**Miscibility.** The ability of two or more phases to mix to produce one homogeneous phase.

**Miscibility gap.** A compositional range in a solution series that is not stable as a single phase; a compositional range where unmixing occurs.

**Mississippi Valley-type deposit.** An epigenetic ore deposit hosted by carbonate rocks; typically, a source of lead and zinc.

**Mode (igneous rock).** The mineral composition of a rock; generally expressed in volume percentage.

**Mohs' hardness scale.** A relative scale of 1 to 10, based on reference minerals, that can be used to describe a mineral's hardness.

**Molar volume.** The volume of one mole of a compound.

**Mole.** The quantity in grams of an element or compound that equals the molecular weight of the substance; one mole of a substance contains Avogadro's number ( $6.022 \times 10^{23}$ ) of atoms/molecules of that substance.

**Monochromatic radiation.** A term describing radiation consisting of one wavelength.

**Monoclinic.** Of or related to the monoclinic crystal system.

**Monoclinic (system).** A crystal system characterized by lattice symmetry  $2/m$ .

**Monovalent.** An ion having a charge of  $\pm 1$ .

**Monzonite.** An intrusive igneous rock of intermediate composition containing approximately equal amounts of plagioclase and K-feldspar; minor quartz, clinopyroxene, biotite, and hornblende may be present.

**Mössbauer spectroscopy.** An analytical technique based on emission and absorption of gamma rays by solids.

**Mother lode.** An ore body that is the source for ore minerals found in a placer.

**Motif.** A pattern that is repeated by symmetry.

**Mud.** Unconsolidated sediment composed of clay and silt.

**Mudstone.** General term for a fine-grained clastic sedimentary rock composed of clay or silt; sometimes used only for such rocks if they are not foliated.

**Native element.** An element that occurs naturally as a mineral.

**Natural.** A product of nature, not of humans or human activities.

**Nesosilicates.** Silicate minerals characterized by individual  $\text{SiO}_4$  tetrahedra linked by bonding to common cations island silicates (*see also* isolated tetrahedral silicates and island silicates).

**Network silicates.** Silicate minerals characterized by  $\text{SiO}_4$  tetrahedra joining to form three-dimensional networks and (*see also* tectosilicates and framework silicates).

**Neutron.** A subatomic particle of neutral charge, generally found in atomic nuclei, which has about the same mass as a proton.

**Noble gas.** Any of the generally unreactive elements (such as Ne, Ar, or Kr) in the eighteenth group of the Periodic Table of the Elements (*see also* inert gas).

**Noncrystalline.** Having a random atomic structure (*see also* amorphous).

**Nonmetal (native element).** A mineral composed of a single nonmetallic element; principally sulfur, graphite, and diamond.

**Nonmetallic (element).** Elements that do not possess the properties of a metal. Nonmetallic elements generally ionize easily to become anions, have a nonmetallic luster, and are poor conductors of heat and electricity when pure.

**Nonmetallic luster.** A mineral luster that is not metallic (*see also* adamantine, vitreous, resinous, silky, pearly, and greasy).

**Nonopaque (mineral).** A mineral that transmits light in thin section.

**Nonprimitive.** Used to describe a unit cell containing more than one lattice point.

**Nonspecial angle.** An angle unrelated to angles between symmetry elements (*see also* general angle).

**Normalization.** The process of converting a mineral analysis to a chemical formula.

**Nuclei.** Plural of nucleus; the central parts of atoms consisting of protons, or of combinations of protons, neutrons, and other particles.

**Numerical aperture.** A number describing the size of the cone of light that can enter a lens.

**O ray.** *See* ordinary ray.

**Obsidian.** Volcanic glass produced by the rapid cooling of a magma.

**Obtuse bisectrix.** The direction bisecting the obtuse angle between the optic axes of a biaxial crystal; perpendicular to the acute bisectrix.

## Glossary

**Obtuse bisectrix figure (Bxo).** The biaxial interference figure seen when looking down the obtuse bisectrix.

**Octahedral (cleavage).** A term used to describe four cleavages that produce octahedral cleavage fragments; for example, fluorite has octahedral cleavage.

**Octahedral (coordination).** The bonding of an ion to six others arranged so that connecting their center forms an octahedron.

**Octahedron.** A 3-dimensional geometric shape composed of eight identical faces, each an equilateral triangle; a form of crystal class  $4/m\bar{3}2/m$ .

**Ocular.** A lens in an eyepiece of a microscope.

**Olivine.** A mafic mineral with general composition  $(\text{Mg},\text{Fe})_2\text{SiO}_4$ .

**Opalescence.** The play of colors seen in some minerals that resembles that of opal.

**Opaque.** The inability to transmit light or to be seen through.

**Open form.** A form that, by itself, cannot enclose three-dimensional space.

**Operation (symmetry).** An operation that repeats a motif, crystal face, or other entity in a symmetrical pattern.

**Operator (symmetry).** Any symmetry element that repeats a motif crystal face or other entity in a symmetrical pattern; rotation axis, mirror plane, inversion center, rotoinversion axis, translation, glide plane, or screw axis.

**Optic axis.** A direction through a crystal along which no double refraction occurs.

**Optic axis (OA) figure.** The interference figure seen when looking down an optic axis.

**Optic normal.** The direction perpendicular to the optic plane of a biaxial mineral, corresponding to the Y-axis.

**Optic normal figure (ON).** The interference figure obtained when looking down a optic normal.

**Optic plane.** The plane containing the optic axes of a biaxial crystal.

**Optic sign.** Either + or -, describing the relationship between indices of refraction ( $\alpha, \beta, \gamma, \varepsilon, \omega$ ). In uniaxial positive (+) crystals,  $\varepsilon > \omega$ ; in uniaxial negative (-) crystals,  $\omega > \varepsilon$ ; in biaxial positive (+) crystals,  $\beta$  is closer in value to  $\alpha$  than to  $\gamma$ ; in biaxial negative (-) crystals,  $\beta$  is closer in value to  $\gamma$  than to  $\alpha$ .

**Orbital (atomic).** A specific energy sublevel occupied by an electron in an atom.

**Order of diffraction.** The value of  $n$  in Bragg's law; the number of cycles a diffracted beam lags behind an adjacent beam with which it is in phase.

**Ordinary ray (O ray).** In a uniaxial crystal, the ray of light that vibrates perpendicular to the optic axis and obeys Snell's law.

**Ore.** Anything that can be taken from the ground and sold for a profit.

**Ore deposit.** An economical concentration of ore minerals.

**Ore grade.** The concentration of ore minerals or elements in ore rock.

**Ore mineral.** A mineral, usually metallic, that is profitable when mined.

**Organic.** A compound containing carbon bonded to hydrogen as an essential and major component.

**Orthogonal.** Perpendicular.

**Orthonet.** A two-dimensional lattice characterized by two translations of different magnitudes at  $90^\circ$  to each other.

**Orthopyroxene.** Orthorhombic pyroxene subgroup dominated by end members enstatite and ferrosilite.

**Orthorhombic.** Of or related to the orthorhombic crystal system.

**Orthorhombic (system).** A crystal system characterized by lattice symmetry  $2/m\bar{2}/m\bar{2}/m$ .

**Orthoscopic illumination.** Illumination caused by light rays all traveling parallel to the tube of a polarizing light microscope.

**Orthosilicates.** An obsolete term for silicates in which silicon tetrahedra do not share any oxygen atoms with each other.

**Ostwald ripening.** The observation that nucleation and precipitation of small particles or crystals gives way to growth of larger particles or crystals over time.

**Out-of-phase.** The condition in which the peaks, and valleys, of two waves do not match in time and space.

**Oxidation.** The process of an atom losing one or more electrons through chemical reaction.

**Oxide.** A binary compound of any element or radical with oxygen.

**Oxidize.** To remove one or more electrons from an atom.

**Paired tetrahedral silicates.** Silicate minerals characterized by  $\text{SiO}_4$  tetrahedra joined to form pairs (see also sorosilicates).

**Paragenesis.** An equilibrium assemblage of minerals.

**Parallel extinction.** Extinction condition in which the principal cleavage or length of a crystal is parallel to the crosshairs of a polarizing light microscope.

**Paramagnetism.** Having a small magnetic susceptibility and being weakly attracted by a magnet.

**Parent isotope.** The initial radioactive isotope of a radioactive decay series.

**Partial crystallization.** Separation of a crystallizing magma into parts by the successive crystallization of different minerals (see also fractional crystallization).

**Partial melting.** Melting of only some of the minerals in a high-grade metamorphic rock.

**Parting.** Breaking of a mineral along a plane of weakness; generally caused by twinning or deformation.

**Pauling's rules.** Five empirical rules, first tabulated by Linus Pauling, describing common structural and bonding features of ionic structures.

## Glossary

**Pearly luster.** A type of luster that appears iridescent, similar to pearls or some seashells.

**Pedion.** An open form consisting of one crystal face unrelated to any other by symmetry.

**Pegmatite.** An exceptionally coarse-grained igneous rock; generally formed by crystallization of water-rich magmas.

**Pelite.** A rock with composition equivalent to a clay-rich sediment.

**Penetration twin.** A twin in which two individual crystals, sharing a common volume of atoms, appear to penetrate or grow through each other.

**Pericline twin.** A common twin law in triclinic feldspars; K-feldspars that have both albite and pericline twins develop the (microscopic) scotch-plaid twinning characteristic of microcline.

**Peridotite.** A general term for an intrusive igneous rock of highly mafic composition; typically composed of olivine ± other mafic minerals and minor plagioclase.

**Period (of elements).** Elements that occupy the same row in the Periodic Table of the Elements.

**Periodic chart.** Also called the Periodic Table; a table in which the chemical elements are arranged in order of their atomic numbers and grouped in columns based on atomic structure.

**Petrogenesis.** The branch of petrology dealing with the origin and formation of rock.

**Petrographic microscope.** A microscope that uses polarizing light for observation and analysis of minerals in grain mounts or in thin section (*see also* polarizing light microscope).

**Petrography.** The branch of petrology dealing with the description and classification of rocks.

**Phaneritic.** Having mineral grains visible without a microscope.

**Phase diagram.** Any of a number of different types of diagrams used to depict mineral compositions or stability of various phases in a system; the axes are usually temperature, pressure, or composition.

**Phase rule.** A consequence of the laws of thermodynamics: for any chemical system in equilibrium, the number of chemical components plus two is equivalent to the number of stable phases plus the number of degrees of freedom:  $C + 2 = P + F$  (*see also* Gibbs phase rule).

**Phenocryst.** The relatively large, conspicuous crystals in a porphyritic rock.

**Phosphate (mineral).** Group of minerals characterized by  $(\text{PO}_4)^{3-}$  in their formulas.

**Phosphate (radical).** The  $(\text{PO}_4)^{3-}$  anionic group.

**Phosphorescence.** A type of luminescence in response to exposure to ultraviolet light, X-rays, or cathode rays which continues after the exposure ceases.

**Phosphorite.** A chemical sedimentary rock composed primarily of phosphate minerals, typically varieties of apatite.

**Phyllite.** A foliated metamorphic rock, lacking in schistosity, having a sparkly or silky sheen due to the presence of fine-grained micas.

**Phyllosilicates.** Silicate minerals containing  $\text{SiO}_4$  tetrahedra joined to form sheets; includes micas and clays *see also* layer silicates (*see also* sheet silicates).

**Piezoelectric.** Having the ability to develop a small amount of electrical potential when strained.

**Pinacoid.** An open crystal form comprised of two parallel faces.

**Pipe.** An igneous body with a more or less round cross section formed as a magma ascends rapidly to the Earth's surface.

**Pisolithic.** A term describing crystals that are very small spheres.

**Placer.** A sedimentary mineral deposit, often fluvial, formed by the concentration of heavy minerals due to gravitational forces.

**Planck's law.** An equation that relates the energy ( $E$ ) of an electromagnetic wave to its frequency ( $\nu$ ):  $E = h\nu$  where  $h$  is Planck's constant.

**Plane defect.** A kind of defect that occurs along the boundary plane of two regions of a crystal or between two grains.

**Plane lattice.** A regular periodic array of points in a plane.

**Plane polarized.** A term describing a moving wave, perhaps light, that is constrained to vibrate in one plane.

**Plaster of Paris.** A white calcium sulfate-based plaster that is more hydrated than anhydrate but less hydrated than gypsum.

**Platy (cleavage).** A cleavage that allows a crystal to be broken into plates.

**Platy (crystal).** Appearing to be plate-like, thin in one dimension compared with the other two (*see also* tabular and lamellar).

**Play of color.** The separation of white light into visible individual colors when it interacts with a mineral; often leading to changes in color as a mineral is turned (*see also* schiller).

**Pleochroism.** The property of an anisotropic crystal to absorb different wavelengths, and thus to have different color, depending on orientation; most easily seen by rotating the stage of a polarizing light microscope while viewing an anisotropic crystal in thin section under plane polarized light.

**Plumose.** A term describing an aggregate of crystals having a feathery appearance.

**Plutonic rock.** An igneous rock that crystallizes at depth in the Earth (*see also* intrusive rock).

**Point defect.** A defect that occurs at one point in a crystal structure.

**Point group.** One of the 32 possible symmetry groups to which a crystal can belong; translation-free equivalent of space groups (*see also* crystal classes).

## Glossary

- Point symmetry.** Symmetry about a point that may include rotation axes, mirror planes or an inversion center.
- Polarized (ion).** A term describing an ion with uneven electron distribution so that it does not behave as an isotropic ionic sphere in a crystal structure.
- Polarized (wave).** A term describing a moving wave, perhaps light, that is not free to vibrate in all directions.
- Polarizing light microscope.** A microscope that uses polarizing light for observation and analysis of minerals in grain mounts or in thin section (*see also* petrographic microscope).
- Pole.** A perpendicular to a face on a crystal.
- Polychromatic.** Containing multiple wavelengths (*see also* monochromatic).
- Polyhedron.** A three-dimensional geometric figure having four or more faces.
- Polymer.** A chemical unit formed by the tight linking of individual molecules.
- Polymerization.** The connecting of polyhedra or other structural units into chains, sheets, or networks by sharing of atoms.
- Polymorphs.** Minerals that have identical compositions but different atomic arrangements; for example, calcite and aragonite are polymorphs.
- Polysynthetic twinning.** Repeated twinning of three or more individuals according to the same twin law and in a parallel manner, producing a twinned grain composed of many thin parallel sheet-like twin domains.
- Porcelain.** A special type of high-quality white ceramic.
- Porphyritic.** Containing large crystals in a fine ground-mass of minerals or glass.
- Porphyroblast.** A large mineral crystal, produced by metamorphism, in a finer-grained matrix.
- Porphyry (igneous rock).** A rock containing relatively large crystals (phenocrysts) in a fine-grained ground mass that may be crystalline or glassy.
- Porphyry (ore deposit).** An ore deposit in which the ore is concentrated in closely spaced small veins and veinlets.
- Portland cement.** The most common kind of cement; composed of a mixture of lime, silica, alumina, and iron oxides.
- Powder diffraction.** Diffraction of X rays by a powdered sample.
- Powder Diffraction File (PDF).** The X-ray powder diffraction reference file used by most mineralogists.
- Precambrian shield.** An ancient geological terrane that has been stable for a long time; typically in the central area (craton) of major continents.
- Precious metals.** Gold, silver, platinum, and sometimes other platinum group elements.
- Precipitate.** To form solid material from material dissolved in a liquid; precipitated material generally but not always settles to the bottom of the liquid.
- Prehnite-pumpellyite (facies).** One of the two lowest pressure-temperature facies recognized by Eskola.
- Primary mineral.** A mineral formed at the same time as its host rock (*see also* secondary mineral).
- Primitive.** Describing a unit cell containing in total one lattice point; typically unit cells are chosen so that a primitive unit cell contains one-eighth of a lattice point at each corner.
- Principal axis.** The most prominent or unique crystal axis in a crystal or the most prominent or unique rotational axis of symmetry in a crystal; generally they coincide.
- Principle of parsimony (Pauling's fifth rule).** The number of different components in a crystal tends to be small.
- Prism.** A crystal form characterized by two or more crystal faces parallel to a common direction.
- Prismatic (cleavage).** A term used to describe multiple cleavages all parallel to a common direction in a crystal.
- Prismatic (crystal).** Having the appearance of a prism or prisms; appearing as a long crystal with parallel sides.
- Prograde metamorphism.** Metamorphism in response to increasing temperature.
- Prograde reactions.** Reactions that take place in response to an increase in temperature.
- Progressive metamorphism.** Metamorphism that proceeds by steps from low grade to high grade.
- Proper rotation axis.** A rotation axis of symmetry that does not involve inversion.
- Proton.** A subatomic particle, generally found in the nuclei of atoms, having the smallest amount of positive electric charge occurring in nature.
- Psammite.** A rock equivalent in composition to a sandstone or feldspathic sandstone with minor amounts of clay.
- Pseudohexagonal.** Symmetry that appears to be hexagonal but is not; for example, some books of biotite.
- Pseudosymmetry.** Symmetry that appears to be present but, with better measurement or observation, would be found to be lacking.
- Pycnometer.** A small bottle with a tight-fitting stopper that is used to determine specific gravity.
- Pyralspite.** Refers to a garnet that is a solid solution of pyrope, almandine, and spessartine.
- Pyramid.** An open crystal form of 3, 4, 6, 8, or 12 nonparallel faces that meet at a point.
- Pyramidal cleavage.** Cleavage that gives cleaved crystals a pyramid shape.
- Pyritohedron.** A 3-dimensional geometric solid consisting of 12 irregular pentagonal faces; also refers to a form of crystal class 23 or  $2/m\bar{3}$ .
- Pyroelectric.** Having the ability to develop a small amount of electrical potential when heated.

## Glossary

**Pyroxene-hornfels (facies).** A high-temperature, low-pressure metamorphic facies characterized by temperatures slightly lower than the sanidinite facies.

**Pyroxene quadrilateral.** A quadrilateral with diopside, hedenbergite, enstatite and ferrosilite at the corners that is used to plot ideal pyroxene compositions.

**Pyroxenite.** An ultramafic intrusive rock composed primarily of pyroxene with lesser amounts of olivine, biotite, or hornblende.

**Quartz plate.** An accessory plate for polarizing light microscopes that is composed of quartz of known optical orientation.

**Quartz wedge.** An elongate wedge of clear quartz of known optical orientation that may be inserted in a polarizing light microscope tube to analyze a crystal's optical properties.

**Quartzite.** A hard but unmetamorphosed sandstone or the metamorphic equivalent.

**Quartzose.** Containing quartz as a primary component.

**Radiating.** Emanating from a common point (*see also* divergent).

**Radical.** A chemical group that has acquired an electrical charge; often surrounded by parentheses in mineral formulas.

**Radioactivity.** The spontaneous decay of atoms of certain isotopes into new isotopes, accompanied by the emission of high energy particles.

**Radioisotope.** An isotope that is the product of radioactive decay.

**Radius ratio principle (Pauling's first rule).** Cation-anion distances are equal to the sum of their effective ionic radii, and cation coordination numbers are determined by the ratio of cation and anion radii.

**Raman spectroscopy.** Any of a number of kinds of spectroscopy that involves measuring inelastic scattering (Raman scattering) of monochromatic visible, near infrared, or near ultraviolet light, generally from a laser.

**Rare earth elements.** Elements (such as Ce, Pr, and Nd) with atomic numbers 58 through 71 and valence electrons in  $4f$  orbitals (*see also* lanthanide elements).

**Recrystallization.** Formation of new crystals from preexisting material; the new crystals need not be the same species or composition as the material from which they form.

**Recrystallize.** To form new crystalline mineral grains in a rock, generally by metamorphism.

**Reduce.** Said of an element; to gain one or more electrons.

**Reduction.** The process of an atom gaining one or more electrons through chemical reaction.

**Reentrant angle.** An angle between two crystal faces that points or is directed inward toward the center of the crystal; usually associated with twins.

**Reflected light microscopy.** Microscopic examination using a light source that reflects from the surface of a sample; reflected light microscopy is useful for identifying opaque minerals in thin section.

**Reflection (light).** Coherent scattering of energy by atoms in a two-dimensional surface.

**Reflection (symmetry).** A term describing the operation that relates two crystal faces or other entities across a mirror plane.

**Refraction.** The deflection of a ray, perhaps light, due to its passage from one medium to another of different ray velocity.

**Refractive index.** The ratio of the velocity of light in a vacuum to the velocity of light in a given medium (*see also* index of refraction).

**Refractive index oil.** A liquid of known index of refraction.

**Refractometer.** A device for determining the index of refraction of a crystal or other material.

**Regional metamorphism.** Metamorphism affecting a large region; caused by pressure related to depth in the Earth and temperature related to geothermal gradient (*see also* burial metamorphism).

**Regular polyhedron.** A coordinating polyhedron in which all cation-anion bond lengths are equal.

**Relative hardness.** The hardness of a mineral compared to other minerals, usually based on Mohs' hardness scale.

**Relief.** The apparent topography of a crystal or crystals seen under a microscope.

**Remnant heavy isotope.** Isotopes that formed at the time the universe formed and that still exist today.

**Reniform.** Having a kidney-shaped appearance.

**Reserves.** Ore that has been identified and that could be extracted at a profit.

**Residual (mineral).** A mineral that has been concentrated in place by weathering and leaching of rock.

**Residual (phase).** The remaining liquid, or phases that crystallize from such a liquid, after a magma has mostly solidified.

**Residuum.** Insoluble material remaining after intense weathering.

**Resinous.** A term used to describe mineral lusters that have the appearance of resin.

**Resistate.** Insoluble material produced by chemical weathering; the term is also used in a general sense to refer to any sedimentary material of low solubility.

**Retardation.** The distance that one wave lags behind another; specifically the distance that the fast ray lags behind the slow ray upon emergence from a crystal.

**Reticulated.** Crystals that have a lattice-like appearance.

**Retrograde metamorphism.** Metamorphism that takes place in response to decreasing temperature.

**Retrograde reactions.** Metamorphic reactions that take place in response to decreasing temperature.

**Rhomb.** A parallelogram having equal length sides and interior angles of  $60^\circ$  and  $120^\circ$ .

**Rhombohedral (point groups).** Any of the point groups that include the rhombohedral form ( $\bar{3}, 32, \bar{3}2m$ ).

## Glossary

**Rhombohedral plane lattice.** A two-dimensional lattice characterized by two translations of equal magnitude at  $60^\circ$  to each other (*see also* hexanet).

**Rhombohedron.** A parallelepiped with six identical rhomb-shaped faces.

**Rhyolite.** An extrusive igneous rock of silicic composition containing 10% to 50% quartz and K-feldspar as the major feldspar; plagioclase, biotite, and hornblende may be present (*see also* granite).

**Rietveld method.** A method for determining the arrangement of atoms in a crystal that is based on powder diffraction data.

**Right handed.** A relative phrase referring to objects that rotate or point to the right.

**Ring silicates.** Silicate minerals characterized by  $\text{SiO}_4$  tetrahedra joining to form rings (*see also* cyclosilicates).

**Rotation.** A term describing an operation that relates two crystal faces or other things about a rotational axis of symmetry.

**Rotation axis.** A symmetry element that relates identical crystal faces or other things by rotation of  $60^\circ$ ,  $90^\circ$ ,  $120^\circ$ ,  $180^\circ$ , or  $360^\circ$  about an axis.

**Rotational symmetry.** A type of symmetry that relates identical crystal faces or other things by rotation of  $60^\circ$ ,  $90^\circ$ ,  $120^\circ$ ,  $180^\circ$ , or  $360^\circ$  about an axis.

**Rotoinversion.** A type of symmetry that combines rotation of  $60^\circ$ ,  $90^\circ$ ,  $120^\circ$ ,  $180^\circ$ , or  $360^\circ$  with inversion.

**Salt.** Any of a group of chemical compounds derived from an acid by replacing  $\text{H}^+$  with a metal cation; also a general term used to describe any mineral that has high solubility in water; more specifically used to describe halite, sylvite, and other alkali halides.

**Salt dome.** A diapiric salt body that rises through a sedimentary pile due to its low density in relation to surrounding rocks.

**Sand.** A detrital particle between 0.062 and 2 mm in diameter, or a sediment composed primarily of such particles.

**Sandstone.** A clastic sedimentary rock composed primarily of sand-sized particles with or without a finer matrix.

**Sanidinite (facies).** A low-pressure metamorphic facies characterized by the presence of sanidine and other very high temperature minerals.

**Scalenohedron.** A 3-dimensional geometric solid with 8 or 12 identical faces shaped like a scalene triangle.

**Scanning electron microscope (SEM).** A kind of electron microscope that rasteres a beam of focused electrons across a sample while collecting backscatter or secondary electrons to obtain an image.

**Scattering.** When an incident ray strikes an atom or other object and is reemitted equally in all directions.

**Schiller.** The separation of white light into visible individual colors when it interacts with a mineral; often leading to changes in color as a mineral is turned (*synonymous with* play of colors).

**Schist.** A well-foliated metamorphic rock, characterized by parallel alignment of micas and other planar or tabular minerals, which has minerals grains that are visible with the naked eye.

**Schistosity.** The ability to be split into thin flakes or slabs due to a parallel arrangement of micas or other planar or tabular minerals.

**Schottky defect.** A defect caused when an atom is missing from a crystal structure.

**Schrödinger wave model.** A fundamental mathematical model that describes wavelike motion of electrons and forms the basis for quantum mechanics.

**Scientific theory.** A hypothesis that has been tested and supported by observation so much that it is generally accepted as being correct.

**Screw axis.** A compound symmetry element that repeats a motif or other entity after rotation and translation combined.

**Screw dislocation.** A kind of line defect caused by the apparent spiraling of a crystallographic plane.

**Secondary electrons.** Electrons produced as ionization products when a high-energy electron beam interacts with a sample.

**Secondary ion mass spectrometry (SIMS).** An analytical technique used to analyze surface or thin films that involves bombarding a sample with a focused ion beam and analyzing secondary ions using mass spectrometry (*synonymous with* ion microprobe).

**Second setting.** Refers to choosing monoclinic unit cells so that  $b$  is the only non- $90^\circ$  angle.

**Secondary mineral.** A mineral formed subsequent to the formation of the rock that hosts it (*see also* primary mineral).

**Secondary radiation.** Radiation emitted by oscillating electrons that were perturbed by an incoming beam.

**Sectile.** A term used to describe the tenacity of a mineral that can be cut into shavings with a knife.

**Sediment.** Solid material produced by weathering; sometimes used more specifically to refer to material that has been transported and deposited.

**Sedimentary.** Adjective pertaining to a rock formed from sediment or to a mineral formed by sedimentary processes.

**Sedimentary rock.** A rock produced by lithification of sedimentary material, either clastic or chemical.

**Selenide.** A mineral that is a combination divalent selenium with one or more metallic elements.

**Semimetal (element).** A poorly defined class of elements (such as arsenic) that do not ionize as easily as metals. When pure, semimetals have some of the properties of metals, including shiny appearance, good conduction of heat and electricity, and capability of fusing, hammering, or drawing into sheets or wires.

**Semimetal (native element).** Native elements that are semimetals include arsenic, antimony, and bismuth.

**Series.** Minerals with compositions that can be described in terms of two or a few chemical end members.

## Glossary

**Serpentinite.** A rock, formed by alteration of a preexisting mafic or ultramafic rock, which contains primarily serpentine group minerals.

**Shale.** A foliated, fine-grained clastic sedimentary rock with grain sizes smaller than 0.004 mm.

**Sheet silicates.** Silicate minerals characterized by  $\text{SiO}_4$  tetrahedra joining to form sheets; includes micas and clays (*see also* layer silicates and phyllosilicates).

**Sheetrock.** Construction material used as wall board, composed of gypsum-based plaster encased in a paper jacket (*see also* gypsum board).

**Shock metamorphism.** Metamorphism caused by a transient high-pressure condition such as a meteor impact (*see also* dynamic metamorphism and cataclastic metamorphism).

**Sialic.** A term describing a rock that is rich in silica and alumina (in common usage, synonymous with silicic).

**Siderophile.** An element that has a weak affinity for oxygen and sulfur and that is readily soluble in molten iron and iron alloys.

**Sign of elongation.** Either positive (+) or negative (-); length fast crystals have negative sign of elongation; length slow crystals have a positive sign of elongation.

**Silicate.** A crystalline compound with a crystal structure based on  $\text{SiO}_4$  tetrahedra.

**Silicic.** A term describing an igneous rock that is rich in silica.

**Silky.** A type of luster that gives crystal faces or other surfaces the appearance of being composed of fine fibers.

**Silt.** Clastic sediment composed primarily of grains 0.004 to 0.062 mm in size.

**Siltstone.** A clastic sedimentary rock composed primarily of silt-sized particles.

**Simple substitution.** A substitution of one ion for another of similar size and charge in a crystal structure; for example, the substitution of  $\text{Mg}^{2+}$  for  $\text{Fe}^{2+}$  in many silicates.

**Simple twin.** A twin composed of two individual crystals sharing a common plane of atoms.

**Single chain silicates.** Silicate minerals characterized by  $\text{SiO}_4$  tetrahedra joined to form linear chains one tetrahedron wide; includes pyroxenes and pyroxenoids.

**Single crystal diffraction.** Diffraction of X-rays by a single crystal.

**Skarn.** A contact metamorphic zone surrounding an igneous intrusion; often affected by metasomatism (*see also* contact aureole).

**Skarn deposit.** An economical mineral deposit associated with a skarn.

**Slag.** Calcium-rich silicate waste material from smelting of metal ore concentrates.

**Slaked lime.** Compound of approximate composition  $\text{Ca}(\text{OH})_2$  produced when lime reacts with water (*see also* portlandite).

**Slate.** A very fine-grained foliated metamorphic rock that exhibits fissility.

**Slow ray.** The slower of the two rays produced by double refraction.

**Snell's law.** The arithmetic law that relates the refractive indices of two media to the angles of incidence and refraction.

**Soft radiation.** The relatively low energy X-radiation used in most X-ray diffraction studies; soft radiation is more dangerous to humans than hard radiation.

**Solid-solid reaction.** A reaction involving only solid phases.

**Solid solution.** A homogeneous crystalline solid in which one or more atoms or molecules may substitute for each other.

**Solid solution series.** A crystalline solid with composition that varies between specific end members.

**Solid state diffusion.** The movement of atoms or molecules through solid material, such as the migration of atoms through minerals.

**Solidus.** The line on a temperature-composition diagram that shows the temperatures below which a system is completely solidified.

**Solubility.** The extent to which a material will dissolve in another; generally used to refer to the dissolution of compounds in water, but sometimes used to refer to the solubility of compounds in other liquids or solids.

**Solvus.** The line on a phase diagram that outlines a miscibility gap.

**Sorosilicates.** Silicate minerals characterized by  $\text{SiO}_4$  tetrahedra joined to form pairs (*see also* paired tetrahedral silicates); for example, epidote.

**Space group.** Permissible three-dimensional symmetry groups of all types of symmetry operations; one of the 230 possible symmetries a crystal structure may have.

**Space group operators.** Symmetry operators that are manifested in space groups but not in point groups: translation, screw axes, glide planes.

**Space symmetry.** The symmetry of a three-dimensional atomic structure; symmetry including space group operations.

**Sparry.** Used to describe clean, coarse-grained calcite, especially a clean, coarse-grained calcite cement in a sedimentary rock.

**Special angles.** Angles between symmetry axes or planes, or faces on a crystal, that result in the faces having special orientations with respect to crystal symmetry.

**Special form.** A crystal form with face normals at special angles to each other.

**Special point.** On a stereo diagram, a point that is located at a special position, coincident with an inversion center, rotational axis, or mirror plane.

**Specific gravity (G).** The mass of a mineral divided by the corresponding mass of water at 1 atm, 4 °C.

**Spectrometer.** An instrument used to determine the wavelength of electromagnetic radiation.

**Spectroscopy.** Any of the different analytical techniques that involve measuring the interaction of energy of different

## Glossary

### Glossary: Mineralogy

wavelengths with a sample, generally involving either differential absorption or emission, or both.

**Sphenoid.** An open crystal form having two nonparallel faces related by a 2-fold axis of symmetry.

**Square net.** A two-dimensional lattice characterized by two translations of equal magnitude at 90° to each other.

**Stability field.** A range of conditions over which a mineral or mineral assemblage is stable.

**Stable (thermodynamics).** Adjective describing a mineral or mineral assemblage that has the minimum possible Gibbs free energy and so is not prone to change.

**Stable equilibrium.** The most thermodynamically stable conditions possible for a chemical system; systems at stable equilibrium will not react or change unless conditions change.

**Stable isotope.** An isotope that is not spontaneously radioactive.

**Stable mineral.** For a chemical system, an individual mineral or a mineral of an assemblage that has the lowest possible Gibbs free energy; stable minerals do not react to form other minerals or compounds.

**Stacking fault.** A type of plane defect caused by stacking irregularities in a crystal structure.

**Stalactitic.** Having the appearance of a stalactite or other speleothem.

**Stellated.** A term describing an aggregate of crystals having a star-like appearance.

**Steno's law.** Also termed the "constancy of interfacial angles"; a law that says angles between comparable crystal faces of the same mineral will always be the same regardless of crystal shape or size.

**Stereo diagram.** Projection of a crystal or other shape onto a circle so that three-dimensional relationships may be depicted on a piece of paper.

**Stoichiometry.** The exact proportions, specified by a chemical formula, of the elements that comprise a mineral or other compound.

**Strain energy.** Energy associated with the physical distribution and alignment of mineral grains within a rock.

**Streak.** The color of a mineral when finely powdered; usually determined using a ceramic streak plate.

**Striation (twin).** One of a set of fine lines that may appear on a crystal face or cleavage surface due to the presence of twinning.

**Subgroup.** Minerals within a mineral group that are naturally related for chemical or other reasons.

**Subhedral.** A term describing a crystal that is only partly bounded by well-developed crystal faces or whose growth was partially restrained by adjacent crystals.

**Submetallic luster.** A type of luster that appears somewhat metallic.

**Substage.** An assembly of filters, polarizers, condensing lenses, and apertures located below the stage of a polarizing light microscope.

**Sulfate (mineral).** Group of minerals characterized by  $(SO_4)^{2-}$  in their formula.

**Sulfate (radical).** The  $(SO_4)^{2-}$  anionic group.

**Sulfide.** A chemical group, or group of minerals, with structures characterized by metals bonding to sulfur; for example, galena ( $PbS$ ).

**Sulfosalt.** A type of sulfide in which both a metallic and a semimetallic element are present; for example, enargite ( $Cu_3AsS_4$ ).

**Supergene.** A term describing an ore deposit enriched by flowing fluids after the time of initial deposition.

**Swelling clay.** Clay material, such as bentonite or other clays of the smectite group, that is capable of expanding greatly and absorbing water between individual clay layers.

**Syenite.** An intrusive igneous rock of intermediate composition in which the amount of K-feldspar exceeds the amount of plagioclase; biotite and hornblende may be present but quartz is generally absent.

**Symmetrical extinction.** Extinction that occurs at equal angles, in either direction, to a principal cleavage or length of a crystal when viewed with a polarizing light microscope.

**Symmetry (crystal).** The relationship between the crystal faces or other features, including physical properties, of a mineral that reflect internal ordering of atoms.

**Symmetry element.** A single inversion center, rotation axis, mirror plane, or other symmetry operator.

**Symmetry operation.** An operation that repeats a motif, crystal face, or other entity in a symmetrical pattern.

**Syngenetic.** Refers to a mineral deposit that is formed at the same time as its host rocks.

**System (chemical).** Any rock, mineral assemblage, or theoretical composition that is chemically isolated.

**Tabular.** Having a tab-like appearance; being thin in one dimension compared to the other two (*see also* platy and lamellar).

**Tailings.** Waste material that remains after processing of ore.

**Tectosilicates.** Silicate minerals characterized by  $SiO_4$  tetrahedra joined to form three-dimensional networks (*see also* network silicates and framework silicates).

**Telluride.** A compound that is a combination of tellurium with one or more other metallic elements.

**Tenacity.** A term referring to the ease with which, and the way in which a mineral breaks or bends.

**Terminating face.** A face, or one of a collection of faces, that terminates (closes) an open form; common terminating faces are pedions, pinacoids, or pyramids.

**Ternary solution.** A solid solution series that can be characterized by three end members.

**Tetartoid.** A 3-dimensional geometric solid having 12 identical five-sided faces; a form of crystal class 23.

**Tetragonal.** Of or related to the tetragonal system.

**Tetragonal (system).** A crystal system characterized by lattice symmetry  $4/m2/m2/m$ .

## Glossary

**Tetragonal packing.** The planar arrangement of spheres of identical size in a square pattern; each sphere is surrounded by eight others.

**Tetrahedral (coordination).** The bonding of an ion to four others arranged so that connecting their centers forms a tetrahedron.

**Tetrahedron.** A geometric solid bonded by four equilateral triangles; specifically refers to a crystal form of the cubic system having four equilateral triangular faces.

**Tetrahedron (silica).** A tetrahedral arrangement of  $\text{Si}^{4+}$  and  $\text{O}^{2-}$  ions having an overall composition and charge of  $(\text{SiO}_4)^{4-}$ .

**Tetravalent.** An ion having a charge of  $\pm 4$ .

**Thermodynamics.** The branch of physics and physical chemistry that deals with the relationships between heat and other forms of energy, and of the conversion of one into the other.

**Thermoluminescence.** A type of luminescence caused by heating a mineral.

**Thin section.** A thin piece of rock glued on a glass slide and uniformly ground to a thickness of about 0.03 mm.

**Tie line.** A line connecting two mineral compositions on a phase diagram; tie lines show possible mineral assemblages.

**Till.** Unsorted and unstratified glacial deposits.

**Tonalite.** An intrusive igneous rock of silicic composition in which the only major feldspar is plagioclase; biotite and hornblende are typically present.

**Trace element.** An element that is not essential in a mineral but that is found in very small quantities in its structure or absorbed on its surface (*see also* major element and minor element).

**Trachyte.** An extrusive igneous rock of intermediate composition in which the amount of K-feldspar exceeds the amount of plagioclase; quartz, biotite, and hornblende may be present.

**Transition element.** An element from the fourth and thirteenth group of the Periodic Table of the Elements and characterized by valence electrons in *d*-orbitals (*see also* transition metal).

**Transition metal.** *See* transition element.

**Translating.** Moving in one direction by a fixed increment.

**Translation.** A shift in position without rotation.

**Translucent.** The ability to transmit light without being transparent.

**Transmitted light microscopy.** Microscopic examination using light that passes through a crystal before reaching the eye; the standard kind of microscopy used by petrologists.

**Transparent.** The ability to be seen through; to transmit light with little loss in intensity.

**Trapezohedron.** A crystal form of 6, 8, or 12 faces, each a trapezium.

**Travertine.** A type of limestone formed by rapid precipitation of calcite, often but not necessarily associated with hot springs.

**Triangular (coordination).** Coordination of an ion to only three others.

**Triclinic.** Of or related to the triclinic system.

**Triclinic (system).** A crystal system characterized by lattice symmetry  $\bar{1}$ .

**Trigonal (system).** A subsystem of the hexagonal system containing all point groups lacking a 6-fold or  $\bar{6}$ -fold axis of symmetry.

**Trioctahedral.** Describing a layered mineral structure in which three of three available octahedral sites are occupied.

**Trisoctahedron.** A 3-dimensional geometric solid having 24 identical faces, each of which is an isosceles triangle; also refers to a form of crystal class  $432$ ,  $2/m\bar{3}$ , or  $4/m\bar{3}2/m$ .

**Trivalent.** An ion having a charge of  $\pm 3$ .

**Tumble.** To polish a gem in a revolving box or barrel.

**Twin.** An intergrowth of two or more single crystals of the same mineral that share common atoms, typically along planes.

**Twin domain.** Part of a twinned crystal that contains no twins and has a contiguous atomic arrangement.

**Twin lamellae.** Thin parallel individual twin domains that are part of a polysynthetic twin.

**Twin law.** A definition of a twin relationship in a mineral or mineral group, specifying the twin axis, center, or plane, defining the composition surface or plane if possible, and giving the type of twin.

**Twin plane.** A plane that separates two twin domains.

**Twinnning.** The development of intergrowths of two or more single crystals of the same mineral that share common atoms, typically along planes.

**Ugrandite.** A garnet that is a solid solution of uvarovite, grossular and andradite.

**Ultramafic.** A general adjective referring to igneous rocks rich in magnesium and iron, and relatively poor in silicon, and containing primarily mafic minerals.

**Ultraviolet light.** Electromagnetic radiation with wavelengths slightly less than visible light.

**Uneven fracture.** A fracture that produces rough and irregular surfaces (*see also* irregular fracture).

**Uniaxial.** A term describing a crystal that has only one optic axis; such crystals belong to the tetragonal or hexagonal crystal systems.

**Unit cell.** Parallelepiped defined by three noncoplanar unit translations in a lattice; all crystals may be thought of as a collection of unit cells.

**Unit cell parameters.** The dimensions and angles that characterize a unit cell shape; typically symbolized by  $a$ ,  $b$ ,  $c$ ,  $\alpha$ ,  $\beta$ , and  $\gamma$ .

**Univariant line.** A line on a phase diagram; generally representing a reaction and having one degree of freedom.

**Unmixing.** The separation of an initially homogeneous solid, liquid, or gas phase into two or more of different compositions.

## Glossary

**Unpolarized.** A term describing light or any other wave that is free to vibrate in any direction.

**Unstable (thermodynamics).** Adjective describing a chemical system that does not have the minimum possible Gibbs energy; an unstable chemical system will react to obtain metastable or stable equilibrium if slightly perturbed.

**Unstable isotope.** A radioactive isotope of an element (*see also* radioisotope).

**Upper polarizer.** A polarizing filter that may be inserted in the tube of a polarizing light microscope in order to view a sample under crossed polars (*see also* analyzer).

**Vacancy.** A site in a mineral structure that is vacant but capable of holding an atom or ion under some circumstances.

**Valence.** The charge of an ion.

**Valence electron.** The outermost electrons of an atom that contribute most to the atom's bonding.

**Van der Waals bond.** A weak type of electrostatic bond, generally insignificant in minerals, created by brief fluctuations in the balance of positive and negative charges. Important in talc and graphite.

**Vapor.** Used in a general sense to refer to a liquid, gas, or supercritical fluid; also used to refer to any gaseous phase emanating from a liquid or a solid.

**Variety.** A division of a mineral species based on particular physical characteristics such as color; for example, chalcedony is a variety of quartz.

**Verneuil technique.** A technique for synthesizing gems that involves melting powder and allowing it to accumulate and crystallize on a boule.

**Vesicle.** A cavity in a lava formed by a gas bubble trapped during cooling of the lava.

**Viscosity.** The thickness, or internal resistance to flow, of a liquid.

**Visible light spectroscopy.** A type of spectroscopy that deals with the visible region of the electromagnetic spectrum, typically involving measuring the absorption of light by a sample.

**Vitreous.** A type of luster resembling that of glass.

**Volatile.** A chemical material, such as water or carbon dioxide, in a magma or rock, that may concentrate as a gas or vapor.

**Volcanic rock.** An igneous rock that crystallizes at or very near Earth's surface (*see also* extrusive rock).

**Volumetric analysis.** Any kind of quantitative analysis that is based on measured volumes of chemical solutions, often involving titration.

**Wave front.** The front, or leading edge, of multiple in-phase waves traveling in the same direction.

**Wavelength dispersive X-ray spectroscopy (WDS).** An analytical technique that involves measuring the wavelength of X-rays emitted, in order to identify the elements present and their concentrations.

**Weathering.** Alteration of a rock by surface agents; for example, water, wind, sun.

**Wet chemical analysis.** Any of several kinds of chemical analysis that involve dissolving a sample to create a solution, often involving titration, precipitation, gravimetry, or colorimetry.

**White light.** Light composed of a spectrum of different wavelengths.

**White radiation.** Electromagnetic radiation composed of a spectrum of wavelengths in some interval (*see also* continuous radiation).

**Whiteschist.** A very high pressure-temperature metamorphic rock containing white micas and talc.

**X-radiation.** Electromagnetic wave with wavelength much shorter than visible light, on the order of 0.1Å to 100Å.

**X-ray.** Electromagnetic wave with wavelength much shorter than visible light, on the order of 0.1Å to 100Å (*see also* X-radiation).

**X-ray diffraction.** The apparent bending or channeling of X rays when they pass through a crystal structure.

**X-ray fluorescence (XRF).** Fluorescence of X rays caused by an incident X-ray beam striking a sample.

**Xenolith.** A rock inclusion picked up by a magma and present after the magma has solidified.

**Zeolite (facies).** The lowest pressure-temperature metamorphic facies; characterized by zeolites and other very low-grade minerals.

**Zone (compositional).** An area in a crystal of distinct chemical composition.

**Zone (crystallographic).** A collection of two or more crystal faces all parallel to the same line.

**Zone (metamorphic).** A region in a metamorphic terrane that is characterized by a specific mineral or mineral assemblage.

**Zone axis.** A line parallel to multiple crystal faces in a crystal.

**Zoned.** A term describing a crystal that has compositional zonation.

**Zoning.** Variation in the composition of a crystal, typically from core to margin (*see also* compositional zoning).



# Elements and Minerals

The Earth is composed of minerals. If we are to understand the properties of the Earth and its minerals, we must understand basic chemistry and the elements. In this chapter we define minerals and elements and discuss why they are important. We review the development of modern chemistry and how it relates to mineralogy and discuss the behavior of elements in minerals and the significance of mineral formulas.

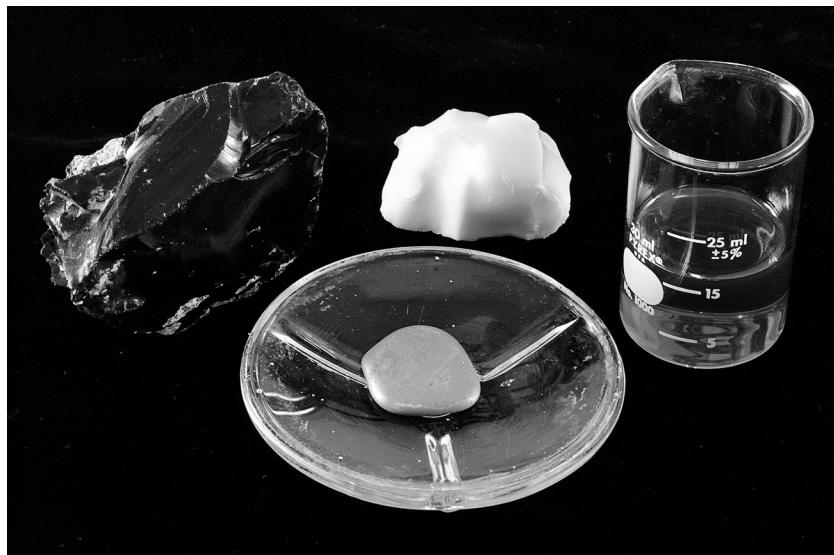
## MINERALS

The word **mineral** means different things to different people. In ancient times, people divided all things on Earth into the animal, vegetable, or mineral kingdoms, so a mineral was any natural inorganic substance. Today, dieticians use the term to refer to nutritional elements such as calcium, iron, or sodium, while miners often use it for anything they can take out of the ground—including coal, sand, or gravel. Mineralogists and geologists of the twentieth century developed a more specific definition: Minerals are chemical compounds that are normally crystalline and form by geological processes. They must also have a well-defined chemical composition. For now it is sufficient to know that **crystalline** means “having an orderly and repetitive atomic structure,” and well defined means “varying within limits.” In the past, a substance was not considered a mineral if it was the result of an organic process. Today, however, that part of the definition has been dropped by some people who consider biogenic crystalline substances such as calcium phosphate (apatite) in bones or teeth, or calcium carbonate (calcite) in shells, to be minerals. Mineralogists

have named and described more than 3,000 minerals; they discover about 50 more each year.

Many mineral-related substances exist but do not fit the definition for one reason or another (Figure 1). Synthetic diamonds and rubies, for example, are not considered true minerals because they are not natural. Ice is a mineral, but its liquid counterpart, water, is not. Refined sugar is crystalline but is not considered a mineral because it is human made and organic. Window glass, made mostly from quartz, is not a mineral because it is not crystalline. The rust that forms on our cars is not considered a mineral, although the mineral goethite has nearly the same composition and properties. For historical reasons, elemental mercury is considered a mineral, even though it is liquid at normal temperatures.

Two major factors set most minerals apart from other crystalline materials: time and temperature. Many minerals form at high temperatures, and many form over long periods of time. Igneous and metamorphic minerals grow at temperatures hundreds or even 1,000°C (3,630°F) hotter than normal Earth surface conditions. Their crystallization and metamorphism may take millions of years. Sedimentary minerals, while not forming at high temperatures,



**FIGURE 1** Natural materials that are not minerals: coal (upper left), opal (top center), oil (right), and mercury (bottom). These are not minerals because they are not crystalline. Oil and mercury also flunk the definition of a mineral because they are liquids. The watch glass and beaker flunk because they are not crystalline and they are not natural.

often crystallize or recrystallize over long periods of time. High temperatures and long periods of time lead to highly ordered crystal structures that synthetic and organic processes cannot normally imitate. Scientists can make synthetic gems in the laboratory; many of these are beautiful and valuable. However, if we examine the fine details of their structures, we find they are generally not as well ordered as their natural equivalents. In addition, there are many subtle differences between minerals and their synthetic or organic counterparts.

## THE IMPORTANCE OF MINERALS

An understanding of minerals is important for many reasons. A geologist considers minerals as the basic building blocks comprising nearly the entire crust of

the Earth. If geologists and others are to understand the Earth, its formation, and its dynamics, they must understand minerals. Knowledge of minerals is essential in many engineering fields. Constructing an office building would later prove foolish when the building collapsed because the underlying rock did not provide a sound foundation, or if construction materials were not adequate (Box 1). Miners and gem dealers view minerals as commodities to process and sell, while industrial manufacturers see minerals as the raw materials for marketable products (Figure 2). In the electronics industries, minerals or their synthetic equivalents are used to make computer chips, diodes, capacitors, superconductors, and other crucial components. A basic and wondrous asset of our natural world, historically minerals have been the foundation of much, if not all, technology.

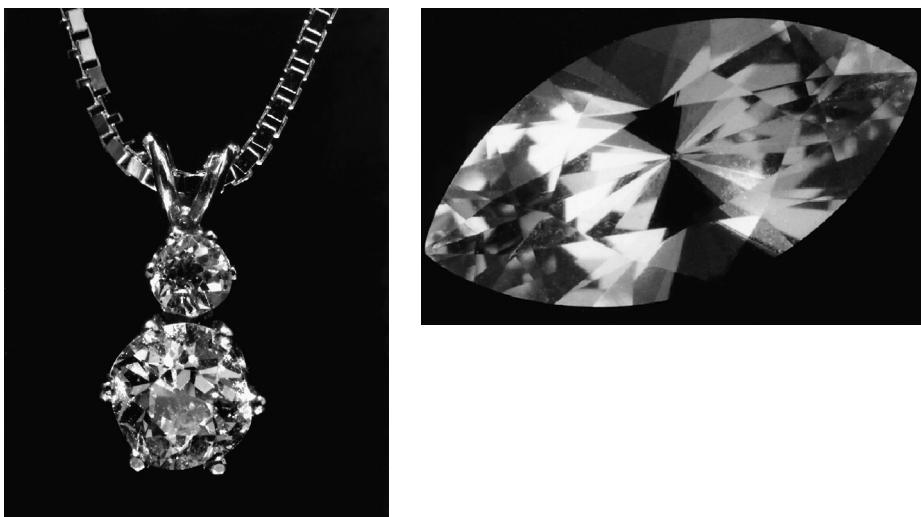
### BOX 1

#### The Aon Center, Chicago

The Aon Center, formerly the Amoco Building, is the third tallest building in Chicago. At the time of its original construction, and for a short time after, it was the largest marble-clad building in the world. It was also a hazard for people walking beneath it.

The thin slabs of marble, made nearly entirely of the mineral calcite, were unable to withstand Chicago's harsh climate, and they began to warp and fall off as soon as the building was completed. In a two-year project ending in 1992, the marble was replaced with granite. The K-feldspar and quartz of the granite are better able to handle the weather, and pedestrians can once again walk beneath the building safely.





**FIGURE 2** (a) Two diamonds, the largest about 3 carats (600 mg). Diamonds have traditionally been the most popular gemstones because of their beauty and durability. (b) Morganite, a variety of beryl named after J. Pierpont Morgan, normally has a pink color. Here it has been faceted to produce an almond shape.

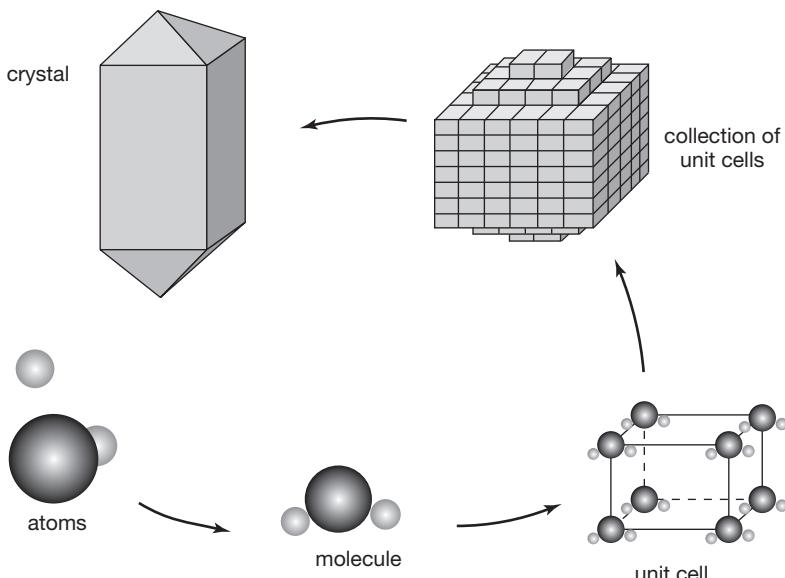
## ELEMENTS: THE BASIC BUILDING BLOCKS

### Historical Views of Elements and Matter

All matter is composed of fundamental building blocks called **elements** that exist as discrete atoms, and may combine to form molecules, crystals, and minerals (Figure 3). While we accept this statement as true today, its significance and meaning have been debated for more than two thousand years. Greek philosophers recognized that there must be some order and structure to Earth materials. Empedocles (490 to 430 B.C.) summarized current thought when he spoke of “four fundamental elements”: earth, air, fire, and water. Aristotle (384 to 322 B.C.) described matter, as opposed to something he called *essence*, and he supported Leucippus’s (500 B.C.) theory of atoms as the smallest, indivisible building blocks. Democritus adopted and advanced the theory, describing atoms as

small, invisible hard particles with no color, taste, or smell. A student of Aristotle’s, Theophrastus (372 to 287 B.C.), applied the atomic theory to rocks and minerals. His short book *Concerning Stones* is considered by many to be the first mineralogy book ever written. After the Greeks, there seems to have been a period of more than fifteen hundred years when little progress was made in the science of mineralogy. While people collected minerals and tabulated their properties, no one understood how or why they possessed those properties.

The processing and isolation of individual minerals and chemical elements dates as far back as 2900 B.C., when furnaces for melting gold were used in Egypt, and the Bronze Age began in Greece. The refining of gold and silver for coins and art was widespread. Other elements, such as lead and antimony, were known at the time of the Sumerians and in ancient China. Gemstones such as



**FIGURE 3** This diagram shows the relationships between atoms; molecules, which are compounds of several atoms; unit cells made up of several molecules; a collection of unit cells; and mineral crystals.

jade and turquoise were collected and hoarded as early as 3000 b.c. Practitioners of alchemy and related “arts” appeared in Greece, China, and India as early as 1500 b.c. They developed laboratory techniques for isolating and purifying elements from minerals, and began to study their properties. The Semitic Chetites processed iron to make tools in 1500 b.c., and Asian Indians forged iron before 1000 b.c. Mercury has been found in Egyptian tombs of about the same age.

Pliny (A.D. 23 to 79) expanded on the work of Theophrastus and others in his book *Natural History*, but major advances in mineralogy did not occur until the Middle Ages. The apparent slow development of all sciences during this time was due to a dichotomy. Philosophers and theoreticians, who tried to understand science, were isolated from the practical world. At the same time, understanding eluded practitioners who improved upon techniques and applications. The utility of combining theory and practice was not realized until the beginnings of the Industrial Revolution. Rapid advances in science soon followed. Atomic theory was developed, accepted, and acclaimed as “modern,” leading rapidly to new developments in the sciences of chemistry and mineralogy.

### Modern Views of Elements and Matter: A Review of Basic Chemistry

In 1660 the term *element* was first used in the same sense as it is today. Robert Boyle, in his book *The Sceptical Chemist* [sic], said elements “are certain

primitive and simple, or perfectly unmixed bodies, which not being made of any other bodies or of one another, are the ingredients of which all...bodies are immediately compounded, and into which they are ultimately resolved.” This definition launched the search for a complete list of elements. In the early and mid-eighteenth century, Joseph Proust and others observed that elements combine in definite proportions to form **compounds**. By 1800 chemists such as William Higgins and John Dalton extended this **law of definite proportions** and began to discuss molecules as combinations of discrete numbers of atoms. However, some fundamental errors in their ideas made experimental confirmation of their theories impossible.

In the early 1800s Sweden’s Jöns Jakob Berzelius invented new techniques in analytical chemistry. Berzelius, who had nearly flunked out of high school, snubbed theoreticians and devoted himself to analyzing and isolating chemical elements in the laboratory. He started mostly with mineralogical materials, many from rich ore deposits. Berzelius determined atomic weights for many elements, including lead, chlorine, potassium, sulfur, silver, and nitrogen, basing his values on weights determined for oxides. Working before understanding of the Periodic Table and ionic charge, Berzelius had to speculate about the formulas for some oxides. Because he used incorrect oxide formulas, some of his values were off by factors of 2 or 4. After corrections, his results (Table 1) are remarkably close to those accepted today. Berzelius also is responsible for the one- and two-letter chemical symbols, based on elemental names, used today.

**TABLE 1** Atomic Weights of Berzelius

Name of Element Today	Name of Element in Berzelius's Time	Symbol	100 × wt <sub>element</sub> /wt <sub>oxygen</sub> (Berzelius, 1813)	100 × wt <sub>element</sub> /wt <sub>oxygen</sub> (Today)
oxygen	oxygen	O	100.0	100.0
hydrogen	hydrogen	H	6.6	6.9
carbon	carbon	C	75.1	75.1
sulfur	sulfur	S	201.0	200.4
molybdenum	molybdenum	Mo	601.6	599.6
chromium	chromium	Cr	354.0	325.0
platinum	platinum	Pt	1,206.7	1,219.3
silver	argentum	Ag	672.1	674.2
mercury	hydrargyrum	Hg	1,265.8	1,253.7
copper	cuprum	Cu	403.2	397.2
lead	plumbum	Pb	1,298.7	1,295.0
tin	stannum	Sn	735.3	741.8
iron	ferrum	Fe	346.8	349.1
calcium	calcium	Ca	255.1	250.5
sodium	natrium	Na	144.8	143.7
potassium	kalium	K	244.5	244.4

Modified from values in Farber, 1952.

## Grouping of Elements and the Periodic Table

The successes of Berzelius spawned further study of the elements. Nineteenth-century scientists isolated and described tellurium, zirconium, titanium, cerium, chromium, beryllium, selenium, and vanadium; 55 elements were known by 1830. Chemists began to see similarities between various groups of elements and sought theories to explain the relationships, if for no other reason than they wanted to know just how many more there were. In 1829 Döbereiner, for example, described four “triads” of elements with similar behavior:

Triad 1: calcium (Ca), strontium (Sr), barium (Ba)

Triad 2: lithium (Li), sodium (Na), potassium (K)

Triad 3: chlorine (Cl), bromine (Br), iodine (I)

Triad 4: sulfur (S), selenium (Se), tellurium (Te)

In each triad the properties of the elements were similar, and the difference in atomic weights between the first and second elements was the same as that between the second and third. In 1862 Alexandre Béguer de Chancourtois devised a “telluric helix” in which he arranged all known elements on a spiral. A few years later, in separate studies, Julius Lothar Meyer and John A. R. Newlands presented the elements in rows and columns based on their atomic weights and similar properties.

The great breakthrough came in 1868 when Dmitry Ivanovich Mendeleyev wrote his handbook of chemistry. Mendeleyev used atomic weights and charges to devise a **periodic chart** remarkably like those in use today. In 1870 he published the chart in his *Natural System of the Elements*, which had some

blanks and predicted the future discoveries of scandium (Sc), gallium (Ga), and germanium (Ge) 10 to 15 years later (Table 2). Mendeleyev’s chart and papers explained the periodicity of elemental properties in such detail that few contested it. Less than a year later, J. L. Meyer published a graph of atomic volumes versus atomic weights that confirmed most of Mendeleyev’s findings (Figure 4). The periodic table allowed mineralogists and chemists to explain why the properties of some minerals were similar and to predict the existence of minerals not yet found.

## ATOMS AND ELEMENTS

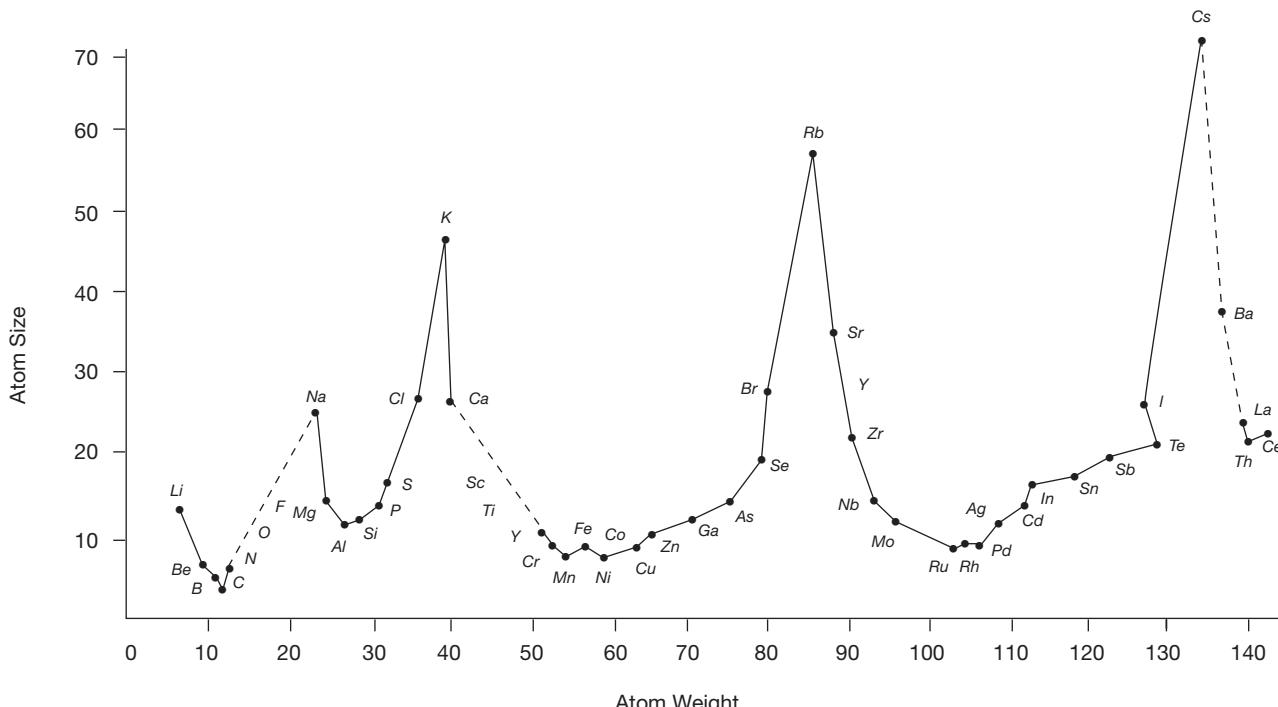
Mendeleyev developed his chart using empirical methods. He relied on what he could measure and left the theories for others to develop. In spite of many uncertainties, throughout this period most physicists and chemists, including Sir Isaac Newton, continued to believe that atoms were hard, spherical particles. A major change in thinking occurred around 1897, when J. J. Thomson discovered **electrons**, and hypothesized both negatively and positively charged particles in atoms. Soon, Ernest Rutherford completed a series of experiments that led him to predict the existence of small **nuclei** of high mass in the center of atoms. He subsequently predicted the existence of **protons** and **neutrons**, which led to the first modern model of the atom.

### The Bohr Model

Niels Bohr made the most significant breakthrough in the development of modern atomic theory. Following in the footsteps of Max Planck and others,

**TABLE 2** Arrangement of Elements and Atomic Weights in Mendeleyev’s First Periodic Table

		Ti	50	Zr	90		
		V	51	Nb	94	Ta	182
		Cr	52	Mo	96	W	186
		Mn	55	Rh	104.4	Pt	197.4
		Fe	56	Ru	105.4	Ir	198
		Co	59	Pd	106.6	Os	199
		Cu	63.4	Ag	108	Hg	200
				Cd	112		
				Ur	116	Au	197
				Sn	118		
				Sb	122	Bi	210
				Te	128		
H 1				I	127		
	Be 9.4	Mg 24	Zn 65.2				
	B 11	Al 27.4	(Ga)				
	C 12	Si 28	(Ge)				
	N 14	P 31	As 75				
	O 16	S 32	Se 79.4				
	F 18	Cl 35.5	Br 80				
Li 7	Na 23	K 39	Rb 85.4				
		Ca 40	Sr 87.6				
		(Sc)	Ce 92				
		Er 56	La 94				
		Yt 60	Di 95				
		In 57.6	Th 118				



**FIGURE 4** A modern version of Meyer's (1870) graph of elemental weights. Meyer's study, which showed the periodic variation of elemental weights, confirmed the basic validity of Mendeleyev's periodic chart.

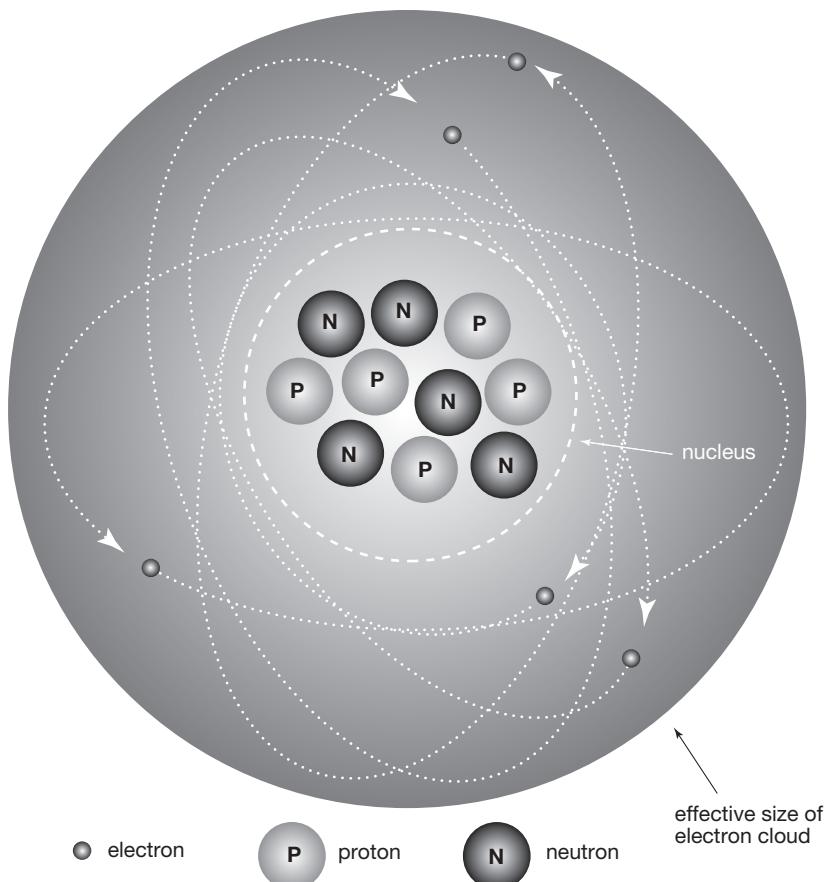
Bohr introduced the idea of **energy levels**. He envisaged the atom as a small planetary system and used equations analogous to Kepler's astronomical laws to describe the orbits (Figure 5). His first major publications appeared in 1913 and, like all radical ideas, found little acceptance in the scientific community. A prominent physicist, Otto Stern, expressed his disdain: "If this nonsense is correct, I will give up being a physicist" (Holton, 1986). However, by 1922, when most physicists agreed with Bohr's basic ideas, he was awarded the Nobel Prize in Physics.

In the **Bohr model**, electrons are like small, spherical particles orbiting around the nucleus. Positively charged protons in the nucleus attract and hold onto the negatively charged electrons. The number of protons is called the **atomic number** ( $Z$ ). Each element has a different atomic number, beginning with hydrogen, H ( $Z = 1$ ), and continuing to the named element with the highest number, lawrencium, Lr ( $Z = 103$ ). The protons in the nucleus are accompanied by neutrons; together, they add up to nearly all the mass of the atom, because electrons—the only other substantial particles in an atom—have little mass. (Electrons, protons, and neutrons have atomic weights of 0.0005486, 1.007276, and 1.008665 mass units, respectively.) Bohr showed that electrons can only occupy discrete energy levels. He designated the levels by a number  $n$ , called the first quantum number. For the known elements,

$n$  ranges from 1 to 7, from lowest to highest energy levels. The seven levels are also designated, in order, K, L, M, N, O, P, and Q. When an electron moves from a higher energy level to a lower one, the energy difference is given off as electromagnetic radiation, often as X-rays.

Within each energy level there are sublevels characterized by electron orbitals of different shapes (Figure 6). From the lowest to the highest energy, the sublevels are designated by the letters *s*, *p*, *d*, and *f*: *s* orbitals are spherical, *p* are dumbbell-shaped, *d* are shaped like a four-leaf clover, and *f* are more complicated. A shorthand notation is used to name **orbitals**. For example,  $1s$  stands for the lowest energy level and the *s* sublevel;  $2p$  indicates the second lowest energy level and the *p* sublevel, and so on. Different orbitals contain different numbers of electrons; *s*, *p*, *d*, and *f* orbitals may hold up to 2, 6, 10, and 14 electrons, respectively.

The electron configuration of atoms is, in general, predictable and quite regular. Available electrons fill orbitals from lowest to highest energy. This process is known as the **Aufbau principle**. Elemental strontium, for example, has 38 electrons occupying the  $1s$ - through  $5s$ -orbitals. The outermost electrons in an atom are called **valence electrons**. The valence electrons strongly affect chemical properties; elements with valence electrons in similarly shaped orbitals are chemically similar.



**FIGURE 5** Bohr's model of the atom showing protons and neutrons in the nucleus, with electrons circling them to form an enclosing cloud.

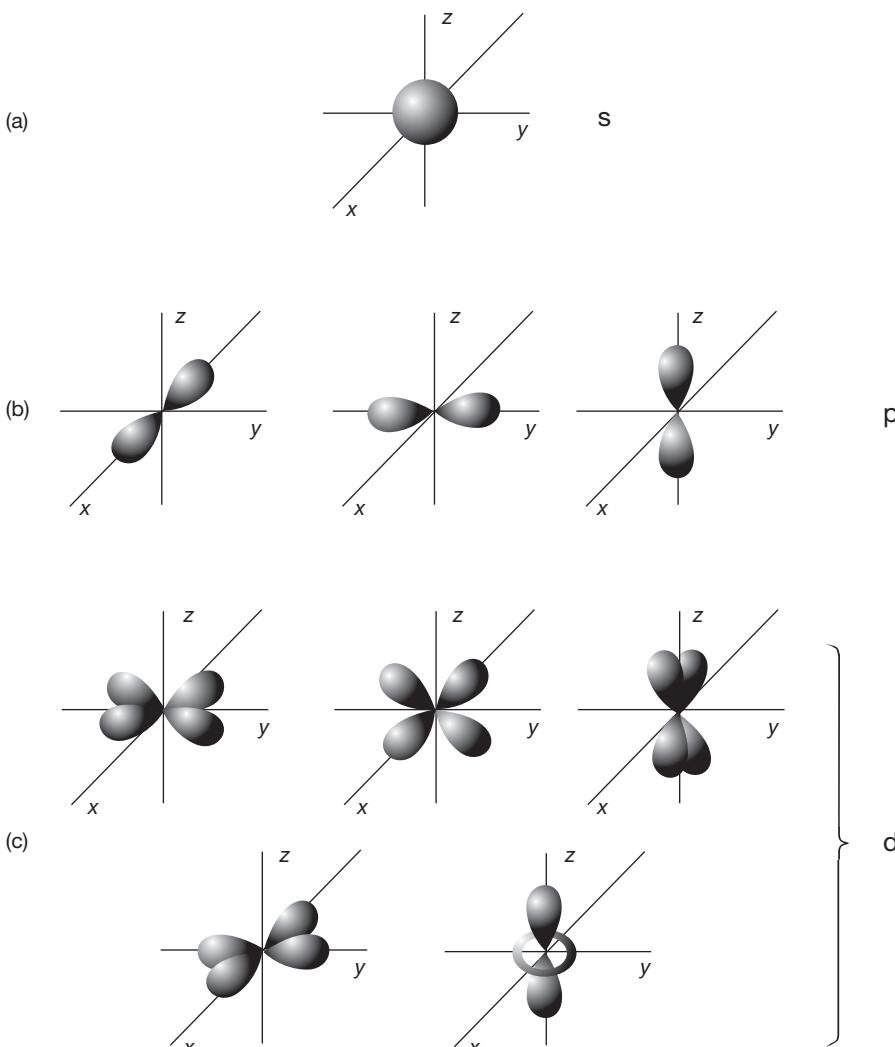
### Modifications to the Bohr Model

Bohr's model worked well for the hydrogen atom, but not for heavier elements. A fundamental problem with Bohr's mathematical model was that it predicted electrons should not remain in orbitals, but instead should be attracted to the center of the nucleus. The solution to this problem became possible when, in 1923, Louis de Broglie showed that electrons are not simple particles but instead have wavelike properties. Werner Heisenberg soon pointed out that, due to wave motion, electrons could not follow simple orbits around a nucleus, and their exact location must be uncertain. The **Heisenberg uncertainty principle** was incorporated into the **Schrödinger wave model** published in 1926. The Schrödinger model, which defines the probable energy distribution in an atom, improved on Bohr's work and is the basis for all modern treatments of atomic properties and structure.

### IONS

An important corollary to the Aufbau principle is that atoms are more stable if electrons completely fill energy levels and sublevels. Atoms may give up or borrow electrons, becoming **ions**, to obtain this stability.

As a result, they may become **cations**, which have a net positive charge because there are more protons than electrons, or **anions**, with a net negative charge because there are more electrons than protons. The **ionic charge**, also called the **valence**, is the number of protons less the number of electrons. We usually indicate valence by a superscript number after the elemental symbol (for example,  $\text{Fe}^{2+}$  indicates iron with two more protons than electrons). We call all ions with a charge of +1 or -1 **monovalent**. Those with a charge of +2 or -2 are **divalent**. **Trivalent** and **tetravalent** refer to charges of  $\pm 3$  and  $\pm 4$ . Since hydrogen, with atomic number 1, has only one electron in the first energy level (1s), it may either borrow an electron from a donor to fill the first energy level and become a monovalent anion  $\text{H}^-$ , or (more commonly) donate an electron to another atom and become a monovalent cation  $\text{H}^+$ . Helium, with atomic number 2, has two protons and two electrons that completely fill the first energy level. Because the level is filled, helium has no tendency to accept or donate an electron, and so maintains a valence of 0. Elements such as helium, in which electrons completely fill the *s*-orbitals and *p*-orbitals, are called **noble** or **inert** elements because they are extremely stable and unreactive. Other noble gases include neon (Ne), argon (Ar), krypton (Kr),



**FIGURE 6** Shapes of electron orbitals: (a) s-orbitals are spherical; (b) p-orbitals are dumbbell-shaped; (c) d-orbitals are generally shaped like a four-leaf clover.

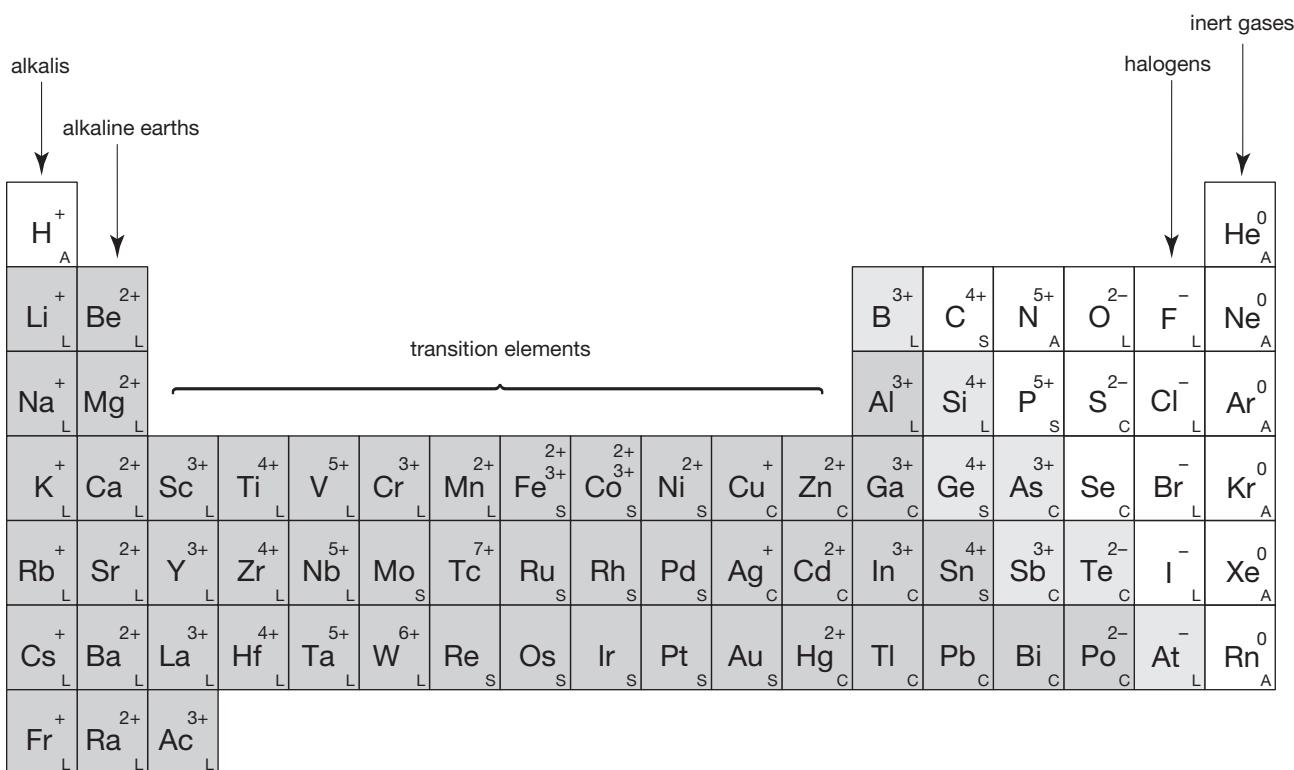
xenon (Xe), and radon (Rn). They have atomic numbers 10, 18, 36, 54, and 88, respectively. Although filling or emptying the 1s-orbital in hydrogen to achieve stability is a simple concept, predicting the valence of other elements is not always straightforward. The formation of ions is often complicated because elements may achieve at least partial electronic stability in different ways. This is especially true when *d*-electrons and *f*-electrons are involved. For most ions, however, the number of electrons is close to the number of protons, and the ionic charge is small.

The process of losing an electron is called **oxidation**. Gaining an electron is called **reduction**. Oxidation leaves metals with a positive charge. They may combine with oxygen anions ( $O^{2-}$ ) to form oxides. Fe-metal ( $Fe^0$ ) for example, may oxidize to become  $Fe^{2+}$  or  $Fe^{3+}$ . If  $Fe^{2+}$  combines with oxygen, it may form wüstite ( $FeO$ ); if  $Fe^{3+}$  combines with oxygen, it may form hematite ( $Fe_2O_3$ ). Wüstite and hematite are both minerals, but hematite is more common because under normal Earth surface conditions,

iron easily oxidizes. Many elements besides hydrogen and iron may exist in more than one valence state. Carbon may reduce to become  $C^{4-}$  or oxidize to become  $C^{4+}$ , although the cationic form is more common. Adding further complication, carbon may at times have a charge of +2. The complexities of predicting electronic configurations and valence are many. Simplifying the matter, however, is that for ions with more than one potential ionic state, a single state is usually much more common. Figure 7 shows the most common valences of elements in minerals. Those with no indication of valence may ionize but have no common ionic forms in minerals.

## THE MODERN PERIODIC TABLE

Although the Periodic Table of the Elements has appeared in many forms, the basic relationships are the same today as they were in 1870. Development of the Schrödinger wave model led to a slight rearrangement of the table so that it mirrors the order in which



**FIGURE 7** Typical ions in minerals. Elements with no indication of valence have no common ionic state in minerals. Small letters indicate classification of an element according to Goldschmidt (discussed later in this chapter): S = siderophile, C = chalcophile, L = lithophile, a = atmophile.

electrons occupy orbitals. The present version, depicted in Figure 8, separates the elements into **periods** (rows) and **groups** (columns).

## Periods

Elements are ordered by increasing atomic weight. The number of the period (row) indicates the orbitals occupied by the electrons. For example, elements in the first period contain electrons in the 1s orbital; elements in the second period have electrons in the 2s- and 2p-orbitals; elements in the third period have electrons in the 3s- and 3p-orbitals; and so on. The first period has only two elements, while the second and third have eight each. The fourth through seventh periods contain 10 extra elements having electrons in *d*-orbitals. The sixth through seventh periods contain an additional 14 elements with electrons in *f*-orbitals (which are listed separately at the bottom of the table as the **lanthanides**—also called **rare earth elements**—and **actinides** to keep the table from becoming too wide).

## Groups

Elements in the same groups (columns) have valence electrons in similar orbitals. Hence they have similar chemical properties. Elements in groups on the left side of the table have a few “extra” electrons in outer orbitals, and these readily give up electrons to become

cations. Elements in group 1 (**alkali elements**) generally have a valence of +1. Those in group 2 (**alkaline earth elements**) usually have a valence of +2. Both alkalis and alkaline earth elements have valence electrons in *s*-orbitals. Elements on the right side of the Periodic Table, excluding group 18, have room for a small number of additional electrons in their outer orbitals and consequently easily accept extra electrons to become anions. Elements in group 17 (**halogens**) typically have a valence of -1 because they acquire an extra electron to fill their outermost *p*-orbital. The properties of elements in the central portion of the table (groups 3 through 12) called **transition metals**, with partially filled *d*-orbitals and *f*-orbitals, are less predictable. Elements in groups 3, 4, and 5 usually have valences of +3, +4, and +5, respectively. The rest of the transition metals exist in a number of valence states, typically +2 or +3. The three most abundant elements in the Earth's crust (O, Si, and Al) are on the right-hand side of the Periodic Table, in groups 13, 14, and 16. Oxygen typically has a charge of -2, silicon of +4, and aluminum of +3.

## Atomic Number and Mass

An element's atomic number is the number of protons in its nucleus ( $Z$ ). It is equal to the number of electrons orbiting the nucleus in neutral (nonionized) atoms.

# Periodic Table of the Elements

GROUP	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18		
	alkalis	alkaline earths															halogens	inert gases		
transition metals (groups 3–12)																				
1	2.20 1 H 1.01	1.57 2 Be 9.01															2 He 4.00			
2	0.98 3 Li 6.94	1.31 12 Mg 24.31																		
3	0.93 11 Na 22.99	1.31 12 Mg 24.31																		
4	0.82 19 K 39.10	1.00 20 Ca 40.08	1.36 21 Sc 44.96	1.54 22 Ti 47.88	3.4 23 V 50.94	1.63 24 Cr 52.00	2.3,4,5 25 Mn 54.94	1.66 26 Fe 55.85	2.3,4,5,6 27 Co 58.93	1.88 28 Ni 58.69	2.3,4,5,6 29 Cu 63.55	1.91 30 Zn 65.39	2.3,4,5,6 31 Ga 69.72	1.90 32 Ge 72.61	2.19 33 As 74.92	2.3,4,5,6 34 Se 78.96	2.3,4,5,6 35 Br 79.90	2.3,4,5,6 36 Kr 83.80		
5	0.82 37 Rb 85.47	0.95 38 Sr 87.62	1.22 39 Y 88.91	1.33 40 Zr 91.22	2.1 41 Nb 92.91	1.6 42 Mo 95.94	3.5 43 Tc (99)	1.9 44 Ru 101.07	2.2 45 Rh 102.91	2.28 46 Pd 106.42	2.3,4,5,6 47 Ag 107.87	1.93 48 Cd 112.411	1 49 In 114.82	1.69 50 Sn 118.71	2.4 51 Sb 121.75	2.4 52 Te 127.60	2.4 53 I 126.90	2.4 54 Xe 131.29		
6	0.79 55 Cs 132.91	0.89 56 Ba 137.33	1.10 57 La 138.91	1.3 72 Hf 178.49	4 73 Ta 180.95	1.5 74 W 183.85	2.3,4,5,6 75 Re 186.21	2.2 76 Os 190.2	2.3,4,6,8 77 Ir 192.22	2.28 78 Pt 195.08	2.4 79 Au 196.97	2.00 80 Hg 200.59	1.2 81 Tl 204.38	2.33 82 Pb 207.2	2.4 83 Bi 208.98	2.4 84 Po (209)	2.4 85 At (210)	2.4 86 Rn (222)		
7	0.7 87 Fr (223)	0.9 88 Ra (226)	2 89 Ac (227)	1.1 104 Rf (261)	4 105 Db (262)	1.06 106 Sg (263)	1.07 107 Bh (262)	1.08 108 Hs (265)	1.09 109 Mt (266)	1.10 110  (269)	1.11 111  (272)	1.12 112  (277)								
Lanthanide series:																				
	1.12 58 Ce 140.12	3.4 59 Pr 140.91	1.13 60 Nd 144.24	3.4 61 Pm (147)	1.14 62 Sm 150.36	3 63 Eu 151.97	2.3 64 Gd 157.25	3 65 Tb 158.93	3 66 Dy 162.50	3 67 Ho 164.93	3 68 Er 167.26	3 69 Tm 168.93	3 70 Yb 173.04	3 71 Lu 174.97						
Actinide series:																				
	1.3 90 (232)	4 91 (231)	1.5 92 (238)	4.5 93 (237)	1.38 94 (244)	3,4,5,6 95 (243)	3,4,5,6 96 (247)	3,4,5,6 97 (247)	3,4,5,6 98 (251)	3,4,5,6 99 (252)	3,4,5,6 100 (257)	3,4,5,6 101 (258)	3,4,5,6 102 (259)	3,4,5,6 103 (260)						

\*The mass number of an important radioactive isotope—not the atomic mass—is shown in parenthesis for an element with no stable isotopes.

**FIGURE 8** The modern Periodic Table of the Elements.

atoms, and is close to the number of electrons in most ions.  $\text{Fe}^0$ , for example, has 26 protons ( $Z = 26$ ) in its nucleus and 26 electrons, creating an **electron cloud** around the nucleus.  $\text{Fe}^{2+}$  has 26 protons and 24 electrons. Because the size of its electron cloud controls the diameter of an atom, elements with many protons, having many electrons, tend to be large; those with few electrons are small. According to the Aufbau principle, electrons fill orbitals in a predictable manner. Thus atomic number determines the number and nature of valence electrons and atomic or ionic size. Atomic number is the most significant factor controlling elemental properties.

The number of neutrons ( $N$ ) in the nucleus of a given element may vary. This leads to isotopes of different **mass numbers** ( $A$ ):

$$A = Z + N \quad (1)$$

Most chemical elements have several different naturally occurring **isotopes**. Thus, for example, oxygen may be  $^{16}\text{O}$ ,  $^{17}\text{O}$ , or  $^{18}\text{O}$ , where the preceding superscript denotes  $A$ . Examination of Equation 1 indicates that the three isotopes of oxygen must have 8, 9, and 10 neutrons, respectively, because all must have 8 protons.

The **atomic weight of an atom** is calculated by summing the weights of its atomic particles, and subtracting a small amount to account for mass lost to energy holding the nucleus together. The **atomic**

**weight of an element** is the sum of the masses of its naturally occurring isotopes weighted in accordance with their abundances. Although isotope mass numbers are always integers, atomic weights are not. For example, many tables and charts give the atomic weight of oxygen as 15.9994 and that of iron as 55.847. The scale used to measure atomic masses has changed slightly over time. Today, it is standardized relative to carbon so that the mass of  $^{12}\text{C} \equiv 12.0000$ . All atomic masses are given in **atomic mass units** (amu), defined as  $\frac{1}{12}$  of the mass of  $^{12}\text{C}$ . Atomic weights of elements are dimensionless numbers because they are all calculated relative to the atomic weight of  $^{12}\text{C}$ .

A **mole** (mol) of an element is defined as the amount of that element that has its weight in grams equal to its atomic weight. A mole of an element always contains  $6.022 \times 10^{23}$  atoms. The number  $6.022 \times 10^{23}$  is known as **Avogadro's number**. One mole of  $^{12}\text{C}$ , equal to  $6.022 \times 10^{23}$  carbon atoms, by definition weighs exactly 12 grams. Using atomic weights and Avogadro's number, it is possible to convert from weight to number of atoms and vice versa. Atomic weights of compounds (combinations of elements) are just the sum of the weights of the elements (Box 2).

Most elements have very small isotopic variation, no matter where they are found. Thus, all quartz ( $\text{SiO}_2$ ) contains about the same relative amounts of the three natural oxygen isotopes:  $^{16}\text{O}$ ,  $^{17}\text{O}$ , and  $^{18}\text{O}$ .

## BOX 2

### What Is a Mole of Quartz?

Quartz,  $\text{SiO}_2$ , is one of the most common and well-known minerals. We might wonder: How much quartz comprises a mole? To answer this question, we use the atomic weights of silicon and oxygen as well as some crystallographic data.

Silicon and oxygen have atomic weights of 28.0855 and 15.9994, respectively. The atomic weight of quartz,  $\text{SiO}_2$ , is therefore 60.0843 ( $28.0855 + 15.9994 + 15.9994$ ). A mole of quartz,  $6.022 \times 10^{23} \text{SiO}_2$  molecules, weighs 60.0843 gm.

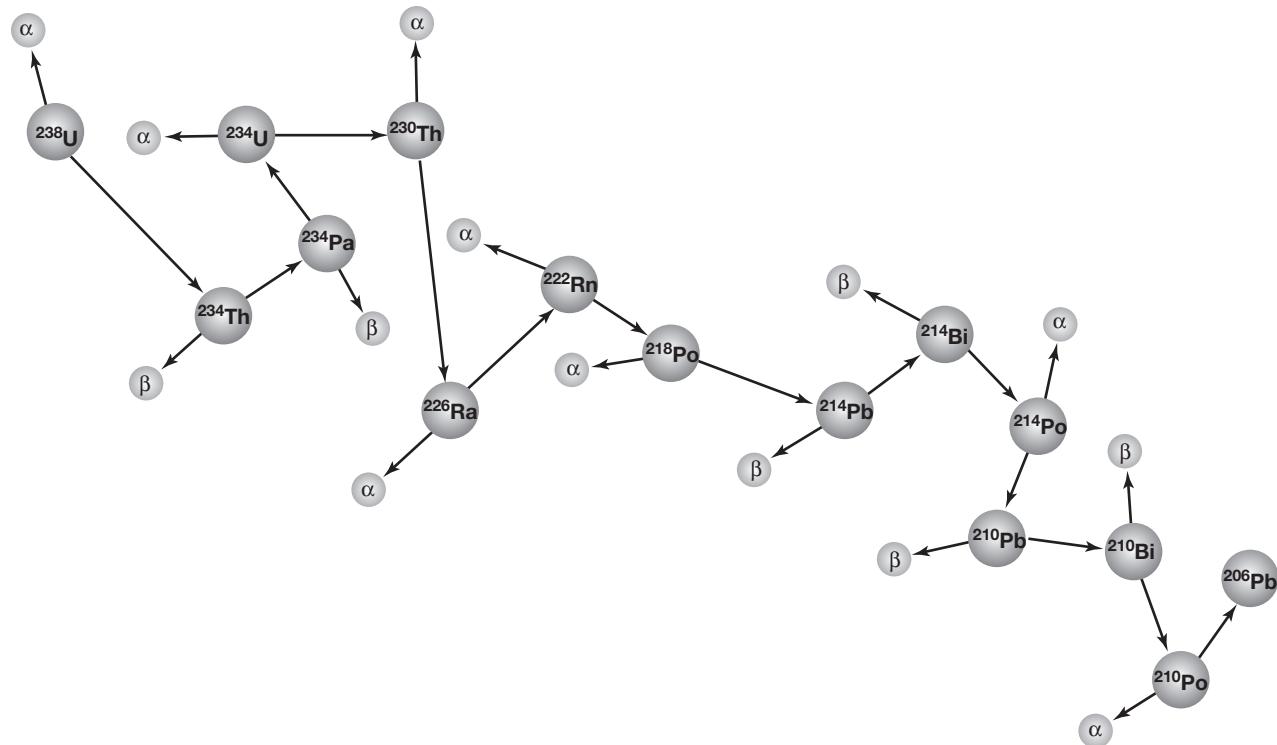
Crystallographers have determined that quartz crystals are made of fundamental unit cells shaped like hexagonal prisms containing three  $\text{SiO}_2$  molecules. Each unit cell has a volume of  $112.985 \text{\AA}^3$ . So we may calculate the volume of a mole of quartz as:

$$\begin{aligned} V &= N \times v/Z \\ &= 6.022 \times 10^{23} \text{SiO}_2/\text{mole} \\ &\quad \times 112.986 \text{\AA}^3/\text{unit cell} \div 3 \text{SiO}_2/\text{unit cell} \\ &= 2.268 \times 10^{25} \text{\AA}^3 \\ &= 22.68 \text{ cm}^3 \text{(slightly smaller than a golf-ball)} \end{aligned}$$

where  $V$ ,  $N$ ,  $v$ , and  $Z$  are the molar volume, Avogadro's number, the unit cell volume, and the number of molecules per unit cell, respectively.

We can, if we wish, then calculate the density ( $\rho$ ) of quartz from the molar data:

$$\begin{aligned} \rho &= \text{molar weight}/\text{molar volume} \\ &= 60.0843 \text{ gm/mole} \div 22.68 \text{ cm}^3/\text{mole} \\ &= 2.649 \text{ gm/cm}^3 \end{aligned}$$



**FIGURE 9** Decay of  $^{238}\text{U}$  to  $^{206}\text{Pb}$  (after Richardson and McSween, 1989).  $\alpha$  and  $\beta$  particles are emitted during decay.

Furthermore, isotopic variations have extremely small effects on the properties of minerals. Most mineralogists, therefore, do not worry very much about isotopes. The small isotopic variations, however, may be significant to a geochemist trying to determine the genesis of a particular mineral or rock.

Most common isotopes are **stable isotopes**. In 1896 Henri Becquerel discovered **unstable isotopes** and radioactivity when he unintentionally conducted an experiment. He put some radioactive samples in a drawer along with a photographic plate and subsequently found that the plate had recorded the image of a key that had been sitting on top of it. Although Becquerel didn't know it, X-rays given off by uranium-rich minerals had caused the image. During the following decade, researchers including Marie and Pierre Curie and Ernest Rutherford determined that some elements, termed **radioisotopes**, emit  $\alpha$  and  $\beta$  particles and  $\gamma$  radiation as they decay, forming **daughter isotopes**. A few **remnant heavy isotopes** are decaying so slowly that they remain from before the creation of the solar system. Others decay so rapidly that they only exist for brief periods in nuclear reactors or explosions. Many radioisotopes decay in one step to a stable daughter isotope. Others decay in many steps from an original radioactive **parent isotope** to a final stable (not decaying) daughter element. Figure 9 shows such a decay

chain for  $^{238}\text{U}$ . Geochemists use  $^{238}\text{U}$  and other radioisotopes to estimate the ages of minerals and rocks.

## BONDING IN MINERALS

Negatively and positively charged particles attract each other. Protons (positively charged) attract electrons (negatively charged) in atoms. Similarly, positively charged cations attract negatively charged anions, producing **ionic bonds** in minerals. In fact, all the forces that bond elements together to form compounds are electrical. Chemists have identified different types of bonds, and three are most significant for minerals: **ionic**, **covalent**, and **metallic** (see Box 3). The general properties of minerals with ionic, covalent, and metallic bonds are predictable (Table 3).

Because atoms are unstable if electrons do not completely fill energy levels and sublevels, most elements ionize. Some ionize more easily than others, and we call those that easily ionize to become cations **metallic elements**. The degree to which elements are metallic generally decreases from left to right in the Periodic Table. We call elements on the right-hand side of the table, which ionize to become anions, **nonmetallic**. The formation of cations and anions go hand in hand. Nonmetals becoming anions gain electrons given up by metals becoming

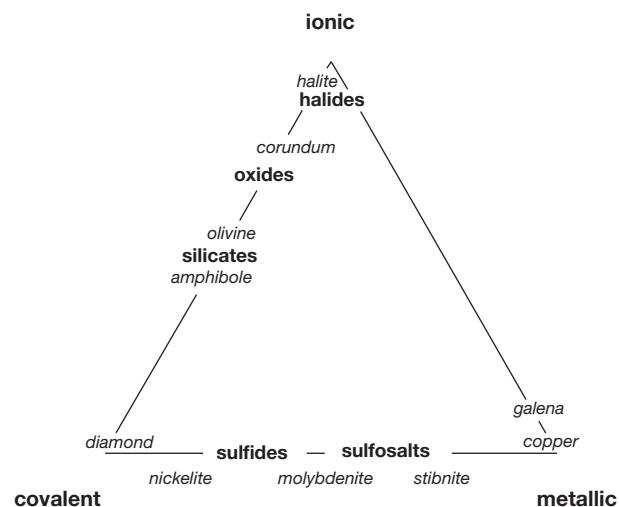
## BOX 3

**Ionic, Covalent, and Metallic Crystals**

Most minerals are neither 100% ionic, 100% covalent, nor 100% metallic, but some come close (see Figure 10). In halite ( $\text{NaCl}$ ),  $\text{Na}^+$  and  $\text{Cl}^-$  exhibit such a minor amount of electron sharing that for all practical purposes halite can be considered perfectly ionic. Fluorite ( $\text{CaF}_2$ ), too, is nearly completely ionic. In contrast, diamond (C) is nearly completely covalent, while copper (Cu) represents end-member metallic bonding.

Chemical bonding in minerals controls many properties. Covalent bonds are stronger than ionic bonds, which in turn are stronger than metallic bonds. As a consequence, covalent minerals are hard and tenacious, while metallic ones are usually not, and ionic minerals fall in between. Melting temperatures follow a similar pattern (covalent compounds generally melt at the highest temperatures due to their stronger bonds), while solubility in water is greatest for ionic crystals (because of their weak bonds and easy ionization).

Crystal symmetry is also affected by bond type. Both ionic and metallic bonds are nondirectional so bonding can occur equally in all directions. In contrast, covalent bonds involve pairs of atoms and are linear. Consequently, metallic and ionic minerals generally have high symmetry compared to covalent ones.



**FIGURE 10** Different minerals contain different kinds of atomic bonds; most minerals have combinations of ionic and covalent bonds, or combinations of covalent and metallic bonds. Mineral names are in italics above; mineral classes are in bold.

cations. Thus, sodium (Na) and chlorine (Cl) react to produce the ions  $\text{Na}^+$  and  $\text{Cl}^-$ . Because cations and anions have opposite charges, they attract each other, forming ionic bonds. With Na and Cl, this results in the mineral halite,  $\text{NaCl}$ .

Rather than giving up or gaining electrons to become ions, atoms may become stabilized by

sharing electrons. We call the sharing of electrons between atoms a **covalent bond**. If the sharing is complete, the bond is 100% covalent. This is the case for diatomic gases such as  $\text{H}_2$ ,  $\text{N}_2$ , or  $\text{O}_2$ . Covalent bonds are stronger than ionic bonds. Many elements form both covalent and ionic bonds. As mentioned,  $\text{Cl}^-$  forms ionic bonds with  $\text{Na}^+$  to make

**TABLE 3 General Characteristics of Minerals with Ionic, Covalent, and Metallic Bonds**

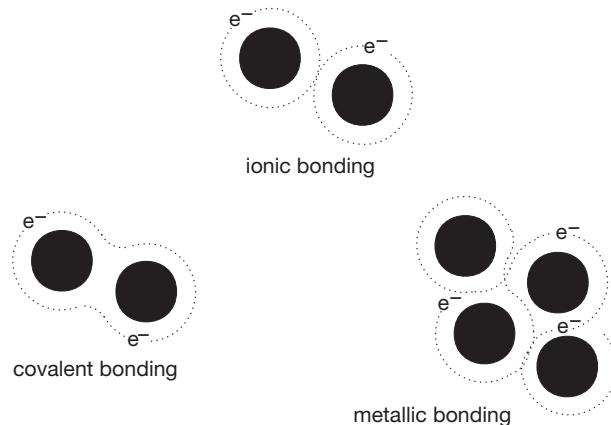
	Ionic Bonds	Covalent Bonds	Metallic Bonds
<b>Common Elements Involved</b>	<b>Elements from Opposite Sides of the Periodic Table, such as Alkalies and Halides, or Alkaline Earths and Oxygen</b>	<b>Elements Close Together in Periodic Table</b>	<b>Transition Metals</b>
Electrical conductivity	Low	Low	High
Thermal conductivity	Low	Low	High
Solubility in water	High	Low	Very low
Melting temperature	Moderate to high	High	Variable
Hardness	Medium to hard	Very hard	Variable; often minerals are malleable
Breaking	Brittle, good cleavage	Brittle; often conchoidal fractures	Variable
Crystal form	High symmetry	Low symmetry	Very high symmetry
Transparency	Fully to partially transparent	Partially transparent or opaque	Opaque
How common? Examples	Most minerals $\text{Halite}, \text{NaCl}; \text{calcite}, \text{CaCO}_3$	Some minerals $\text{Diamond}, \text{C}; \text{sphalerite}, \text{ZnS}$	Most metals $\text{Copper}, \text{Cu}; \text{silver}, \text{Ag}$

the mineral halite. Two Cl atoms also bond covalently to form a stable gas,  $\text{Cl}_2$ . Bonds may also be partially ionic and partially covalent if electron sharing is limited. Thus, a continuum exists between substances such as halite, in which the bonding is nearly 100% ionic, and diatomic gases or diamond, in which it is 100% covalent.

The degree to which a particular bond is ionic depends on both elements involved. Linus Pauling introduced the idea of electronegativity in 1932. Electronegativity is a value that describes an atom's ability to attract electrons. If two atoms have similar electronegativities, they have similar abilities to attract and hold on to electrons. So, a bond between the two will be essentially covalent. If, on the other hand, two atoms with significantly different electronegativities bond together, one will give up an electron to the other, creating a cation-anion pair and an ionic bond. The Periodic Table in Figure 8 gives electronegativity values for all elements. Those with high electronegativity values have a strong tendency to attract electrons and become anions; those with low electronegativity tend to give up electrons and become cations. Electronegativity generally increases from left to right across the Periodic Table. Consequently, bonds involving elements from opposite sides of the Periodic Table, excluding the noble gases, are more ionic than bonds involving elements from the center. Because alkali elements (group 1) have a very strong tendency to become cations, and halogens (group 17) have an equal tendency to become anions, halite ( $\text{NaCl}$ ) and other alkali halides form crystals in which bonds are nearly 100% ionic (Figure 10). Alkaline earth oxides such as periclase ( $\text{MgO}$ ) or lime ( $\text{CaO}$ ), involving cations from group 2 and  $\text{O}^{2-}$  from group 16, are about 75% ionic. The Si-O bonds in **silicates**, minerals with structures based on  $\text{SiO}_4$  groups, are generally about 50% ionic and 50% covalent. Silicates are the most common kind of mineral in the Earth's crust.

In covalent bonding, pairs of atoms share electrons. In a third kind of bonding, **metallic bonding**, many atoms share the same electrons. **Metallic bonding**, is especially common in minerals involving transition metals such as copper (Cu), gold (Au), or zinc (Zn). Good examples of metallic crystals are the minerals gold, silver, and copper. Since valence electrons move easily throughout the structure, metallically bonded compounds are good conductors of heat and electricity. They may be malleable and have only low-to-moderate hardness, reflecting the loose nature of their bonds.

Many ore minerals have little ionic character, but most other minerals are partially to dominantly



**FIGURE 11** In ionic bonds, electrons ( $e^-$ ) are localized around individual ions (black circles); in covalent bonds they are shared between two atoms (black circles); in metallic bonds, they are shared within a structure.

ionically bonded (Figure 10). Some minerals are combinations of ionic and covalent bonding. Others, especially sulfides and sulfosalts, are combinations of covalent and metallic bonding. Metallic and ionic bonds do not often combine, although galena ( $\text{PbS}$ ) may be one example in which they do. Figure 11 illustrates the three types of bonds, emphasizing the locations of the valence electrons that set them apart.

Besides the three bond types mentioned, other types such as **van der Waals** and **hydrogen** bonds exist in minerals. These bonds do not involve valence electrons but instead result from relatively weak electrostatic forces due to uneven charge distribution in a crystal structure. Very weak van der Waals bonds are important in graphite and some clay minerals, for example. This explains why graphite is much softer than diamond, which has the same composition but covalent bonds. In the mineral brucite, combinations of hydrogen and van der Waals bonds hold sheets of  $\text{Mg}^{2+}$  together. Clays have excellent cleavage: covalent and ionic bonds create strongly bonded layers, and weak van der Waals and hydrogen bonds hold the layers together. Fortunately for mineralogists and mineralogy students, we may ignore van der Waals and hydrogen bonds for most purposes. In fact, we will concentrate only on ionic bonds in our further discussions. We do this because:

- Consideration of ionic bonds explains most mineral properties even if the minerals are not completely ionic.
- Most minerals have predominantly ionic bonds.
- Ionic bonds are simpler to understand.

## ORIGIN OF THE ELEMENTS AND THE EARTH

### Hubble's Contributions

How did elements form in the first place? How did they get where we find them today? Perhaps the first real insight into these questions was made in 1929 by Edwin Hubble. Hubble determined the speed at which some galaxies (in the Virgo cluster) were moving away from Earth. Hubble and others then noticed that the universe seems to be expanding; all matter is moving away from a central location. This led scientists to hypothesize that the expansion started at one place and time. Based on his observations, Hubble later estimated that one nearly instantaneous event created the universe about two billion years ago. Hubble's calculations were not widely accepted, particularly because they conflicted with radioactive age dates, which suggested that the Earth was older than two billion years. In spite of the contradictions, Arno Penzias and Robert Wilson confirmed the basic validity of Hubble's ideas in 1964, for which they subsequently won the Nobel Prize in Physics. Errors have since been found in some constants used in Hubble's calculations. Current best estimates are that the universe originated in a fraction of a second, during the big bang, about 15 billion years ago (Figure 12). All of its mass and energy were created nearly instantaneously.

### In the Beginning

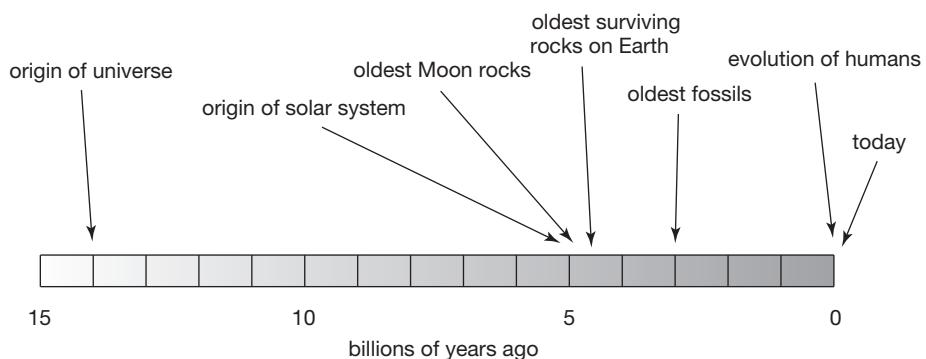
At its creation, the universe and all matter in it were at extremely high temperatures. As the universe expanded, it cooled to temperatures near a billion degrees and subatomic particles combined to form nuclei of hydrogen and helium, the lightest elements. This process was incredibly brief; most present-day chemists and cosmologists estimate it continued for only a half hour or so. No elements heavier than

helium ( $Z = 2$ ) formed. After another 750,000 years, scientists estimate that temperatures had cooled to 1,649 °C (3,000 °F) and electrons began to attach themselves to nuclei.

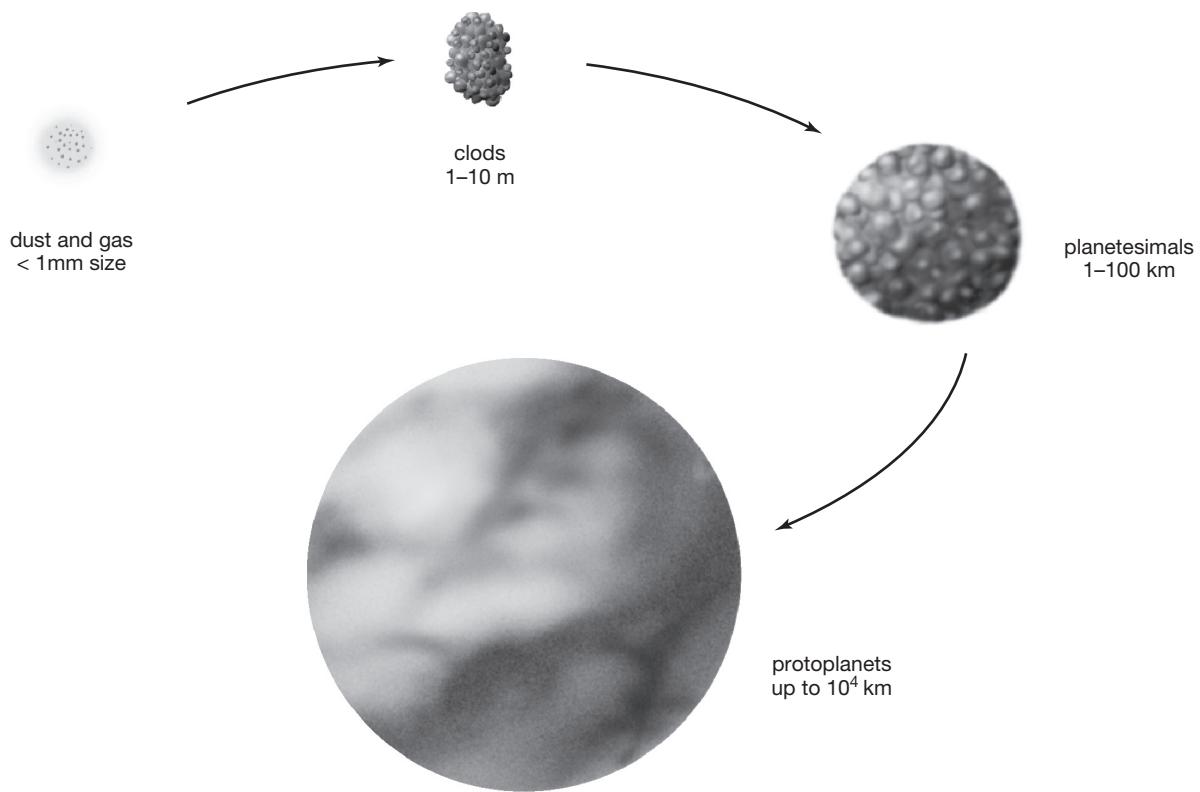
The cooler temperatures overall permitted some clumps of matter to begin to come together, even as the universe as a whole continued to expand. Stars, nebulae, and galaxies began to form, increasing their mass and gravitational attraction and the temperatures in their cores. Ultimately, temperatures became hot enough to sustain a "nuclear furnace" powered by hydrogen fusion. The nuclear reactions created heavier elements through a series of complicated reactions occurring in steps at different temperatures. Many stars acquired planets and other orbiting bodies. Today, the space between stars is filled with hydrogen and helium, dating from the original creation of the universe, and remnant-heavier elements formed in the interior of stars that have exploded.

### The Formation of Our Solar System

Our own solar system formed when a nebula condensed about six billion years ago. The process was very fast at first; hydrogen fusion in our Sun began during the first 100,000 years. The solar nebula contained primordial hydrogen (H) and helium (He) and, for the most part, these elements dominate our solar system today. As the nebula condensed, refractory (unreactive) elements remained in hotter regions. Pressure and temperature gradients led to differentiation of the solid/gas nebula—elements that easily vaporized only remained in the cooler outer parts. Various clumps of matter condensed to form planetesimals (with radii ranging from a few meters to 1,000 km/620 mi.) with compositions varying predictably from the center of protosolar system to the outside (Figure 13). Minerals formed, with oxides and iron-nickel (Fe-Ni) alloy minerals collecting in the center of the protosolar system and



**FIGURE 12** Time line for our universe.



**FIGURE 13** Planets and planetesimals.

magnesium-iron (Mg-Fe) silicates concentrating farther out. Water, methane, and other volatiles concentrated in the outermost sections.

Today, remnant-heavy elements from previously existing stars are concentrated in the terrestrial planets (Mercury, Venus, Earth, and Mars) and parent bodies of meteorites (now asteroids). The Earth and other terrestrial planets seem to have condensed in stages. The core formed first from Fe-Ni-rich planetesimals. More planetesimals, richer in silicon (Si), were added to the outside, thus giving the sharp compositional boundary between the core and mantle. Finally, planetesimals rich in volatile elements were added, ultimately leading to the Earth's early atmosphere. It seems that, in its early history, the Earth was entirely molten, but it soon cooled and developed a crust.

## ABUNDANT ELEMENTS AND MINERALS

### Goldschmidt's Classification

V. M. Goldschmidt and other geochemists in the early twentieth century believed that the Earth formed by processes involving interactions between various molten material, solids, and gases. They hypothesized that the Earth was originally completely homogeneous and molten, subsequently

cooling and separating into the layered structure we know today. Although many of their ideas are now known to be incorrect, their basic observations were correct.

As a model for the internal processes of the Earth, Goldschmidt made observations of copper-smelting furnaces at Mansfeld, Germany, and found that molten materials often divided into several different sorts of liquid melts: one rich in Fe alloys, another rich in sulfide compounds, and one containing silicates. In most smelting processes, the latter two were considered waste, forming **matte** and **slag**, respectively. Goldschmidt also studied meteorites and igneous rocks, where he found minerals falling into the same three general chemical groups.

Goldschmidt and his colleagues devised a classification scheme for elements based on their behavior in a hypothetical iron alloy-silicate-sulfide-gas system (see Figure 7). They divided elements into four groups: **siderophile** (elements that concentrate in an iron-rich liquid), **chalcophile** (elements that concentrate in a sulfur-rich liquid), **lithophile** (elements that concentrate in a silica-rich liquid), and **atmophile** (elements that form a gas). Although the distinction between siderophile, chalcophile and lithophile elements is sometimes ambiguous, this classification scheme is significant because it implies that properties and behavior of elements are

**TABLE 4** The Most Abundant Elements in the Earth's Crust, Mantle, and the Entire Earth

Element	Crust Weight %	Mantle Weight %	Earth Weight %
oxygen (O)	46.60	43.68	30.10
silicon (Si)	27.72	21.13	15.10
aluminum (Al)	8.13	1.85	1.40
iron (Fe)	5.00	6.22	32.10
calcium (Ca)	3.63	2.22	1.50
sodium (Na)	2.83	0.42	0.35
potassium (K)	2.59	0.11	0.13
magnesium (Mg)	2.09	22.61	13.90
titanium (Ti)	0.44	0.10	0.08
hydrogen (H)	0.14	<0.10	<0.10
phosphorus (P)	0.10	0.03	0.02
manganese (Mn)	0.09	0.11	0.08
fluorine (F)	0.08	<0.10	<0.10
barium (Ba)	0.04	<0.10	<0.10

not random. Since its origin, Earth has undergone differentiation, in large part due to magmatic processes. Lithophile elements have become enriched in the crust. Chalcophile and siderophile elements have become more concentrated in the mantle and core. Atmophile elements escaped Earth's interior and formed the atmosphere we enjoy today.

### Abundance of Elements

About a dozen elements account for 99.9% of Earth's composition (Table 4). Iron is the most abundant overall (32 wt %) but is mostly in the core. Iron is only about 5 to 6 wt % of the crust and mantle. Oxygen and silicon make up more than half the crust and mantle, so silicate minerals are common. The other major elements in the crust and mantle are similar but the proportions are different. The mantle contains substantially more magnesium and significantly less silicon, aluminum, sodium and potassium than the crust; consequently, the mantle is dominated by magnesium-rich mafic minerals (olivine, pyroxene, garnet, and spinel) while much of the crust contains quartz and/or feldspars.

Some elements are common in many different minerals. Oxygen (O) and silicon (Si) are perhaps the best examples. Many sedimentary rocks and nearly all igneous and metamorphic rocks are composed of multiple minerals containing O and Si. In contrast, because of their properties, some other elements tend to be found mainly in only a few distinct minerals. For example, titanium (Ti) may occur as a minor component in biotite, amphibole, or other minerals. In many rocks, however, Ti is concentrated in Ti-rich minerals such as rutile ( $TiO_2$ ), titanite ( $CaTiSiO_5$ ), and ilmenite ( $FeTiO_3$ ). Rocks rich in Ti always contain one of these latter three minerals. Similarly, rocks

containing significant amounts of phosphorous usually contain apatite,  $Ca_5(PO_4)_3(OH, F, Cl)$ , or monazite,  $(Ce, La, Th, Y)PO_4$ .

### Anionic Complexes

While thinking of individual elements coming together to form minerals is convenient, in reality, atoms are seldom unbonded to others. Single atoms are very reactive. They tend, when possible, to bond to other atoms to form compounds. Sometimes, they bind to other atoms of the same element. For example,  $N_2$ , composed of molecules containing two nitrogen atoms, dominates the Earth's atmosphere. Small atoms with several valence electrons, such as silicon or carbon, are especially reactive. They seldom exist by themselves, readily combining with oxygen, and sometimes other elements, to form strongly bonded units called **anionic complexes**. Thus, silicon, carbon, phosphorous, nitrogen, and sulfur are usually found in silicate, carbonate, phosphate, nitrate, or sulfate minerals (Table 5). Anionic complexes such as  $(SiO_4)^{4-}$  and  $(CO_3)^{2-}$  are so strongly bonded that they behave just like individual anions in many minerals. Most mineralogical and geological texts (this one included) classify minerals based on their anions or

**TABLE 5** Common Anionic Complexes in Minerals

Element	Complex
silicon (Si)	$(SiO_4)^{4-}$
carbon (C)	$(CO_3)^{2-}$
nitrogen (N)	$(NO_3)^{-}$
sulfur (S)	$(SO_4)^{2-}$
phosphorous (P)	$(PO_4)^{3-}$

**BOX 4****Chemical Formulas of Minerals**

Throughout this text, we follow standard chemical conventions. We list elements with subscripts to indicate the relative numbers of atoms present. We list cations before anions and anionic complexes, with the largest cations coming first. The following are some examples of formulas:

marialite	$\text{Na}_4(\text{AlSi}_3\text{O}_8)_3\text{Cl}$
skutterudite	$(\text{Co}, \text{Ni})\text{As}_3$
clinohumite	$\text{Mg}_9(\text{SiO}_4)_4(\text{OH}, \text{F})_2$
olivine	$(\text{Mg}, \text{Fe})_2\text{SiO}_4$
natrolite	$\text{Na}_2\text{Al}_2\text{Si}_3\text{O}_{10} \cdot 2\text{H}_2\text{O}$
montmorillonite	$(\text{Na}, \text{Ca})(\text{Al}, \text{Mg})_2(\text{Si}_4\text{O}_{10})(\text{OH})_2 \cdot n\text{H}_2\text{O}$

Subscripts outside parentheses apply to everything within if no commas are present. The formula unit of marialite indicates that 4 Na, 3 Al, 9 Si, 24 O, and 1 Cl are in one formula of marialite. Commas show an either-or situation. In one formula of clinohumite, for example, there are two atoms of OH or of F, or of the two combined. If we had omitted the comma, it would indicate that there were both 2 OH and 2 F per formula. Elements separated by commas, then, can be thought of as substituting for each other. For example, montmorillonite may contain either Al or Mg, or both; olivine may contain either Fe or Mg, or both.

Parentheses surround complexes such as  $\text{SiO}_4$  or  $\text{CO}_3$  when it helps with clarity. In clinohumite, parentheses around  $\text{SiO}_4$  emphasize clinohumite's chemical similarity to forsterite and other olivines, all of which have  $\text{SiO}_4$  in their formulas. In montmorillonite, the  $\text{Si}_4\text{O}_{10}$  is in parentheses to emphasize that the structure is that of a sheet silicate, many of which have  $(\text{Si}_4\text{O}_{10})$  in their formula.

Loosely bonded interstitial components (such as Cl in marialite, or OH and F in clinohumite) are on the right. We indicate loosely bonded  $\text{H}_2\text{O}$ , often called nonstructural water, by a dot preceding  $n\text{H}_2\text{O}$  at the far right in a formula. The  $n$  in the formula for "clay" indicates that an unknown amount of nonstructural water is present. Natrolite, a zeolite, has  $\text{H}_2\text{O}$  in holes in its structure. When completely hydrated, there are two moles of  $\text{H}_2\text{O}$  for each  $\text{Na}_2\text{Al}_2\text{Si}_3\text{O}_{10}$  formula.

When useful, we use superscripts to indicate ionic charge:  $(\text{OH})^-$  indicates the hydroxyl radical, which has a charge of  $-1$ . Similarly  $(\text{SiO}_4)^{4-}$  indicates an Si atom bonded to 4 O, with a net charge of  $-4$ . Sometimes showing coordination (the number of bonds) of an atom is useful. We do this with superscript roman numerals; they are discussed later.

anionic complexes because the properties of minerals with the same anions are generally very similar. Mineral formulas are usually written to emphasize any anionic groups that exist (Box 4).

Mineralogists can acquire mineral analyses in many ways. In the past, most chemical analyses were determined by titration and other "wet chemical" techniques. Today we use sophisticated analytical machines, including **atomic absorption spectrophotometers** and **electron microprobes**. We normally report analytical results by listing oxide weight percents. These values must be normalized if we wish to have **mineral formulas** (Box 5).

### MAJOR ELEMENTS, MINOR ELEMENTS, AND TRACE ELEMENTS

Most natural minerals are formed from combinations of many elements. Unlike mechanical mixtures (such as two things being ground up together) the elements are ordered and intimately bonded together. The resulting crystalline solutions are **solid**

**solutions.** Common olivine, for example, is a solution of  $\text{Fe}_2\text{SiO}_4$  and  $\text{Mg}_2\text{SiO}_4$  (Box 4). Some minerals, such as hornblende, contain many elements in solid solution and have long and complicated formulas, while others such as fluorite ( $\text{CaF}_2$ ) or quartz ( $\text{SiO}_2$ ) vary little from their ideal compositions. We must use sophisticated analytical instruments to determine the composition of natural hornblendes and many other solid solution minerals.

The elements that comprise a mineral may be broadly classified in one of three categories: **major elements**, **minor elements**, and **trace elements**. Major elements are those fundamental to the mineral, and control its basic atomic structure and gross properties. Minor elements are those present in small amounts, usually as replacements for some of the major elements. Such elements, present in amounts up to a few weight %, may affect color and some other properties, but the basic atomic structure is fixed by its major element chemistry. Minerals also contain extremely small amounts of other elements called *trace elements*. Trace elements

**BOX 5****How to Normalize a Mineral Analysis**

We normally report mineral analyses in oxide weight % (wt %), but mineral formulas are written in terms of numbers of atoms. **Normalization** is the process of converting an analysis into a formula. Normalization is a tedious but straightforward arithmetical operation when done by hand.

The table below gives the chemical analysis of a feldspar from Grorud, Norway. Column A lists the oxides, columns B through D give chemical data for the oxides, and column E displays the actual results of the mineral analysis. The Grorud feldspar contains 65.90 wt % SiO<sub>2</sub>, 19.45 wt % Al<sub>2</sub>O<sub>3</sub>, 1.03 wt % Fe<sub>2</sub>O<sub>3</sub>, 0.61 wt % CaO, 7.12 wt % Na<sub>2</sub>O, and 6.20 wt % K<sub>2</sub>O. We can think of the values in column E as being the number of grams (g) of each oxide in 100 grams of the feldspar: 65.90 gm of SiO<sub>2</sub>, 19.45 gm of Al<sub>2</sub>O<sub>3</sub>, 1.03 gm of Fe<sub>2</sub>O<sub>3</sub>, 0.61 gm of CaO, 7.12 gm of Na<sub>2</sub>O, and 6.20 gm of K<sub>2</sub>O.

To convert from grams of oxides to moles (mol) of oxides, we divide the oxide weight % values (column E) by oxide atomic weight (column B); column F shows the results. The values in column F are relative values only; they total to 1.48569, which has no scientific meaning. In column G, we have multiplied the values in column F by a fudge factor so the total is 100%. We can see then, that the Grorud feldspar is 73.829 mol % SiO<sub>2</sub>, 12.840 mol % Al<sub>2</sub>O<sub>3</sub>, 0.434 mol % Fe<sub>2</sub>O<sub>3</sub>, 0.732 mol % CaO, 7.735 mol % Na<sub>2</sub>O, and 4.430 mol % K<sub>2</sub>O. These values vary from the weight % values in column E because the different oxides have different atomic weights.

To convert the mole % values to numbers of cations, we multiply the values in column G (moles of oxides) by the number of cations in each oxide (column C). To convert the mole % values to numbers of oxygen, we multiply the values in column G by the number of O<sup>2-</sup> in each oxide (column D). Columns I and J give the results of these calculations. Using these numbers, we could write the formula of the feldspar as Ca<sub>0.732</sub>Na<sub>15.469</sub>K<sub>8.860</sub>Fe<sub>0.868</sub>Al<sub>25.680</sub>Si<sub>73.829</sub>O<sub>200.377</sub>, but normal feldspar analyses are written with 8 atoms of O<sup>2-</sup>. So, in column K we have multiplied all the atom numbers in columns I and J by (8 ÷ 200.377) so that the number of atoms of O<sup>2-</sup> is exactly 8. The values in column K give us the normalized formula for the feldspar: Ca<sub>0.03</sub>Na<sub>0.62</sub>K<sub>0.35</sub>Fe<sub>0.03</sub>Al<sub>1.03</sub>Si<sub>2.95</sub>O<sub>8</sub>, equivalent to (Ca,Na,K)(Fe,Al,Si)<sub>4</sub>O<sub>8</sub>; the Grorud feldspar comes close. The small discrepancy is due to analytical error.

A	B	C	D	E	F	G	H	I	J	K
										G = Normalized values from F = E/B column F
Oxide	Atomic wt of oxide (gm/mole)	Number of oxide cations in oxide	Number of O <sup>2-</sup> in oxide	Oxide wt % in the mineral (determined by analysis)	Number of moles of oxide in the mineral	Relative number of moles of cation in the mineral	Relative number of moles of O <sup>2-</sup> contributed by each cation	Number of moles of O <sup>2-</sup> in the mineral	K = Normalized values from Column I	
SiO <sub>2</sub>	60.08	1	2	65.90	1.09687	73.829	Si <sup>4+</sup>	73.829	147.658	2.95
Al <sub>2</sub> O <sub>3</sub>	101.96	2	3	19.45	0.19076	12.840	Al <sup>3+</sup>	25.680	38.520	1.03
Fe <sub>2</sub> O <sub>3</sub>	159.68	2	3	1.03	0.00645	0.434	Fe <sup>3+</sup>	0.868	1.302	0.03
CaO	56.08	1	1	0.61	0.01088	0.732	Ca <sup>2+</sup>	0.732	0.732	0.03
Na <sub>2</sub> O	61.96	2	1	7.12	0.11491	7.735	Na <sup>+</sup>	15.469	7.735	0.62
K <sub>2</sub> O	94.20	2	1	6.20	0.06582	4.430	K <sup>+</sup>	8.860	4.430	0.35
Total				100.31	1.48569	100.000		Σ cations =	Σ O <sup>2-</sup> =	Σ O <sup>2</sup> =
								125.438	200.377	8.00

are present in all minerals and provide valuable information for geologists attempting to determine how, when, and where specific minerals formed. They have little effect on most mineral properties. A notable exception to this is sometimes color; even

trace amounts of some elements can have major effects on a mineral's color.

As an example of chemical variability in minerals, let's consider olivine. Major and minor element analyses of some olivines from different

**TABLE 6 Analyses of Major and Minor Elements in Some Olivines (Element Weight %)**

<b>Rock:</b>	<b>Marble</b>	<b>Marble</b>	<b>Peridotite</b>	<b>Mafic Sill</b>	<b>Fe-Gabbro</b>	<b>Fe-Formation</b>
<b>Location:</b>	<b>Burma</b>	<b>Finland</b>	<b>New Zealand</b>	<b>Minnesota</b>	<b>East Greenland</b>	<b>Germany</b>
Si	19.50	19.21	19.15	14.22	14.09	13.94
Ti	0.00	0.03	0.01	0.72	0.12	0.00
Al	0.00	0.29	0.11	0.26	0.04	0.00
Fe	0.86	3.39	6.11	44.79	50.84	54.01
Mn	0.00	0.18	0.10	0.00	0.78	0.22
Mg	34.88	32.60	31.27	4.93	0.63	0.00
Ca	0.00	0.00	0.11	0.94	1.56	0.00
Na	0.00	0.00	0.01	0.00	0.00	0.00
O	45.42	44.73	44.30	33.37	32.05	31.42
Total	100.66	100.43	101.17	99.23	100.11	99.59

geologic environments are given in Table 6 (element weight %), Table 7 (oxide weight %), and Table 8 (number of atoms). The three tables are redundant; values from one can be converted to another by an arithmetical process called normalization (Box 5). Table 6 lists element weight %, but most mineralogists and petrologists prefer to consider oxide weight % or numbers of atoms because numbers of atoms directly translate into mineral formulas. As can be seen from the tables, Mg, Fe, and Si are major elements in olivines. Olivine may also contain Ca, Mn, Ti, alkalis, and alkaline earths, but except in extremely rare circumstances, only as minor or trace elements. Many other elements may be present at trace levels in olivine as well; Ni and Cr are good examples.

The weight % values in Tables 6 and 7 show a wide range of chemical composition for

olivine. The major elements Si, Mg, and Fe are especially variable. How can we make sense of it all? The answer is to look at numbers of atoms (Table 8) rather than weight %. The values in Table 8 yield mineral formulas. Thus, the olivine from New Zealand has a formula  $\text{Ca}_{0.004}\text{Mg}_{1.859}\text{Mn}_{0.003}\text{Fe}_{0.158}\text{Al}_{0.006}\text{Si}_{0.985}\text{O}_4$ . The ideal stoichiometry of olivine is  $\text{R}_2\text{SiO}_4$ , where R is usually Fe, Mg, Mn, or Ca; all analyses in Table 8 have close to ideal stoichiometry. Apparent deviations from ideal stoichiometry can mostly be attributed to inclusions of other minerals within the olivine, or to analytical error.

While chemical substitutions are common in most minerals, in some minerals the substitutions are complex. In olivine they are quite simple. We can describe the major and minor elemental compositions of most natural olivines as combinations of the **end members** (represented by ideal formulas)

**TABLE 7 Analyses of Major and Minor Elements in Some Olivines (Oxide Weight %)**

<b>Rock:</b>	<b>Marble</b>	<b>Marble</b>	<b>Peridotite</b>	<b>Mafic Sill</b>	<b>Fe-Gabbro</b>	<b>Fe-Formation</b>
<b>Location:</b>	<b>Burma</b>	<b>Finland</b>	<b>New Zealand</b>	<b>Minnesota</b>	<b>East Greenland</b>	<b>Germany</b>
$\text{SiO}_2$	41.72	41.07	40.96	30.42	30.15	29.83
$\text{TiO}_2$	0.00	0.05	0.01	1.20	0.20	0.00
$\text{Al}_2\text{O}_3$	0.00	0.56	0.21	0.50	0.07	0.00
$\text{Fe}_2\text{O}_3$	0.00	0.65	0.00	0.00	0.43	0.00
FeO	1.11	3.78	7.86	57.62	65.02	69.48
MnO	0.00	0.23	0.13	0.00	1.01	0.28
MgO	57.83	54.06	51.84	8.17	1.05	0.00
CaO	0.00	0.00	0.15	1.32	2.18	0.00
$\text{Na}_2\text{O}$	0.00	0.00	0.01	0.00	0.00	0.00
Total	100.66	100.43	101.17	99.23	100.11	99.59

**TABLE 8 Analyses of Major and Minor Elements in Some Olivines (Ions per 4 Oxygen)**

<b>Rock:</b>	<b>Marble</b>	<b>Marble</b>	<b>Peridotite</b>	<b>Mafic Sill</b>	<b>Fe-Gabbro</b>	<b>Fe-Formation</b>
<b>Location:</b>	<b>Burma</b>	<b>Finland</b>	<b>New Zealand</b>	<b>Minnesota</b>	<b>East Greenland</b>	<b>Germany</b>
Si <sup>4+</sup>	0.978	0.979	0.985	0.971	1.002	1.011
Ti <sup>4+</sup>	0.000	0.001	0.000	0.029	0.005	0.000
Al <sup>3+</sup>	0.000	0.016	0.006	0.019	0.003	0.000
Fe <sup>3+</sup>	0.000	0.012	0.000	0.000	0.011	0.000
Fe <sup>2+</sup>	0.022	0.075	0.158	1.538	1.807	1.970
Mn <sup>2+</sup>	0.000	0.005	0.003	0.000	0.028	0.008
Mg <sup>2+</sup>	2.021	1.919	1.859	0.389	0.052	0.000
Ca <sup>2+</sup>	0.000	0.000	0.004	0.045	0.078	0.000
Total	3.021	3.007	3.016	2.991	2.986	2.989

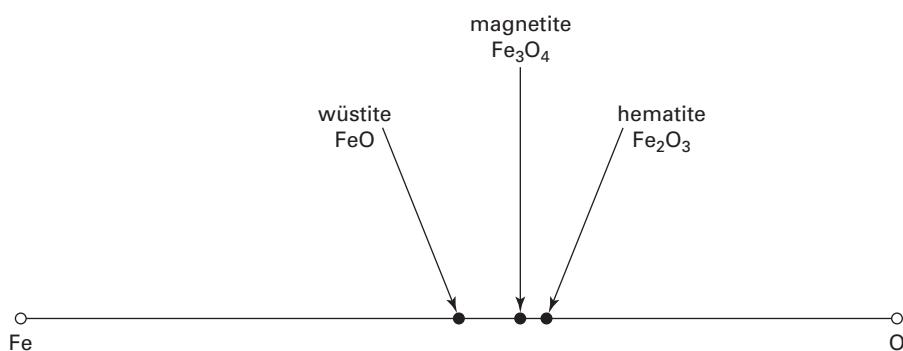
forsterite ( $\text{Mg}_2\text{SiO}_4$ ), fayalite ( $\text{Fe}_2\text{SiO}_4$ ), tephroite ( $\text{Mn}_2\text{SiO}_4$ ), and calcio-olivine ( $\text{Ca}_2\text{SiO}_4$ ). The sample from Burma is nearly 100% forsterite ( $\text{Mg}_2\text{SiO}_4$ ), while that from Germany is nearly 100% fayalite ( $\text{Fe}_2\text{SiO}_4$ ). The other olivines fall in between. In contrast with olivines, amphiboles, micas, and some other minerals have complex formulas and may have many elements substituting in their structures. Consequently, choosing appropriate end members is difficult and arbitrary.

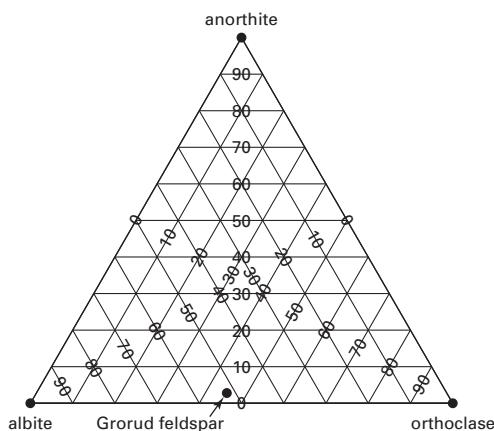
The degree to which elements may substitute for each other depends on the elements and on the mineral. In olivine, Fe and Mg mix freely, so any composition between fayalite and forsterite is possible. Olivines can incorporate only minor amounts of Ca, however, so no compositions midway between calcio-olivine and forsterite are found in nature. In contrast, Ca, Mg, and Fe mix freely in garnets; natural garnets can have any composition between end members grossular ( $\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ ), almandine ( $\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ ), and pyrope ( $\text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ ).

## PLOTTING MINERAL COMPOSITIONS

One way to depict mineral compositions is to plot them on composition diagrams. In simple chemical systems, where the minerals being discussed are only made of two components, they can be plotted on a line as shown in Figure 14. Pure iron (Fe) plots on one end of the line and pure oxygen (O) on the other. Neither element exists as a mineral, but the three compositions in the middle (wüstite, magnetite, and hematite) do. The ratio Fe:O determines where on the line the minerals plot. Hematite, for example, has the composition  $\text{Fe}_2\text{O}_3$ , so it is two-fifths iron, and it plots 2/5 of the way from pure oxygen toward iron.

Most minerals have more than two components. Figure 15 shows a three-component system. We can use any chemical components we want when plotting mineral compositions. In this figure we have used the components anorthite ( $\text{CaAl}_2\text{Si}_2\text{O}_8$ ), albite ( $\text{NaAlSi}_3\text{O}_8$ ), and orthoclase ( $\text{KAlSi}_3\text{O}_8$ ) because we want to show feldspar compositions. The Grorud feldspar, discussed

**FIGURE 14** The system Fe-O.



**FIGURE 15** The system albite-anorthite-orthoclase.

in Box 5, is 3% anorthite, 62% albite, and 35% orthoclase (ignoring the minor Fe impurity). It plots as shown on the triangular diagram. The vertical row of numbers within the triangle shows the amount of anorthite. The two diagonal rows show the amounts of albite and orthoclase. If a feldspar contained no anorthite, it would plot on the bottom side of the triangle (between albite and orthoclase). But, the Grorud feldspar contains 3% anorthite so it plots 3% of the way from the bottom toward the anorthite apex at the top. Similarly, it plots 62% of the way from the anorthite-orthoclase side toward albite (in the lower left corner), and 35% of the way from the albite-anorthite side toward orthoclase (in the lower right corner).

## Questions for Thought

Some of the following questions have no specific correct answers; they are intended to promote thought and discussion.

1. Why are minerals important in our daily lives?
2. Understanding chemistry is a key to understanding minerals. Yet the field of mineralogy predates chemistry by well over a thousand years. Explain this apparent contradiction. Why were there mineralogists before there were chemists?
3. The Bohr model of the atom, the Aufbau principle, and related discoveries were a key to understanding bonding in minerals. Why?
4. Why is the Periodic Table of the Elements useful when considering mineral chemistry?

5. Different ions may have different numbers of protons, neutrons, and electrons. How do these variations relate to, or control, mineral chemistry and crystal structure?
6. There are relatively few common minerals. Why?
7. What is the difference between major elements, minor elements, and trace elements? Can there be a major element in one mineral, a minor element in another, and a trace element in a third?
8. All olivines are not the same. Why do we use one name to describe minerals, such as olivine, that do not have a fixed chemical composition?

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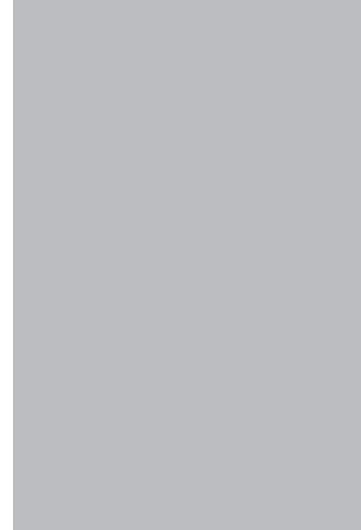
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# Crystallization and Classification of Minerals



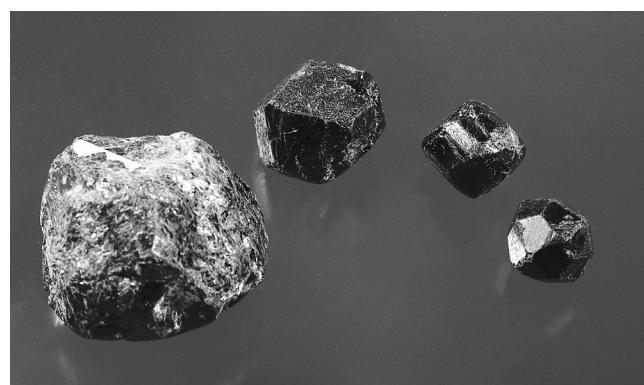
# Crystallization and Classification of Minerals

All minerals are crystalline. In this chapter we look in more detail at what *crystalline* means and how crystals form. We discuss crystal growth and examine why some minerals are more abundant than others. We also introduce and discuss a mineral classification scheme.

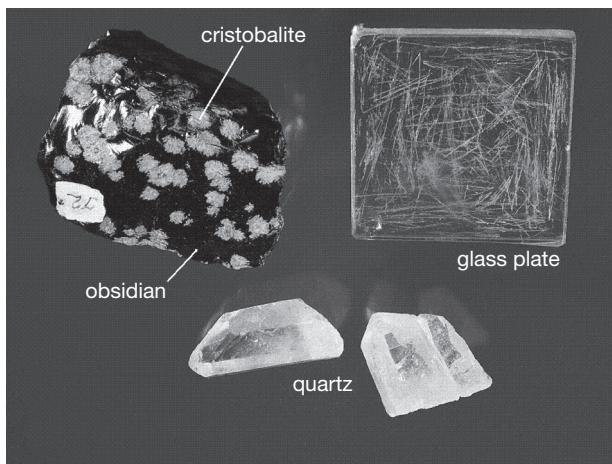
## CRYSTALS AND CRYSTALLIZATION

To most people, a crystal is a sparkling gem-like solid with well-formed faces and a geometric shape. For many scientists, including mineralogists, *crystal* and *crystalline* also refer to any solid compound having an ordered, repetitive, atomic structure. The atomic structure may or may not result in flat crystal faces and a gemmy appearance. We use the term *crystal* in both ways. When a mineralogist refers to a quartz crystal, the reference is usually to a six-sided prismatic shape with pyramidal ends. On the other hand, petrologists

and mineralogists may refer to crystals of quartz in a rock such as a granite. Such crystals rarely have perfectly developed smooth faces. All minerals are crystalline by definition, but perfectly formed crystals are rare. When faces on a mineral are flat and fully developed, giving the mineral a geometric shape, we say the crystal is **euhedral**. When no crystal faces are visible, we say it is **anhedral**. Those minerals that fall in between are **subhedral** (Figure 1).



**FIGURE 1** In this group of garnets, the sample on the left is anhedral; the others are euhedral. The one on the right is the most perfectly formed; it has 12 nearly identically shaped faces.



**FIGURE 2** Obsidian (with patches of “snowflake” cristobalite), a glass plate used to determine mineral hardness, and two quartz crystals. The obsidian exhibits conchoidal fracture, the quartz has flat crystal faces that formed as the crystals grew, and the glass plate has manufactured flat surfaces. All materials shown in this photograph are made predominantly of  $\text{SiO}_2$ , but only quartz and cristobalite are minerals because everything else is amorphous (not crystalline).

Some mineral-like substances are **amorphous**, which means they have a random atomic structure. Natural volcanic glass, obsidian, is an example (Figure 2). Window glass, too, is amorphous. Glassmakers melt mixtures containing mostly quartz sand, and allow the melt to solidify quickly so atoms can’t arrange themselves in a regular, repetitive atomic structure. The process produces a glass that, unlike a mineral, is **noncrystalline**. Noncrystalline materials, and a few minerals, are **isotropic**, meaning they have the same properties in all directions. Most minerals are **anisotropic**, meaning they have

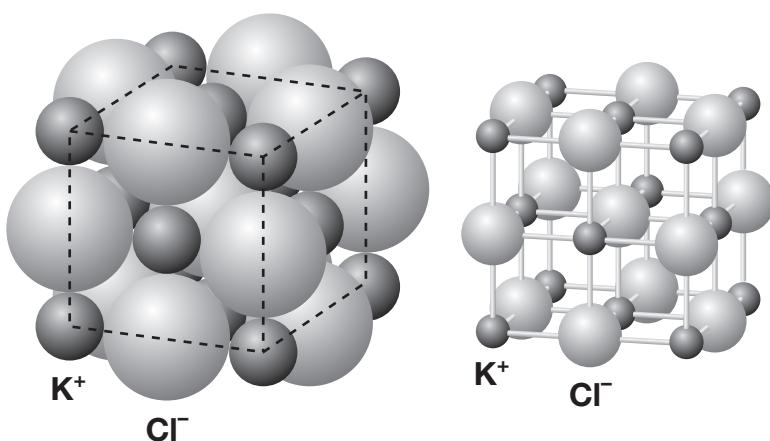
**FIGURE 3** Atoms come together to produce crystals in igneous, metamorphic, or sedimentary systems. Here we see two views showing  $\text{K}^+$  and  $\text{Cl}^-$  combined to form  $\text{KCl}$ , a salt mineral called sylvite found in some sedimentary rocks. These two views show the same atomic arrangement. Although ions are not really hard spheres, the model on the left most closely resembles the real structure. In the ball-and-stick view on the right, the size of the ions has been decreased to make it possible to see the arrangement of cations and anions in the interior, and individual bonds (shown as sticks) between ions. This depiction, however, is unrealistic because ions in crystals bond much more closely than shown. Sylvite has a very simple atomic arrangement. The ions bond in an overall cubic pattern, so sylvite sometimes forms cubic crystals. Most minerals have more complicated atomic arrangements and do not form cubic crystals.

different properties in different directions. For this reason, glass makes better windows than most minerals because light passes through it equally well in all directions. Artisans make geometrical crystal shapes and imitation gems from glass, but that does not make them minerals. Because minerals and glass do not have identical properties, a gemologist can often identify imitation gems by the way light passes through them.

The formation of crystals involves the bringing together and ordering of constituent elements. For example, potassium and chlorine combine in an ordered way to form the mineral sylvite (Figure 3). Crystals grow from a small single molecule to their final visible form. If the conditions are right, crystals may grow to be very large. Some crystals in **pegmatites** (very coarse-grained igneous rocks; see Box 1) are tens of meters in the longest direction. Many crystals, however, are so small that it takes a microscope to see them.

In magma, kinetic energy means that atoms are always in motion. Some collide and may form bonds temporarily before breaking apart again. There is a balance between the formation of bonds and the rate at which they break apart. As long as bonds break as fast as they form, there will be no net crystallization. Kinetic energy is greater at higher temperatures, so magmas will be completely molten at high temperatures. When a magma cools sufficiently, however, atoms slow down and some bonds begin to persist. This is the beginning of the formation of crystals from a melt. The initial crystals form nuclei, many of which continue as the centers of continued crystal growth.

A similar process occurs in aqueous systems. Atoms of different sorts may be dissolved in water and, as long as the water is not saturated, no crystals will form. Atoms will bond temporarily, only to break apart and return to solution. Most substances are more soluble in water at high temperature. So, a



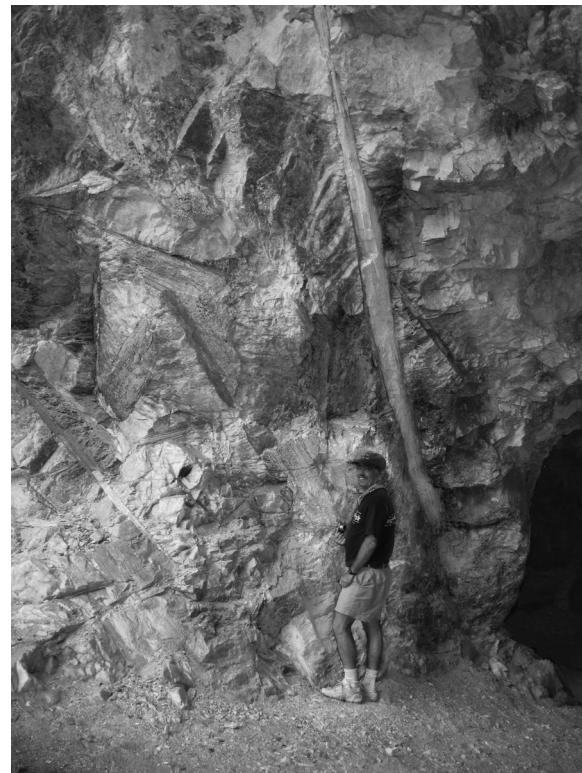
**BOX 1****Pegmatites Contain Very Large Crystals**

Pegmatites are extremely coarse-grained igneous rocks, usually of granitic or granodioritic composition (Figure 4). Granitic and granodioritic pegmatites typically are dominated by quartz, alkali feldspars, biotite, and muscovite. They probably form during the end stages of crystallization, when remaining magma is enriched in volatiles and elements that do not easily enter into common rock-forming minerals. Such elements include boron, cesium, beryllium, zirconium, niobium, uranium, thorium, tantalum, tin, rare earth elements, chlorine, fluorine, lithium, and phosphorus. The presence of abundant fluids and uncommon elements often results in the formation of large, unusual, and sometimes valuable minerals. Gemstones from pegmatites include tourmaline, bright green feldspar (amazonite), beryl, chrysoberyl, topaz, cryolite, and spodumene.

The largest crystals in the world have been found in pegmatites. A single crystal of phlogopite from Ontario, Canada, was described as being 4.2 m (14 ft.) wide and 10 m (33 ft.) long. A quartz crystal from a Russian pegmatite weighed more than 907 kg (2,000 lbs.). The largest quartz crystal on record, however, was from Brazil and weighed more than five tons. Pegmatites in the Black Hills of South Dakota (Figure 4) are famous for "logs" of white spodumene, which are up to 15.2 m (50 ft.) long. In some Black Hills pegmatites, mineralogists have found tourmaline crystals that are 2.7 m (9 ft.) long, topaz crystals that weigh hundreds of pounds, and amblygonite crystals that are several feet across.

Gem-grade tourmalines in pegmatites come in a variety of colors. The most common form of tourmaline is the black or iron-rich variety, called *schorl*. Brown tourmaline (dravite) contains magnesium. Lithium is primarily responsible for the green (verdelite), yellow, pink (rubellite), and blue (indicolite) varieties. Colorless tourmaline, called *achroite*, is rare. Individual tourmaline crystals may also contain zones of different colors, which resulted from chemical changes during the growth of the crystal (Plate 1.1). The most famous multicolor tourmalines are the "watermelon" variety, which consist of a red core with green "rinds."

Most spodumene in pegmatites is white and opaque. However, the rare gem variety, kunzite, is pink and transparent. Emerald-green spodumene is called *hiddenite* and was named after W. E. Hidden, who first discovered the mineral when he overturned a tree on a farm near Stony Point, North Carolina. Beryl from pegmatites is usually yellow-green to blue-green. One variety of beryl is aquamarine, which varies from transparent blue to sea green. Heliodor refers to the golden-yellow variety of beryl that is found in Namibia. Chrysoberyl, whose color ranges from white to yellowish-green to green, is found in a number of different lithologies, but some of the best specimens are found in pegmatites. One variety of chrysoberyl, alexandrite, has the unusual property of being emerald green in daylight and red in artificial light.



**FIGURE 4** The wall of the Tin Mountain Pegmatite Quarry, Black Hills, South Dakota. The geologist is standing in front of a large, thin crystal of spodumene that is several meters long. Other large crystals, mostly spodumene, can also be seen in this photograph. Many pegmatites contain crystals much larger than shown here.

decrease in temperature may lead to oversaturation, nucleation, and precipitation of aqueous minerals. Precipitation may also occur if composition changes. Suppose, for example, that seawater evaporates. The concentration of dissolved material in the remaining water will increase, leading to oversaturation and, eventually, precipitation of crystals. Besides changes in temperature and composition, changes in pressure, pH, or other things may also lead to the formation of aqueous or igneous crystals.

Whether in a magma or aqueous solution, initial crystallization usually involves many nuclei and small crystals. As crystallization continues, however, larger crystals form at the expense of smaller ones. So, regions around large crystals become depleted in small ones. This occurs because nucleation is a kinetic process. Small nuclei composed of just a few atoms form relatively fast compared with larger crystals. Larger crystals are, however, more chemically stable because molecules in the interior of crystals

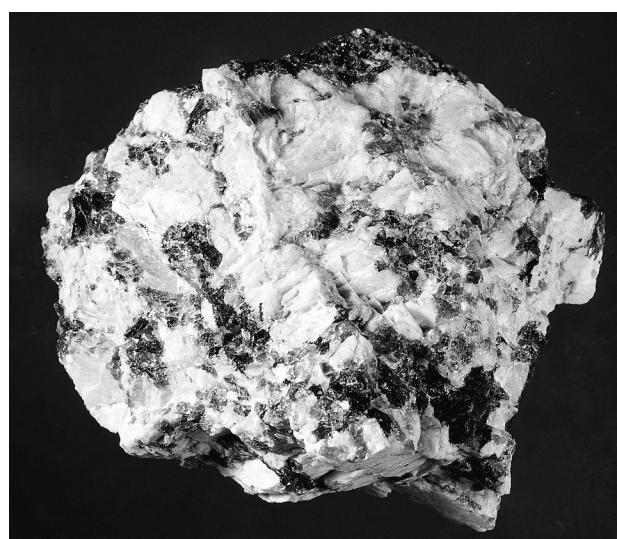
are less reactive and have lower energy than those on the outside. Larger crystals have greater volume-to-surface-area ratio and lower relative surface energy. Consequently, with time, energetics trumps kinetics and molecules on the outside of small crystals diffuse and add to the outside of larger ones. This process is called **Ostwald ripening**. Ostwald ripening explains, for example, why ice crystals form over time in initially smooth ice cream (making old ice cream crunchy), and why large phenocrysts surrounded by a sea of small crystals may form in some volcanic rocks.

Because like charges repel and opposite charges attract, as atoms come together to form crystals, cations bond to, and are surrounded by, anions. Anions bond to, and are surrounded by, cations. This occurs even if bonding is not entirely ionic. So, ionic and partially ionic crystal structures consist of alternating cations and anions in three dimensions (Figure 3). Most common anions, such as  $\text{O}^{2-}$ , are larger than common cations. So, we can think of ionic and partially ionic mineral structures as involving small cations surrounded by larger anions. The number of cations around each anion depends primarily on their relative sizes. In Figure 3 each anion is bonded to six cations, and each cation is bonded to six anions. In other minerals, cations and anions may have fewer or more bonds than this.

There is often more than one way for atoms to combine to form crystals but, as atoms bond, they naturally tend to arrange themselves in a way that minimizes chemical energy. For example, mineralogists have identified more than half a dozen naturally occurring crystalline forms of  $\text{SiO}_2$ , each having its own distinctive arrangement of atoms and bonds. All are minerals. At normal Earth surface conditions  $\alpha$ -quartz is the stable mineral (the mineral with the lowest energy). At different temperatures and pressures, other  $\text{SiO}_2$  minerals (such as cristobalite, coesite, tridymite or stishovite) have the lowest energy and, consequently, are stable. Under normal Earth surface conditions, because  $\alpha$ -quartz has the lowest energy, we would expect it to form to the exclusion of the others. This is generally the case, but there are exceptions, especially at lower temperatures. For kinetic and other factors, natural systems may not always reach lowest (stable) energy conditions.

The most important factors controlling crystal size and perfection are temperature, time, abundance of necessary elements, and the presence or absence of a flux. All work together, but we can make some generalizations. *Temperature* is important because at high temperatures atoms are very mobile. Crystals can grow quickly; large and well-formed crystals may be the result. Principles of

thermodynamics tell us that crystals that form at high temperatures have simpler atomic structures than those that are stable at low temperatures, which may relate to their ability to be large and well ordered. *Time* is important because if a crystal has a long time to grow, it will naturally be larger and better ordered than one that grows quickly; more atoms have time to migrate to the growing crystal and to order themselves in a regular way. This explains why intrusive igneous rocks, which cool slowly underground, are coarser-grained than extrusive igneous rocks of the same compositions. Some extrusive igneous rocks, such as obsidian, cool so quickly that they contain glass. Whatever the time and temperature, crystals cannot grow large if the necessary elements are not available. In most rocks, a dozen elements or less account for 90% of the composition. Minerals composed of those elements will usually be larger than those composed of rarer elements. Even if time, temperature, and atoms are right, crystals may not grow large. Diffusion of atoms through solids is slow, and atoms may not be able to migrate to spots where crystals are growing. However, if a fluid such as interstitial water or a magma is present it acts as a **flux**, transporting atoms to growing crystals. If a flux is present, elements may be carried long distances to sites of mineral growth, and even minerals composed of rare elements may grow to be large. This explains why some minerals of unusual composition are large in pegmatites, coarse-grained rocks that crystallize from water-rich melts left over after most of a magma has crystallized (Figure 5).



**FIGURE 5** Large crystals of quartz, K-feldspar, and biotite in a pegmatite from the Black Hills, South Dakota. This sample measures about 25 cm (10 in.) across.

## CRYSTAL IMPERFECTIONS: DEFECTS

A hypothetical perfect crystal has a perfectly ordered atomic structure with all atoms in the correct places, and it contains no elements other than those described by its chemical formula. As pointed out by C. G. Darwin in 1914, such crystals cannot exist. While a crystal may look perfect on the outside, atomic structures always contain some flaws, called **defects**. In 1921 A. R. Griffiths showed that the low strength of many crystals was due to structural defects. Subsequently, mineral physicists found that plastic deformation of crystals always depends on the presence of defects. During the last few decades, advanced X-ray, transmission electron microscope (TEM), and, most recently, high-resolution transmission electron microscope (HRTM) studies have allowed mineralogists to image such defects (Figure 6).

No mineral is perfectly pure; minerals always contain minor or trace amounts of elements not described by their formula, often at levels that we cannot detect using standard analytical techniques. Perhaps the simplest type of defect is an **impurity defect**, occurring when a foreign atom is present in a mineral's atomic structure. The atom may replace one normally in the structure, or it may occupy an interstitial site (Figure 7a). We call both **point defects** because they occur at one or a few points in the structure. Other types of point defects are **Schottky** and **Frenkel defects** (Figure 7b and c). Frenkel defects occur when an atom is displaced from the position it normally occupies to an interstitial site. Frenkel defects may affect both cations and anions, but cation defects are more common because anions are larger and usually more securely bonded in place. Schottky defects occur when an atom is displaced from a structure altogether. Schottky defects involve both cations and anions. To maintain charge neutrality, missing anions must be compensated by missing cations.

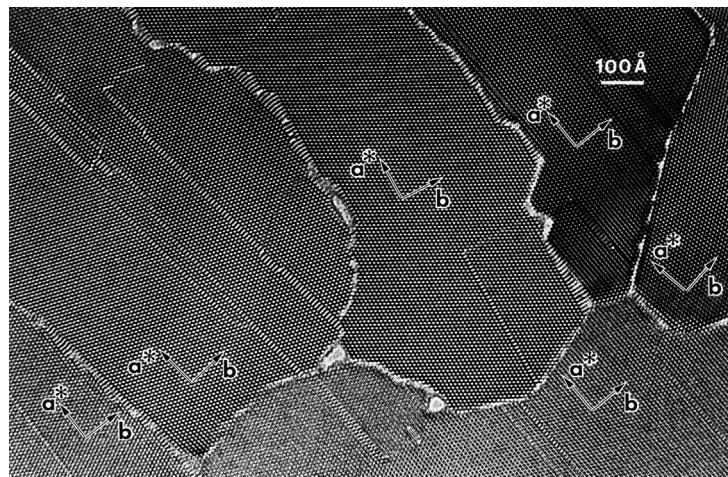
**FIGURE 6** An image of the atomic structure of crocidolite, an asbestos-form amphibole, obtained with a transmission electron microscope. The black and white colors indicate atomic units composed of a small number of atoms. The entire view shows an imperfect grain composed of multiple subgrains with slightly different atomic orientations, as shown by the letters and vectors labeling crystallographic axes. Zipper faults show lines along which the atomic structure is defective. In some places, especially along subgrain boundaries, a coarsening of texture indicates small areas that have atomic structure dissimilar from that of normal crocidolite. Photo courtesy of the Mineralogical Society of America and *American Mineralogist* from "Microstructures and fiber-formation mechanisms of crocidolite asbestos" by Jung Ho Ahn and Peter R. Buseck, *American Mineralogist*, 76 (1991), 1467–1478.

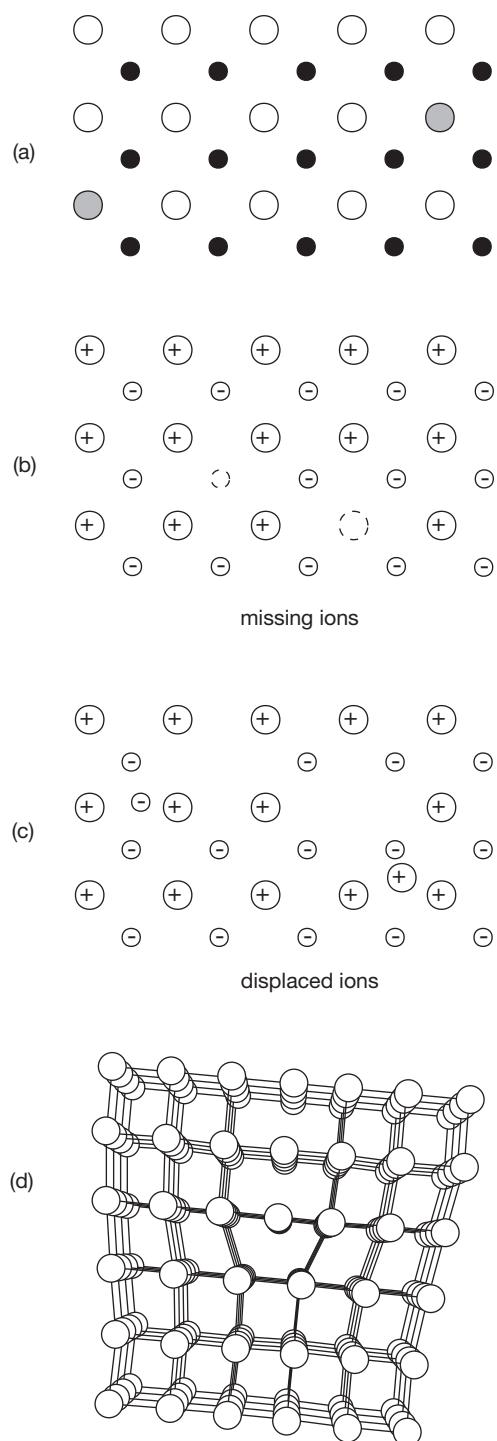
Other types of defects include **line defects** and **plane defects** (Figure 7d). Line defects, such as **edge dislocations** and **screw dislocations** are defects that end at lines in a structure. Plane defects, as their name implies, are planes along which a crystal's structure is displaced or distorted. On a macroscopic scale, grain boundaries can be considered plane defects. At the atomic level, irregular **lineage structures** may separate slightly misoriented portions of a crystal structure or, in layered atomic structures, **stacking faults** may separate layers that are out of order. Because of defects, many crystals consist of **domains** of slightly different atomic orientation (Figure 6).

## CRYSTAL IMPERFECTIONS: ZONING

Crystallizing magmas may produce uneven mineral distribution (Plate 1.4). On a smaller scale, individual minerals develop **compositional zoning** if different parts of a mineral have different compositions. Zoning is present in many minerals but often on such a small scale that we have difficulty detecting it. Occasionally, zoning results in distinct color changes, such as those shown in Plates 1.1 and 1.2. In many cases zoning can be seen with a petrographic microscope because zones of different composition have different optical properties. In still other cases detailed chemical analyses are needed to detect its presence.

Most zoning is an artifact of crystal growth. It may result from changes in pressure or temperature during crystallization. It may also result from changes in magma or fluid composition as crystals grow. The principles of thermodynamics dictate that zoned minerals are unstable, but they are common in nature because diffusion of elements is often not fast enough for growing minerals to remain homogeneous. Most zoning is concentric, representing growth rings about





**FIGURE 7** Diagram illustrating different types of crystal defects: (a) impurity defects occur when a foreign atom (gray) replaces one normally in a crystal structure; (b) Schottky defects occur when atoms are missing from a structure; (c) Frenkel defects occur when atoms are displaced to interstitial sites not normally occupied; (d) edge dislocations occur when a plane of atoms in a structure terminates at a line in the crystal's interior.

an original crystal seed. In some minerals it is more complex and results in compositional zones that are difficult to explain and interpret.

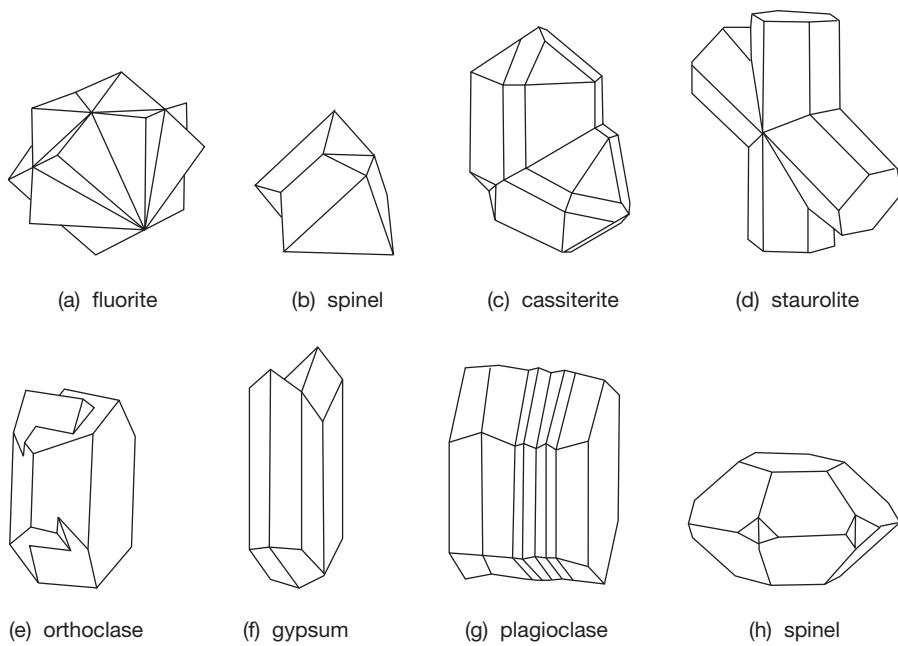
## CRYSTAL IMPERFECTIONS: TWINNING

In ideal crystals, atoms are in repetitive arrangements that are oriented the same way in all parts of the crystal. **Twins** result when different domains of a crystal have different atomic orientations. The domains share atoms along a common surface, typically a plane called the **composition plane**. Twins differ from crystal **intergrowths** composed of crystals that grow next to each other. In a twinned crystal the structure and bonds continue across the composition plane; in intergrowths they are discontinuous. **Simple twins** comprise two domains that share common planes of atoms that separate them. **Complex twins** comprise more than two individual domains.

Figure 8a–f show some simple twins composed of two individual domains. In some the twins appear to be crystals in contact; we call these **contact twins**. In others (Figure 8a, d, and e), the crystals appear to have grown through each other. In such twins, called **penetration twins**, a volume of atoms is shared by both domains, not just a plane. Plate 1.5 shows orthoclase crystals with penetration twins; compare this plate with Figure 8e. Figure 8g shows another type of twinning, **polysynthetic twinning**, composed of alternating domains. Such twins are common in plagioclase, calcite, and some other minerals but usually cannot be seen without a microscope. In Na-rich plagioclase they may result in fine lamellae on crystal faces that can be seen with the naked eye. The presence of twin lamellae is one way to tell plagioclase from K-feldspar in hand specimens. Figure 8h shows **cyclic twinning**, which is rare but sometimes spectacular. Some minerals twin to form domains with irregular shapes and boundaries. Quartz is a good example, but the twins in most quartz crystals are difficult to see.

Different types of twins in different minerals are given names, referred to as **twin laws**. The laws refer to the way **twin domains** are related. Feldspars exhibit many twin laws. K-feldspars often contain simple twins related by the **Carlsbad**, **Baveno**, **albite**, or **pericline** laws. Plate 1.5 shows orthoclase twinned according to the Carlsbad Law. Albite and pericline twinning combine to give the characteristic Scotch-plaid pattern that can be seen when microcline is viewed under crossed polars with a petrographic microscope. Plagioclase may twin according to the same laws as orthoclase, and according to the albite law. Albite and pericline twins are often polysynthetic and give plagioclase a characteristic zebra stripe appearance when viewed under crossed polars with a petrographic microscope.

Twinning comes at all scales and may be difficult to detect. Sometimes we can see it with the naked eye, sometimes we can only see it with a microscope, and sometimes we can't detect it without more sophisticated devices. Identifying twins in hand specimens



**FIGURE 8** Examples of different types of twinning (and a mineral in which it occurs): (a) penetration twin (fluorite); (b) contact twin (spinel); (c) contact twin (cassiterite); (d) penetration twin (staurolite); (e) penetration twin (orthoclase); (f) contact swallowtail twin (gypsum); (g) polysynthetic twin (plagioclase); and (h) cyclic twin (spinel).

can be difficult, especially in poorly formed crystals. One diagnostic feature is the presence of **reentrant angles**, visible in Figure 8a–h. Two crystal faces intersect to form a reentrant angle when they produce an angular concavity that points toward the interior of a crystal instead of the (normal) exterior.

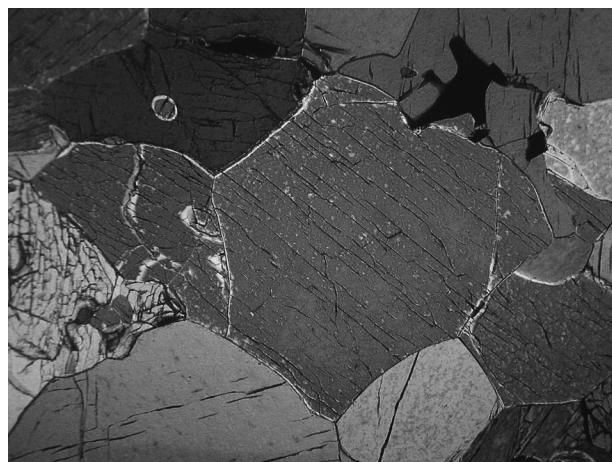
## IGNEOUS MINERALS

Several different processes lead to crystal growth. **Igneous minerals** form from molten rock (**magma**). When magma is at high temperature, it is completely liquid because high kinetic energy ensures that no solid is stable. As magma cools, atoms slow down and bond together, resulting in the formation of crystals. Because of high temperatures and the molten state of magma, atoms are quite mobile and easily move to surfaces of growing crystals. The result may be a rock with crystals forming a mosaic pattern if crystal growth is uniform (Figure 9). The crystals are often large, euhedral, and homogeneous. Olivine, pyroxenes, feldspars, and many other minerals form in this way. Table 1 lists some common minerals in igneous rocks.

Igneous processes are quite variable. Some magmas cool slowly underground, so mineral crystals grow to be large. Other magmas are extruded as lavas and cool quickly to form an extrusive rock. Mineral crystals in extrusive rocks may be so small that they cannot be seen with the naked eye or even with a microscope. Igneous rocks are generally dominated by silicate minerals because most magmas are rich in silicon and oxygen. However, magma compositions vary, so igneous rocks have variable composition and consequently the minerals are not the same in all igneous rocks.

## MINERALS THAT PRECIPITATE FROM AQUEOUS SOLUTIONS

Many minerals grow from **aqueous solutions** (water containing dissolved elements). If the solutions are not saturated, kinetic energy ensures that dissolved atoms do not bond together. If temperature decreases, or if water evaporates to increase the concentration of dissolved material, the solution may become saturated. Atoms will bond together and solid **chemical precipitates**, usually crystalline, will form. Calcium carbonate precipitates to form calcite ( $\text{CaCO}_3$ ) if concentrations of  $\text{Ca}^{2+}$  and  $\text{CO}_3^{2-}$  in water are high enough. Inland lakes or



**FIGURE 9** This is a microscope view of an igneous rock. Note that in many places, three minerals intersect at about  $120^\circ$  angles. This is typical of many plutonic igneous rocks that cooled slowly, indicating that atoms had lots of time to migrate and form large crystals.

**TABLE 1** Common Minerals in Igneous Rocks

Mineral Class or Group	Examples of Important Minerals or Mineral Series	Chemical Formula
olivine	olivine	$(Mg,Fe)_2SiO_4$
pyroxene	diopside augite orthopyroxene	$CaMgSi_2O_6$ $(Ca,Mg,Fe,Na)(Mg,Fe,Al)(Si,Al)_2O_6$ $(Mg,Fe)_2SiO_6$
amphibole	hornblende	$(K,Na)_{0-1}(Ca,Na,Fe,Mg)_2(Mg,Fe,Al)_5(Si,Al)_8O_{22}(OH)_2$
mica	biotite muscovite	$K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$ $KAl_2(AlSi_3O_{10})(OH)_2$
feldspar	orthoclase microcline sanidine plagioclase	$KAlSi_3O_8$ $KAlSi_3O_8$ $(K, Na)AlSi_3O_8$ $(Ca,Na)(Al, Si)_4O_8$
feldspathoid	leucite nepheline sodalite	$KAlSi_2O_6$ $(Na, K)AlSiO_4$ $Na_3Al_3Si_3O_{12} \cdot NaCl$
silica	quartz	$SiO_2$
oxide	magnetite ilmenite rutile	$Fe_3O_4$ $FeTiO_3$ $TiO_2$
sulfide	pyrite pyrrhotite	$FeS_2$ $Fe_{1-x}S$
other	titanite zircon apatite	$CaTiSiO_5$ $ZrSiO_4$ $Ca_5(PO_4)_3(OH,F,Cl)$

seas commonly precipitate calcite, halite, gypsum, and other minerals. In some places evaporating waters have deposited salt beds thicker than 300 m (984 ft.). On a much smaller scale, minerals precipitating from slowly moving groundwater can fill

holes, fractures, and cracks in rocks (Figure 10). If water composition changes during precipitation, different mineral layers may have different compositions. For example, see the smithsonite shown in Plate 1.2.

## BOX 2

### Making Glass from Minerals

Glass manufacturers make glasses by melting ingredients and cooling the melt so quickly that crystals cannot form. We call the most common kind of glass, which is used to make bottles or window panes, *soda-lime-silica* glass. People have manufactured similar glasses since Roman times. Soda-lime-silica glasses typically contain about 75 wt%  $SiO_2$ , 15 wt%  $Na_2O$  and 10 wt%  $CaO$ . Raw ingredients are usually the minerals quartz ( $SiO_2$ ), trona [ $Na_3H(CO_3)_2 \cdot 2H_2O$ ], and calcite ( $CaCO_3$ ). In the United States, we obtain high-quality quartz and calcite from many places. Most of the trona comes from the Green River Formation in Wyoming, where trona beds are up to 9 m (30 ft.) thick. Manufacturers heat the mineral ingredients to between 1,550 and 1,600 °C (2,820 and 2,910 °F), producing a homogeneous melt;  $CO_2$  and  $H_2O$  escape into the atmosphere. Quenching, to produce a final glass, is done in various ways depending on the product wanted.

Manufacturers change glass properties by adding small amounts of other ingredients. The addition of boron produces heat-resistant glass such as Pyrex® or Vycor®. Lead gives glass the optical properties needed for making imitation crystals. Aluminum can make glass resistant to weathering. Fluorine makes glass opaque. Lithium reduces the melting point of glass. Trace amounts of metals change glass color: Iron makes glass green, nickel makes it brown or orange, and cobalt makes it blue.



**FIGURE 10** Celestite (darker crystals in center) and calcite (white material around the celestite) that grew in a vug (hole) in fine-grained limestone. The calcite precipitated on the walls of the vug, and subsequently the celestite precipitated on the calcite. The quartz shown in Figure 11a and 2.11b also grew by precipitation from water.

Table 2 gives examples of minerals that precipitate from water. The most common ones are minerals with high solubilities in water, such as calcite, halite, and other salts. Other minerals, having lower solubility but composed of elements in great abundance, also form from aqueous solutions. Quartz is an example. At low temperature it may precipitate as Herkimer diamonds (Figure 11a) or as quartz crystals in **geodes** (Figure 11b). Low-temperature precipitation typically results in very fine-grained or massive minerals with few well-developed crystal faces. Fine-grained limestones (made of calcite) form at low temperatures. Occasionally, however, coarsely crystallized minerals form at low temperatures. Some spectacular calcite and quartz crystals are examples.

**TABLE 2 Examples of Minerals Formed by Low-Temperature Precipitation from Surface Water or from Groundwater in Sediments and Rocks**

Mineral Class or Group	Examples of Important Minerals or Mineral Series	Chemical Formula
silica	quartz	$\text{SiO}_2$
carbonate	calcite	$\text{CaCO}_3$
	magnesite	$\text{MgCO}_3$
halide	halite sylvite	$\text{NaCl}$ $\text{KCl}$
sulfate	gypsum anhydrite	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ $\text{CaSO}_4$
native element	sulfur	S



**FIGURE 11A** Herkimer diamonds from New York. These crystals, about 1 cm (0.6 in.) in longest dimension, are actually made of quartz, not diamond.



**FIGURE 11B** Quartz crystals in a geode about 15 cm (6 in.) across.

If chemical precipitation occurs at elevated temperatures, we call the process **hydrothermal**. Hydrothermal waters may be of meteoric, magmatic, metamorphic, or oceanic origin. Circulation is driven by high heat flow, as hot water flows toward regions of lower temperature. In some instances, waters flow long distances before precipitating minerals.

Travertine and tufa deposited by hot springs are examples of hydrothermal deposits. Both are primarily composed of calcite. Hydrothermal minerals are also deposited underground and make up many **ore deposits** (Figure 12). Ore deposits include oxides, sulfides, and other ore minerals in



**FIGURE 12** Examples of hydrothermal ore minerals. The dark mineral (top center) is sphalerite ( $\text{ZnS}$ ), the shiny mineral with high reflectivity (bottom) is pyrite ( $\text{FeS}_2$ ). Also present are prismatic quartz crystals ( $\text{SiO}_2$ ).

sufficient concentration to make mining profitable. Table 3 gives examples of some common hydrothermal ore minerals.

### METAMORPHIC AND DIAGENETIC MINERALS

A third way minerals may crystallize is through **metamorphism**. Metamorphism sometimes involves recrystallization and coarsening of a rock with no change in mineralogy. Often, however, it involves replacement of preexisting minerals by new ones (Figure 13). Bonds are broken and atoms migrate by **solid state diffusion** or are transported short distances by **intergranular fluids** to sites

where new minerals crystallize and grow. In sedimentary rocks, a low-temperature form of metamorphism called **diagenesis** takes place.

Metamorphism may involve replacement of one mineral by another. For example, calcite may become aragonite or vice versa. Both minerals are  $\text{CaCO}_3$ , but their atomic structures differ. Mineralogical changes due to metamorphism, however, usually involve several different minerals *reacting* together. Calcite ( $\text{CaCO}_3$ ) and quartz ( $\text{SiO}_2$ ) may react to form wollastonite ( $\text{CaSiO}_3$ ) if a limestone containing quartz is metamorphosed at high temperature. Adding further complications, during metamorphism, a rock's composition may change as fluids carry in or remove soluble materials. Such a process, called **metasomatism**, often leads to large, well-developed metamorphic minerals.

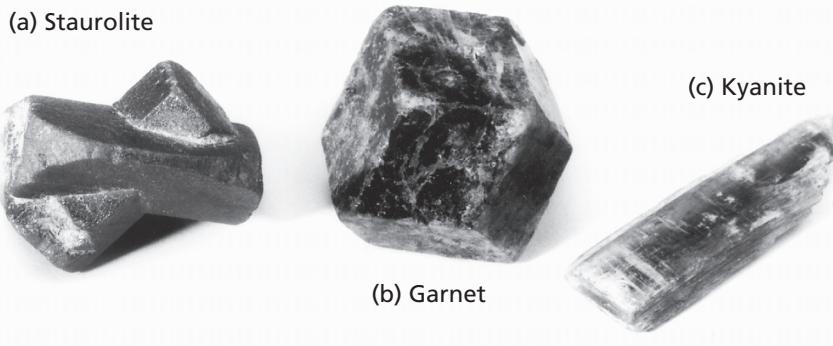
The mineralogy of metamorphic rocks is much more diverse than sedimentary or igneous rocks. Nearly all the minerals found in igneous rocks can be present in metamorphic rocks. Many found in sedimentary rocks may be present as well. In addition, other minerals, uncommon or nonexistent in igneous and sedimentary rocks, form through metamorphism. Table 4 lists only a few of the more common metamorphic minerals.

**TABLE 3 Examples of Minerals Common in Hydrothermal Ore Deposits**

Mineral Class	Examples of Important Minerals or Mineral Series	Chemical Formula
sulfide	pyrite pyrrhotite chalcopyrite galena sphalerite molybdenite	$\text{FeS}_2$ $\text{Fe}_{1-x}\text{S}$ $\text{CuFeS}_2$ $\text{PbS}$ $\text{ZnS}$ $\text{MoS}_2$
tungstate	wolframite	$(\text{Fe}, \text{Mn})\text{WO}_4$
oxide	cassiterite pyrolusite	$\text{SnO}_2$ $\text{MnO}_2$

### COMMON ROCKS AND MINERALS

We classify rock-forming minerals in many ways. Often, petrographers contrast **primary minerals** and **secondary minerals**. Primary minerals are those that are present from the time a rock first forms. Secondary minerals form later by chemical or physical reaction within the rock. Often, such secondary



**FIGURE 13** Some common metamorphic minerals:  
(a) twinned staurolite;  
(b) garnet; and (c) kyanite.

reactions involve  $H_2O$  or  $CO_2$  and occur during low-temperature alteration of a preexisting rock.

We further divide primary minerals into **essential minerals** and **accessory minerals**. Essential minerals are those whose presence is implied by the name of the rock. All limestones, for example, contain calcite or dolomite, and all granites contain quartz and K-feldspar. Accessory minerals are present in minor amounts and do not affect most rock properties. They often involve **incompatible elements**, elements that are not easily incorporated into essential minerals. Zirconium (Zr), for example, often concentrates in zircon,  $ZrSiO_4$ , a common accessory mineral in many rocks. Phosphorus (P) may lead to formation of phosphate minerals such as apatite,  $Ca_5(PO_4)_3(OH,F,Cl)$ , equally common. The distinction between primary and secondary minerals is not exact. A primary mineral in one rock may be an alteration product in another, or

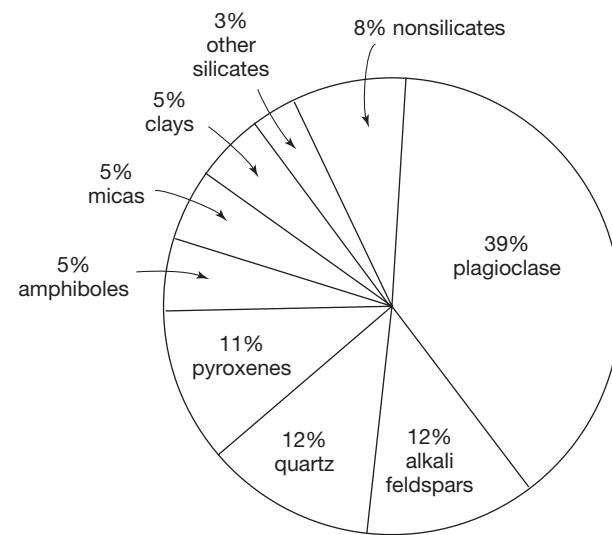
vice versa. In Table 1, the minerals at the top of the chart are often essential minerals in igneous rocks, while the oxides, sulfides, and others at the bottom are rarely essential in igneous rocks.

More than 90 elements are found in nature, and they could combine to form minerals in many ways. Nevertheless, they don't. Mineralogists have identified only 3,000 to 4,000. Of these, less than 200 are common, and less than 50 are common enough to be considered essential minerals. Plagioclase is the most abundant mineral in the Earth's crust; other silicates are abundant, too (Figure 14). In contrast, nonsilicates make up less than 10% of the crust. Why is this?

First, although more than 90 elements exist, many are present in such small amounts that they only exist as minor diluents for major elements. Occasionally they may be concentrated in accessory minerals. Thirteen elements (O, Si, Al, Fe, Ca, Na, K, Mg, Ti, H, P, Mn, Ba) make up nearly 99.5 wt %. We can expect the common

**TABLE 4 Examples of Metamorphic Minerals**

Silicate Mineral Subclass	Examples of Important Minerals or Mineral Series	Chemical Formula
framework silicate	cordierite	$(Mg,Fe)_2Al_4Si_5O_{18}$
chain silicate	tremolite wollastonite	$Ca_2Mg_5Si_8O_{22}(OH)_2$ $CaSiO_3$
isolated tetrahedral silicate	andalusite kyanite sillimanite staurolite chloritoid garnet	$Al_2SiO_5$ $Al_2SiO_5$ $Al_2SiO_5$ $Fe_2Al_9Si_4O_{23}(OH)$ $(Fe,Mg)Al_2Si_5O_5(OH)_2$ $(Ca,Fe,Mg)_3(Al,Fe)_2Si_3O_{12}$
paired tetrahedral silicate	zoisite	$Ca_2Al_3Si_3O_{12}(OH)$



**FIGURE 14** Estimated volume percentages for the common minerals in the Earth's crust.  
Modified from Ronov and Yaroshevsky, 1969.

minerals to be made from these elements. Oxygen and silicon, being the most abundant elements in the Earth's crust, naturally lead to an abundance of silicate minerals. It is no wonder that other types of minerals, or minerals that include rarer elements as key components, are less common.

Second, elements have specific properties that dictate the kinds of bonds they may form and the kinds of mineral structures they may enter. A third reason the number of common minerals is small is that there are only a few basic mineral-forming processes. Although all igneous events are not identical, they all involve the same processes: melting to form a magma that later crystallizes to form a rock. Exceptions exist, but most igneous events involve magmas of similar major-element composition. Most chemical precipitation involves water and elements with high solubilities, and there aren't many of them. Most metamorphism occurs over a relatively small range of pressure and temperature and affects rocks belonging to a small number of distinct chemical groups. It is not surprising then, that these processes yield a limited number of common minerals.

## LIFE SPANS OF MINERALS

Many minerals commonly occurring in modern sediments and rocks are too unstable to survive in great abundance in older terrestrial rocks. For example, olivine was once abundant in many terrestrial Precambrian mafic rocks, but since the Precambrian era, most old olivine has been altered by oxygen, carbon dioxide, and water to make serpentine, iron oxides, and magnesite. Because olivine crystallizes in hot and dry magmas, it is thermodynamically unstable under much cooler and wetter surface and near-surface conditions. Because of olivine's and pyroxene's tendency to weather rapidly, detrital olivine and pyroxene are largely restricted to Cenozoic sediments and sedimentary rocks. However, Precambrian olivine and pyroxene occur in Moon rocks and meteorites that have been isolated from oxygen and water.

Other examples of minerals generally absent from older terrestrial rocks include tridymite, a high-temperature polymorph of quartz, and aragonite, a high-pressure polymorph of calcite. Tridymite is common in Cenozoic siliceous volcanics, including rhyolites, obsidian, and andesites. However, except in stony meteorites and lunar basalts, the mineral changes to quartz over time and is rarely found in rocks that are older than Tertiary age.

Many marine organisms excrete shells that consist of aragonite rather than calcite. Unless aragonite fossils are deeply buried, they will alter to calcite over time. The oldest known aragonite

fossil is from an organic-rich shale of Mississippian age. Geologists have only found Paleozoic aragonite fossils in three localities. One of the rocks is tuffaceous, while the others are black shale and asphaltic limestone. The presence of abundant organic matter in three of the four known rocks with Paleozoic aragonite is probably responsible for the preservation of the aragonite. The organic matter coated the fossils and probably prevented water from reaching them and promoting their conversion to calcite.

Some nonmineral materials are unstable and invert to minerals over time. Opal and volcanic glass are amorphous materials and not minerals. Over time, both weather or alter into more stable crystalline compounds, such as quartz. Obsidian is rarely found in rocks older than the Miocene. The oldest known volcanic glass is in a 70-million-year-old welded tuff. Opal is slightly more stable than obsidian. Reaction rate calculations indicate that opal will entirely convert to quartz in about 180 million years at 20°C (70°F), approximately 4.3 million years at 50°C (120°F), and in only about 47 years at diagenetic temperatures of 200°C (390°F). Not surprisingly, the oldest known opal is of Lower Cretaceous age, about 125 million years old.

## THE LAWS OF THERMODYNAMICS

A fourth and perhaps the most important reason the number of common minerals is limited relates to the **laws of thermodynamics**. There are several different laws of thermodynamics. J. Willard Gibbs pointed out their most important consequences in 1878. Gibbs defined a form of energy that defines compound stability. We now call it the **Gibbs free energy** and indicate it by the variable *G*. Natural chemical systems are most *stable* when energy is minimized, so minerals and mineral assemblages with low Gibbs energy are more stable than those with high energy. Unstable minerals break down to form different minerals, with lower Gibbs free energy, over time. Minerals with relatively low Gibbs energies are more common than others.

An important corollary to the laws of thermodynamics, the **phase rule**, says that the number of stable phases that can coexist in any chemical system must be small. Thus, not only are stable minerals predictable, they are limited to a small number in any given rock. For a given rock, the stable minerals may not be the same under all conditions. If a rock is metamorphosed due to pressure or temperature changes, minerals may react to produce new minerals with lower Gibbs free energy. When they stop reacting, they have reached **equilibrium**. If

**BOX 3****Scientific Laws, Theories, and Hypotheses**

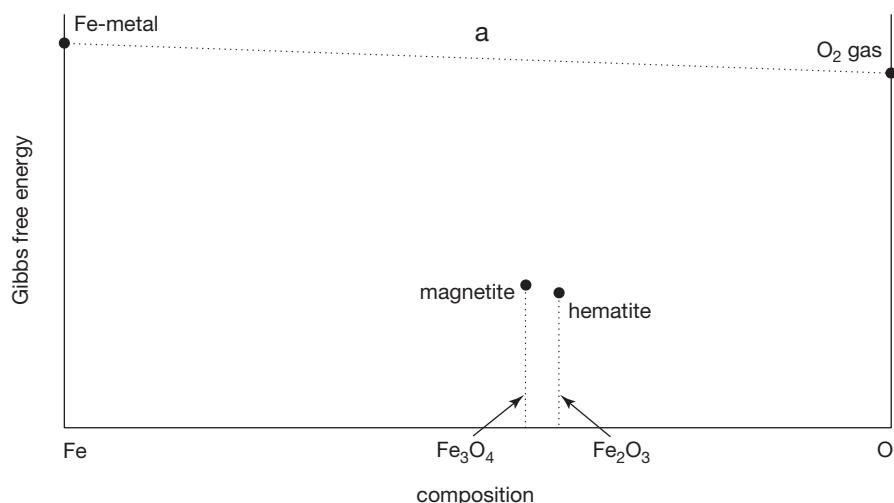
Scientific **laws** are general observations that have never been found to be violated. Examples are Snell's Law (dealing with the refraction of light) and Fick's Law (dealing with diffusion). Laws are empirical, dealing only with observations and not explanations. In contrast, scientific **theories** are explanations for observed events. Theories are often quite general, explaining a large number of related phenomena. They are developed from **hypotheses** through the scientific method. Hypotheses are tentative explanations based on evidence and they must be testable. They only become accepted theories after exhaustive scientific tests support their validity.

the Gibbs free energy is minimized, the system is at **stable equilibrium**.

Consider a chemical system containing Fe-metal and O (Figure 15). These two elements can exist in their pure forms, but when mixed together, they tend to react to produce magnetite ( $\text{Fe}_3\text{O}_4$ ), or hematite ( $\text{Fe}_2\text{O}_3$ ) because both minerals have lower energies than mixtures of Fe-metal and oxygen. This same principle applies to more complicated systems involving many elements, for example a rock. For any given composition rock, there is always one (stable) mineral assemblage with the lowest energy. If the rock reaches stable equilibrium, the stable assemblage will prevail.

Although the laws of thermodynamics tell us what the most stable mineral(s) will be, they do not

tell us how long it will take to reach stable equilibrium. We all know from experience with cars, for example, that it may take a while for the iron in steel to rust. The same is true for reactions involving minerals. Some low-temperature systems never reach stable equilibrium, and obtain an intermediate stage called **metastable equilibrium** when reactions cease. For example, countless numbers of diamonds exist at Earth's surface, even though graphite is a more stable form of carbon. Unless diamonds are heated, they remain metastable and do not change into graphite, no matter how long we wait. In contrast with low-temperature systems such as those at Earth's surface, most higher-temperature natural systems approach stable equilibrium given enough time.



**FIGURE 15** The dots show the relative Gibbs Free energies of iron metal, oxygen gas, magnetite ( $\text{Fe}_3\text{O}_4$ ), and hematite ( $\text{Fe}_2\text{O}_3$ ). Pure iron has the energy shown by the dot on the left vertical axis. Pure oxygen has the energy shown by the dot on the right vertical axis. Any mixture of iron and  $\text{O}_2$  gas must have a total energy that plots on dashed line a, depending on the composition of the mixture. Note that the energies of magnetite and hematite plot below line a. This means that magnetite and hematite have lower energies than a mix of iron and oxygen of the same composition. Consequently, oxygen and iron can react to produce magnetite or hematite, lowering the energy of the entire system. So, iron metal is not very stable when exposed to the atmosphere and tends to oxidize (rust). Additionally, the energy of hematite is slightly less than that of magnetite, and magnetite will react to form hematite if sufficient oxygen is present.

## CLASSIFICATION OF MINERALS

In order to talk about minerals in a convenient manner, it is useful to classify or group them in some way. In 1768 Carolus Linnaeus suggested that minerals may be classified in much the same way that biologists were classifying plants and animals. The external shape of mineral crystals was the basis for his classification scheme. Linnaeus made detailed measurements and drawings of many different minerals, and is often credited with being the founder of the science of crystallography.

Linnaeus's classification scheme and others based on crystal morphology are often ambiguous. Instead, some petrologists and other geologists find it convenient to group minerals according to the types of rocks that contain them. Igneous petrologists, for example, know that granite contains quartz and K-feldspar. To them, quartz and K-feldspar are granitic minerals. Unfortunately, ambiguity remains (Figure 16). A sedimentary petrologist associates the same two minerals with arkosic sandstones, while a metamorphic petrologist knows they occur in a wide range of metamorphic rocks.

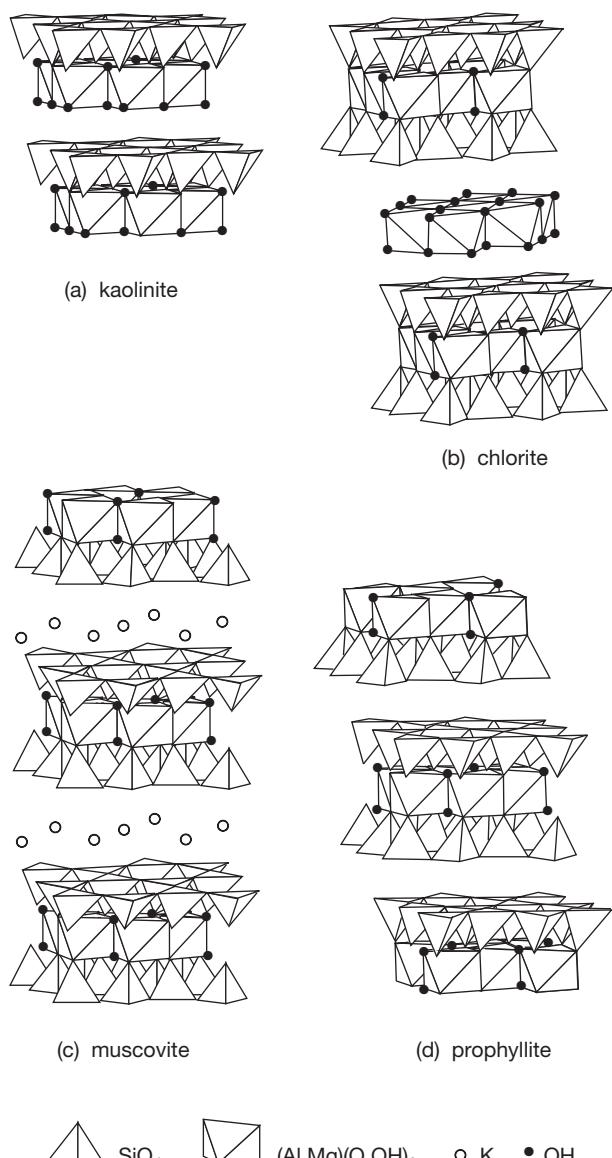
In contrast with petrologists, mineralogists are less concerned about the occurrences of minerals and more interested in understanding how and why certain elements bond together to form certain minerals. They look for patterns in mineral structures and chemistry that will help them understand why minerals form as they do. Rather than consider all minerals individually, they study them in groups. Mineralogists know, for example, that mica and other sheet silicates all have similar atomic structures (Figure 17).

Many mineral classification schemes could be used by mineralogists. The standard ones are based



**FIGURE 16** Feldspathic sandstone (left) and granite (right). Both samples contain predominantly quartz and K-feldspar. However, the sandstone is a sedimentary rock and the granite is an igneous rock. Both samples are about 8 cm (3 in.) wide.

on principles developed by Berzelius. The system used in this text is modified slightly from that presented by Zoltai and Stout (1984). It is similar to Dana's System of Mineralogy described by Palache et al. (1944) and to the classification of silicates presented by Strunz (1957). We assign minerals to **classes** based on their anions or anionic complexes;



**FIGURE 17** The structures of several micaceous minerals. In drawings of this sort, tetrahedra (four-sided pyramids) and octahedra (eight-sided polyhedra) are used to represent  $\text{SiO}_4$  and  $\text{Al}(\text{O},\text{OH})_6$  groups. The tetrahedral depict an Si atom surrounded by four oxygen. The octahedral show an aluminum or magnesium atom surrounded by six O or OH. Open circles indicate  $\text{K}^+$  and solid dots  $\text{OH}^-$ . (a) The two-layer structure of kaolinite; (b) the three-layer structure of chlorite; (c) the three-layer structure of muscovite with  $\text{K}^+$  between the layers; and (d) the three-layer structure of pyrophyllite. All of these structures are closely related and, consequently, the minerals share many properties.

**TABLE 5 Mineral Classes**

Class	Anion, Anionic Complex, or Key Elements	Example Mineral	Chemical Formula
silicates	$(\text{SiO}_n)^{4-2n}$	quartz	$\text{SiO}_2$
halides	$\text{Cl}^-$ , $\text{F}^-$ , $\text{Br}^-$ , $\text{I}^-$	halite	$\text{NaCl}$
oxides	$\text{O}^{2-}$	corundum	$\text{Al}_2\text{O}_3$
hydroxides	$(\text{OH})^-$	gibbsite	$\text{Al}(\text{OH})_3$
carbonates	$(\text{CO}_3)^{2-}$	calcite	$\text{CaCO}_3$
nitrates	$(\text{NO}_3)^{-}$	nitratite	$\text{NaNO}_3$
borates	$(\text{BO}_3)^{3-}$ or $(\text{BO}_4)^{5-}$	sinhalite	$\text{MgAlBO}_4$
sulfates	$(\text{SO}_4)^{2-}$	gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$
chromates	$(\text{CrO}_4)^{2-}$	crocoite	$\text{PbCrO}_4$
tungstates	$(\text{WO}_4)^{2-}$	scheelite	$\text{CaWO}_4$
molybdates	$(\text{MoO}_4)^{2-}$	wulfenite	$\text{PbMoO}_4$
phosphates	$(\text{PO}_4)^{3-}$	apatite	$\text{Ca}_5(\text{PO}_4)_3(\text{OH}, \text{F}, \text{Cl})$
arsenate	$(\text{AsO}_4)^{3-}$	scorodite	$\text{FeAsO}_4 \cdot 4\text{H}_2\text{O}$
vanadate	$(\text{VO}_4)^{3-}$	vanadinite	$\text{Pb}_5(\text{VO}_4)_3\text{Cl}$
native elements	single elements	copper	Cu
sulfides	S	pyrite	$\text{FeS}_2$
sulfosalts	S, As, Sb	niccolite	NiAs

Table 5 lists the most important classes. We group some classes together because minerals of those classes have similar properties. The native metal, sulfide, and sulfosalt classes include minerals in which the dominant type of bonding is not ionic. For that reason we give them their own classes, and no ionic charges are given for them in Table 5.

Dividing minerals into classes based on anion or anionic complex is convenient because we can determine class from chemical formula. Besides being convenient, however, this classification scheme makes sense in other ways. Within each class, the type of structure and bonding are similar. This means that minerals within a class often have similar physical properties, making the classes useful in mineral identification. Such would not be the case if we divided minerals into groups based on cations. For example pyrite,  $\text{FeS}_2$ , and fayalite,  $\text{Fe}_2\text{SiO}_4$ , both contain Fe, but have few properties in common. Minerals within a single class are often found together. Silicates make up more than 99% of the minerals found in igneous rocks and account for more than 90% of the Earth's crust and mantle. Carbonates are similarly dominant in limestones.

Most common minerals belong to the silicate, oxide, hydroxide, or sulfide and sulfosalt classes. Oxides and hydroxides together account for about 500 species. Sulfides and sulfosalts also account for about 500 species. The silicate class contains the largest number of minerals, with more than 800 known. In contrast, the native element class contains few members.

Because there are so many important minerals in the silicate class, we divide it into subclasses

(Table 6). In all silicates, except for some very rare high-pressure minerals, four  $\text{O}^{2-}$  anions surround every  $\text{Si}^{4+}$  cation (Figure 18), forming a **tetrahedron**, a pyramid shape with four identical faces. We name the subclasses according to how the tetrahedra are linked (polymerized) in the atomic structure (Table 6). In the **isolated tetrahedral silicates** (also called *island silicates*), the  $(\text{SiO}_4)^{4-}$  tetrahedra are not polymerized; they are all separated (like a bunch of islands) with cations between them. The Si:O ratio for the structure is 1:4. In contrast, in **framework silicates**, each oxygen is shared between two tetrahedra; the collection of tetrahedra make up a three-dimensional framework with an Si:O ratio of 1:2. Other subclasses have Si:O ratios between 1:4 and 1:2. In Table 6, we give the Greek names (in parentheses) of the subclasses because some mineralogists use them. Unless you know Greek, however, they are not particularly meaningful. Some silicate minerals with complex structures do not fit conveniently into one of the six first subclasses listed in Table 6, but most common silicates do.

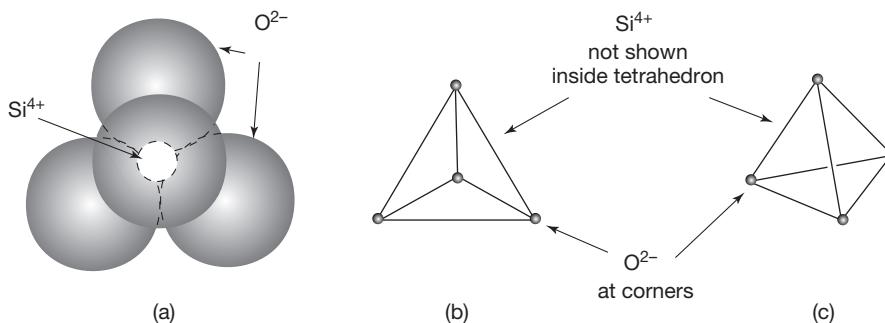
We further divide classes and subclasses of minerals into **groups** based on structural or chemical similarity. For example, we group the feldspar minerals together because, although their compositions vary, they all have similar atomic structures. We group the serpentine minerals (antigorite, chrysotile, lizardite) together because they all have the same composition. When two or more minerals have the same formula but different crystal structures, as in the case of serpentine, we call them **polymorphs**.

**TABLE 6 Silicate Mineral Subclasses**

Subclass	Si:O Ratio	Si Radical	Example	Mineral Formula	Arrangement of $\text{SiO}_4$ Tetrahedra
framework silicates (tectosilicates)	1:2	$\text{SiO}_2$ or $(\text{Al}_x\text{Si}_{1-x})\text{O}_2$	quartz albite	$\text{SiO}_2$ $\text{Na}(\text{AlSi}_3)\text{O}_8$	
sheet silicates (phyllosilicates)	2:5 = 4:10	$(\text{Si}_4\text{O}_{10})^{4-}$	pyrophyllite	$\text{Al}_2\text{Si}_4\text{O}_{10}(\text{OH})_2$	
single-chain silicates (inosilicates)	1:3 = 2:6	$(\text{SiO}_3)^{2-}$ or $(\text{Si}_2\text{O}_6)^{4-}$	enstatite	$\text{Mg}_2(\text{SiO}_3)_2$ or $\text{Mg}_2\text{Si}_2\text{O}_6$	
double-chain silicates (inosilicates)	4:11 = 8:22	$(\text{Si}_8\text{O}_{22})^{12-}$	tremolite	$\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	
ring silicates (cyclosilicates)	1:3 = 6:18	$(\text{Si}_6\text{O}_{18})^{12-}$	tourmaline	$(\text{Na,Ca})(\text{Fe,Mg,Al,Li})_3\text{Al}_6(\text{BO}_3)_3\text{Si}_6\text{O}_{18}(\text{OH})_4$	
isolated tetrahedral (island) silicates (nesosilicates or orthosilicates)	1:4	$(\text{SiO}_4)^{4-}$	forsterite	$\text{Mg}_2\text{SiO}_4$	
paired tetrahedral silicates (sorosilicates)	2:7	$(\text{Si}_2\text{O}_7)^{6-}$	akermanite	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	
more complex silicates	1:4 and 2:7	$(\text{SiO}_4)^{4-}$ and $(\text{Si}_2\text{O}_7)^{6-}$	vesuvianite	$\text{Ca}_{10}(\text{Mg,Fe})_2\text{Al}_4(\text{SiO}_4)_5(\text{Si}_2\text{O}_7)_2(\text{OH})_4$ $= \text{Ca}_{10}(\text{Mg,Fe})_2\text{Al}_4\text{Si}_9\text{O}_{34}(\text{OH})_4$	

Groups may also be further divided into **subgroups** or **series**. Subgroups are minerals that naturally group together for chemical or other reasons. The K-feldspars, for example, are a subgroup because they all have composition  $\text{KAlSi}_3\text{O}_8$ . Series involve minerals with compositions we can describe in terms of two end members. The plagioclase

feldspar series consists of feldspars that are solutions of the two end members albite ( $\text{NaAlSi}_3\text{O}_8$ ) and anorthite ( $\text{CaAl}_2\text{Si}_2\text{O}_8$ ). Albite and anorthite form a **solid solution series**, and plagioclase can have any composition between pure albite and pure anorthite. Usually, atomic structure or composition is identical for all minerals in



**FIGURE 18** Silicon and four oxygen atoms: (a) “marbles” forming a tetrahedron; (b) and (c) are ball-and-stick drawings showing a top view and a side view.

subgroups or series. They are always very similar. Individual mineral species, which make up series and subgroups, are occasionally further divided into **varieties** if the varieties have some special properties. For example, rose quartz, smoky quartz, amethyst, and citrine are all varieties of quartz.

## A CLASSIFIED LIST OF MINERALS

Table 7 shows a few of the most abundant framework silicates. The list includes quartz and the feldspars, the most common minerals in the Earth's crust. It shows most of

**TABLE 7** Framework Silicates

Class (Subclass)	Group	Series or Subgroup	Species	Chemical Formula
silicate (framework silicates)	silica group		quartz cristobalite tridymite coesite stishovite	$\text{SiO}_2$ $\text{SiO}_2$ $\text{SiO}_2$ $\text{SiO}_2$ $\text{SiO}_2$
	feldspar group	potassium feldspars	orthoclase sanidine microcline	$\text{KAlSi}_3\text{O}_8$ $(\text{K}, \text{Na})\text{AlSi}_3\text{O}_8$ $\text{KA}\text{Si}_3\text{O}_8$
		plagioclase feldspar series	albite anorthite	$\text{NaAlSi}_3\text{O}_8$ $\text{CaAl}_2\text{Si}_2\text{O}_8$
	feldspathoid group		analcime leucite nepheline	$\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$ $\text{KA}\text{Si}_2\text{O}_6$ $(\text{Na}, \text{K})\text{AlSiO}_4$
	scapolite group	scapolite series	marialite meionite	$\text{Na}_4(\text{AlSi}_3\text{O}_8)_3\text{Cl}$ $\text{Ca}_4(\text{Al}_2\text{Si}_2\text{O}_8)_3(\text{CO}_3, \text{SO}_4)$
	zeolite group		natrolite chabazite heulandite stilbite sodalite	$\text{Na}_2\text{Al}_2\text{Si}_3\text{O}_{10} \cdot 2\text{H}_2\text{O}$ $\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 6\text{H}_2\text{O}$ $\text{CaAl}_2\text{Si}_7\text{O}_{18} \cdot 6\text{H}_2\text{O}$ $\text{CaAl}_2\text{Si}_7\text{O}_{18} \cdot 7\text{H}_2\text{O}$ $\text{Na}_3\text{Al}_3\text{Si}_3\text{O}_{12} \cdot \text{NaCl}$
	other		beryl cordierite	$\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$ $(\text{Mg}, \text{Fe})_2\text{Al}_4\text{Si}_5\text{O}_{18}$

the features of the classification scheme. Twenty minerals belong to five main groups; two others are classified separately. Five  $\text{SiO}_2$  polymorphs are included in the silica group; three  $\text{KAlSi}_3\text{O}_8$  polymorphs are included in the potassium feldspar group. Solid solution series are represented by

plagioclase feldspar (albite-anorthite) and scapolite (marialite-meionite). Table 7 is not a complete list of framework silicates. We could, for example, list many other zeolite minerals. Some minerals in Table 7, such as the feldspars, are common. Others, such as the scapolite minerals, are rare.

## Questions for Thought

*Some of these questions have no specific correct answers; they are intended to promote thought and discussion.*

1. What is the definition of a mineral, and how do minerals differ from other solid substances? Why do mineralogists use such a restricted definition of a mineral?
2. Why do rocks only contain a few major elements?
3. All minerals have defects. What are the major kinds of defects? We can't normally see defects when we look at a mineral sample, so how do we know they are present?
4. Although there is a great deal of variation, why are sedimentary minerals generally fine-grained compared with igneous minerals?
5. What factors lead to the precipitation of minerals from aqueous solutions? Which minerals are the most common aqueous minerals? Why?
6. Why did we make the debatable assertion that metamorphic minerals are more diverse than igneous or sedimentary minerals?
7. What is the difference between primary and secondary minerals? How do primary minerals form in igneous, sedimentary, and metamorphic rocks? How do secondary minerals form in these same rock types?
8. Why are there so few common minerals?
9. What is the basis for the mineral classification scheme used by mineralogists? What are mineral classes, subclasses, groups, series, subgroups, and species?

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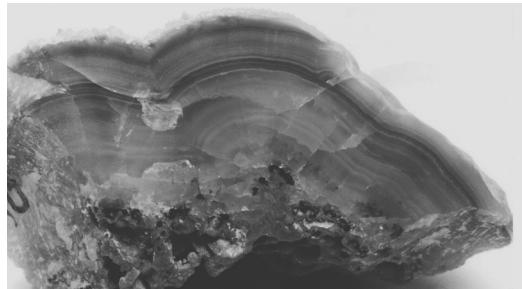
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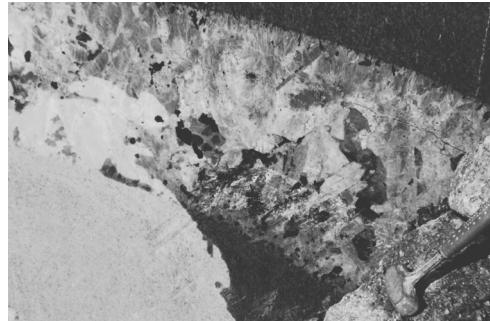
**PLATE 1.1** Tourmaline from Paraiba, Brazil, with colors showing compositional zonation.



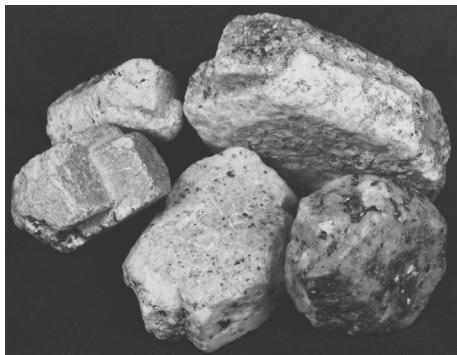
**PLATE 1.2** Smithsonite from Rush Creek, Arkansas, with colors showing compositional zonation.



**PLATE 1.3** Pyrite crystals with pyritohedron form showing growth striations on faces.



**PLATE 1.4** Small pegmatite exposed in Larvikite quarry near Larvik, Norway.

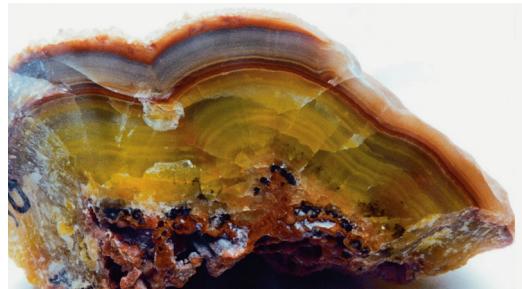


**PLATE 1.5** Orthoclase from Petschau, Bohemia, showing penetration twins.

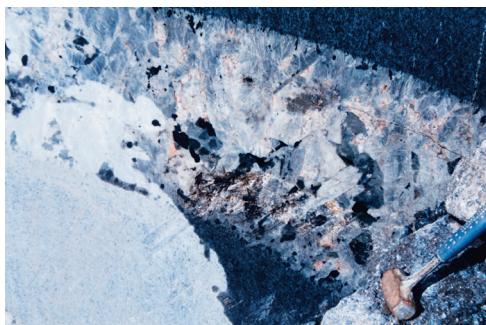
# Crystallization and Classification of Minerals Color Plates



**PLATE 1.1** Tourmaline from Paraiba, Brazil, with colors showing compositional zonation.



**PLATE 1.2** Smithsonite from Rush Creek, Arkansas, with colors showing compositional zonation.



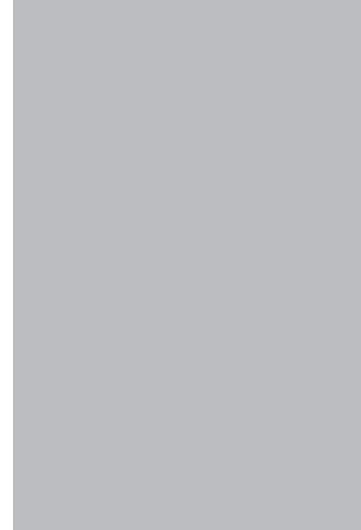
**PLATE 1.4** Small pegmatite exposed in Larvikite quarry near Larvik, Norway.



**PLATE 1.5** Orthoclase from Petschau, Bohemia, showing penetration twins.

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# Mineral Properties: Hand Specimen Mineralogy



# Mineral Properties: Hand Specimen Mineralogy

The properties of minerals derive from their composition and crystal structure, so we can identify minerals, both in the laboratory and in the field, on the basis of their physical properties. In this chapter we look at the most important physical properties, including appearance, crystal shape, hardness, the way in which a mineral breaks or cleaves, and density. We discuss some of the things that control the properties, and we discuss how the properties may be used for mineral identification. We also consider other properties that can be keys to mineral identification in some special cases.

Mineral names are based on mineral appearance, mineral chemistry, where the mineral is found, a famous scientist, or anything else deemed important by a mineral's discoverer. The Commission on New Minerals and New Mineral Names of the International Mineralogical Association reviews proposed new names and descriptions and judges their appropriateness. The Commission also occasionally discredits old names. Absolute identification and classification of minerals requires knowledge of their composition and atomic structure. Such information must be included when mineralogists submit names to the Commission for approval.

Determining mineral composition and structure may require time and equipment unavailable to most mineralogists or to mineralogy students, but fortunately we can use other methods to tell minerals apart. Differences in composition and structure lead to differences in appearance and in many other properties of minerals we use for identification. Most of the properties discussed in this text fall into two general groups: **hand specimen** properties, which are easily determined using large samples, and **optical properties**, which can only be seen with specially prepared slides

and a **polarizing light microscope**, also called a **petrographic microscope**. This chapter reviews hand specimen properties and discusses their use in identification.

## IDENTIFICATION OF MINERALS

Give a mineral specimen to a nongeologist and ask them to describe it. Generally, the appearance, especially color, is mentioned first. With a little prodding, they may go on to describe the shape and nature of visible crystals. For example, pyrite might be described as being metallic, being gold in color, and forming cubic crystals. A piece of rose quartz might be described as being pink, glassy, and transparent, and having a hexagonal shape. *Metallic* and *glassy* are terms describing **luster**. *Gold* and *pink* describe **color**. *Transparent* describes **diaphaneity**. *Cubic* and *hexagonal* describe **symmetry**, a property relating to **shape**. These four properties (luster, color, diaphaneity, and shape) are basic for mineral identification. Other properties including **streak** (the color of a mineral when powdered), the way a

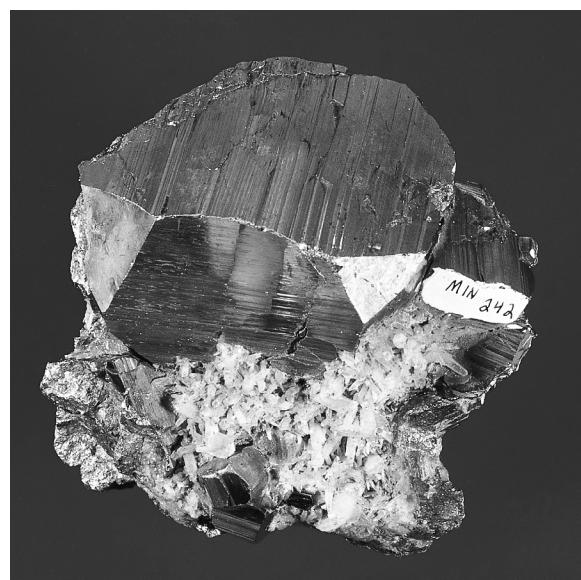
mineral breaks (**cleavage**, **parting**, **fracture**), and **hardness** can be even more important.

Given a single property, for example luster, it is possible to divide minerals into groups. In the case of luster, we usually divide minerals into those that are metallic and those that are nonmetallic. There are, however, many metallic and many nonmetallic minerals; other properties must be considered if minerals are to be identified. Nonmetallic minerals can, for instance, be divided further based on more subtle luster differences (Table 1). Other properties such as color, diaphaneity, crystal shape, cleavage, parting, fracture, and hardness are also diagnostic. Ultimately, minerals can be identified by name or at least placed in small groups. It is tempting, then, to come up with a standard list of properties that should be evaluated when identifying minerals. However, most mineralogists know that, depending on the sample and circumstances, some properties are more important than others. Rather than going through a long list or filling out a standard table, experienced mineralogists focus on the properties that are most diagnostic. In some cases, a single property, such as strong effervescence by hydrochloric acid (diagnostic of calcite), may serve for mineral identification. At first, mineral identification may seem tedious, but with a little experience, it is possible to find shortcuts to make the process more efficient.

## MINERAL APPEARANCE

### Luster

Luster refers to the general appearance or sheen of a mineral. It refers to the way in which a mineral reflects light. Minerals that have the shiny appearance



**FIGURE 1** Pyrite typically has a metallic luster and so reflects light well.

of polished metal are said to have a **metallic luster**. Some could be used as mirrors. Well-crystallized pyrite is a good example (Figure 1). Other examples of metallic minerals are shown in Plates 1.3, 2.7, 7.2, 7.3, and 7.5. Minerals that do not appear metallic are said to have a **nonmetallic luster**. Those that appear only partially metallic are called **submetallic**.

Mineralogists use many terms to describe nonmetallic minerals. **Vitreous** minerals are those with a glassy appearance. Quartz is an excellent example (see Plates 2.1 through 2.8). The term **adamantine** is used to describe crystals that sparkle or appear brilliant; the Herkimer diamonds

**TABLE 1** Terms Used To Describe Luster of Nonmetallic Minerals

Luster	Meaning	Example Minerals That May Exhibit the Luster
vitreous	Having a glassy appearance	quartz, tourmaline
resinous	Having the appearance of resin	sphalerite, sulfur
greasy	Reflecting light to give a play of colors; similar to oil on water	chlorite, nepheline
silky	Having surfaces appearing to be composed of fine fibers	chrysotile (asbestos), gypsum
adamantine	A bright, shiny, brilliant appearance similar to that of diamonds	diamond, cerussite
pearly	Appearing iridescent, similar to pearls or some seashells	muscovite, talc
dull	Not reflecting significant amounts of light or showing any play of colors	kaolinite (clay), niter

in Plate 2.8 are adamantine. In contrast, the pectolite in Plate 3.1 is **dull** and the sphalerite in Plate 7.4 is **resinous**. Some of the more common terms describing luster of nonmetallic minerals are given in Table 1.

## Diaphaneity

Diaphaneity refers to a mineral's ability to transmit light. Some minerals are **transparent**. When they are thick, some distortion may occur, but light passes relatively freely through them. Uncolored quartz is often transparent (Plates 2.1, 2.4, 2.6, 2.7, and 2.8). Minerals that do not transmit light as well as clear quartz may be **translucent**. Although it is not possible to see through them as with transparent minerals, translucent minerals, if thin enough, transmit light. Still a third type of mineral, called an **opaque mineral**, does not transmit light unless the mineral is exceptionally thin. Most opaque minerals have metallic lusters. Pyrite and many other sulfide and oxide minerals are good examples. Their opacity sets them apart from most other minerals.

## Color

Color is often used for quick identification of minerals. In some cases, it can be diagnostic, but in many it is ambiguous or even misleading. The deep red color of rubies may seem distinctive. Ruby is, however, just one variety of the mineral corundum. Sapphires are different colored varieties of the same mineral. To add to the confusion, other minerals, such as spinel or garnet, may have the same deep red color, as does ruby. Color is ambiguous because many things can give a mineral its color.

Color is one of the most misunderstood mineral properties. It's easy to look at a ruby illuminated by white light and say it has a red color. If the ruby is illuminated by light of a different color, it may not appear red. Color, then, is not a property of a mineral. It is instead the result we observe when light and a mineral interact. When we see that something has color, what we are really observing is the color of the light that is being reflected or transmitted to our eye. Normal light, called **white light**, includes many different colors. When white light strikes a mineral surface, if all of the colors are reflected back to our eyes, the mineral will appear white. If none of the colors are reflected back to our eye, the mineral will appear black. Most minerals, like ruby, appear to have color because only one or a few wavelengths make it back to our eye. The other wavelengths of light

are scattered in other directions or are absorbed or transmitted by the mineral in some way.

Metallic minerals, especially sulfides, tend to be constant in their coloration (Plates 7.1 through 8.2), so mineralogists use color as a key tool for sulfide identification. However, metallic minerals easily tarnish, so a fresh surface is needed to see the true color. Plate 7.3 shows pyrite altering and tarnishing to produce purple colors characteristic of covellite. Color is a poor property to use for identifying many nonmetallic minerals because there are so many factors that affect coloration. Quartz may be colorless, rosy (rose quartz), yellow (citrine), purple (amethyst), milky, smoky, or black. Some examples are shown in Plates 2.1 through 2.8. Corundum may be just about any color, including colorless, black, brown, pink, yellow, blue, purple, or red. Gem varieties of corundum are ruby (red), oriental topaz (straw yellow), and sapphire (other colors); Plate 8.5 shows several corundum varieties.

The most significant control on color is a mineral's chemical composition. Elements that give a mineral its color are called **chromophores**. It does not take large amounts of chromophores to color a mineral. Minor amounts, less than 0.1 wt% of transition metals such as iron (Fe) and copper (Cu), may control a mineral's color because electrons in the *d*-orbitals of transition metals are extremely efficient at absorbing certain visible wavelengths of light. The remaining wavelengths are reflected and give minerals their color.

If the elements controlling the selective reflection of certain wavelengths are major components in a mineral, the mineral is called **idiochromatic**, or "self-coloring." Sphalerite (ZnS), for example, is an idiochromatic mineral. It changes from white to yellow to brown to black as its composition changes from pure ZnS to a mixture of ZnS and FeS. Many copper minerals are green or blue, while many manganese minerals are pinkish. These colors derive from selective absorption of certain colors by copper and manganese. Idiochromatic elements may have different effects in different minerals. Malachite is green and azurite is blue, but in both minerals the color is due to copper.

Ruby and sapphire are examples of **allochromatic** varieties of corundum. In allochromatic minerals, minor or trace elements determine the color. Very small amounts of iron (Fe) and titanium (Ti) give sapphire a deep blue color. Small amounts of chromium (Cr) give ruby and some other gemstones deep red colors. The effects of allochromatic elements may be different in different minerals. Allochromatic Cr is also responsible for

the striking green color of emerald (a variety of the mineral beryl), chrome diopside, and some tourmalines.

Structural defects in minerals may also give them color. Radiation damage gives quartz, for example, a purple (Plate 2.3), smoky, or black color. The purple color of many fluorites is caused by Frenkel defects. Other causes of coloration include the oxidation or reduction of certain elements (especially Fe), and the presence of minute inclusions of other minerals.

### Streak

Although it would never occur to many people to check a mineral's streak, streak is in some cases a key diagnostic property. It is not a useful property for identifying most silicates but is especially useful for distinguishing oxide and sulfide minerals. The streak of a mineral is the color it has when finely powdered. For mineral identification, it is much more reliable than mineral color, and it is easy to determine. The usual method of determining streak is to rub the mineral against a ceramic streak plate (Figure 2). Because the mineral is finely powdered, structural and other nonchemical effects are minimized. Calcite, for example, comes in many different colors, but calcite's streak is always white. Pyrite (fool's gold) is yellow but has a dark colored streak, as does chalcopyrite. Gold, which has a color similar to pyrite's (in hand specimen), has a yellow-gold streak.

Streak is routinely used by mineralogists both in the laboratory and in the field, but it cannot be determined for minerals harder than about 6 or 7 (the hardness of a streak plate). It can be extremely useful for telling dark-colored minerals apart, especially



**FIGURE 2** Graphite and a streak plate. Graphite is a very soft mineral that has a black-gray streak.

metallic ones. For example, hematite may be red, gray, or black in hand specimen and may or may not have a metallic luster. It always, however, has a diagnostic red streak that helps distinguish specular hematite from galena, or other kinds of hematite from similarly colored minerals. White and colorless streak are considered to be the same because the distinction cannot be made using a standard streak plate, and most minerals have a white or colorless streak. See Table 2 for examples of minerals that do not have a white streak.

### Luminescence

Some minerals will emit light when they are activated by an energy form other than visible light. Such an effect is called **luminescence**. Examples of luminescence include **fluorescence**, **phosphorescence**, and **thermoluminescence**. Fluorescent minerals give off visible light when they are struck by energy of a shorter wavelength. The invisible radiation from ultraviolet lamps, for example, may cause scheelite, willemite, or fluorite to appear to glow in the dark. If the visible emission continues after the energy source is turned off, the mineral is phosphorescent. Pectolite is an example of a phosphorescent mineral. Thermoluminescent minerals such as some tourmalines give off visible light in response to heating. Some varieties of fluorite, calcite, and apatite also have this property.

**TABLE 2 Examples of Minerals That Do Not Have a White Streak**

Minerals	Streak Color
pyrite, chalcopyrite	black to green-gray
magnetite, ilmenite	black
galena	lead gray
wolframite	brown to black
cassiterite	light gray to brown or white
rutile	pale or light brown
goethite	yellow brown to ochre yellow
sphalerite	white to light brown or yellow
sodalite	very pale blue to white
lazurite	bright to pale blue
azurite	light blue
chrysocolla	very pale blue to gray or tan
malachite	pale green
orpiment	pale yellow to yellow
sulfur	light yellow to white
gold	gold-yellow
zincite	orange yellow
realgar	orange or reddish yellow
cinnabar, cuprite	dark red to scarlet
hematite	rust red to blood red

## Play of Colors

The quartz in Plate 2.4 shows **play of colors**. **Opalescence** (exhibited by opals and a variety of K-feldspar called *moonstone*), **labradorescence** (exhibited by the feldspar variety labradorite), and **pearly luster** (exhibited by some micas and talc) are other examples of play of colors. White light is separated into individual wavelengths of varying intensities emitted in different directions. The play of colors is a form of light scattering due to very fine particles in the minerals or to textures of mineral surfaces. **Chatoyancy** and **asterism** are two other scattering effects; they are most easily seen in gemmy minerals. Chatoyant minerals show a bright band of scattered light, usually perpendicular to the long direction of a crystal. Such minerals are sometimes said to have a cat's-eye (chrysoberyl) or tiger's-eye (crocidolite) appearance. The satin spar variety of gypsum is chatoyant. Chatoyancy is caused by closely packed parallel fibers or inclusions of other minerals within a mineral. Asterism, a property sometimes visible in rubies, sapphires, garnets, and some other gems, refers to scattered light appearing as a "star." As in chatoyancy, asterism results from the scattering of light by small inclusions of a different mineral.

Some minerals exhibit **iridescence** similar to the play of colors that is sometimes seen on an oily surface. Metallic minerals such as bornite may acquire iridescence as they tarnish. Labradorite and some other feldspars exhibit an internal iridescence (also called **labradorescence** or **schiller**) due to fine compositional layering.

## CRYSTAL SHAPE

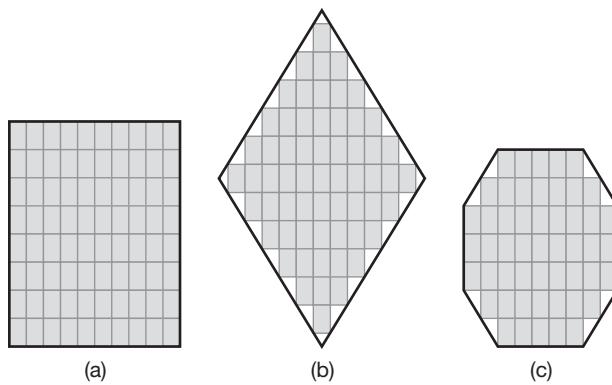
For well-developed crystals, crystal **form** and **habit** are excellent diagnostic properties. Habit refers to the overall shape of a crystal or aggregate of crystals. To mineralogists, the term *form* refers specifically to a group of crystal faces, related by the crystal's symmetry, that have identical chemical and physical properties. Although museum specimens and pictures of minerals in textbooks often show distinctive habits and forms, most mineral samples do not. Small irregular crystals without flat faces, or massive aggregates, are typical, often rendering habit and form of little use for hand specimen identification. Because form and habit reflect the internal arrangement of atoms in a crystal, when visible they are important diagnostic properties (Box 1).

Some crystals have more than one form, that is, more than one kind (shape) of crystal face.

At an atomic level, crystals are made of collections of identical unit cells. The shape of a crystal and the nature of its crystal faces depend on how the unit cells stack together. Figure 3 provides a two-dimensional explanation. Rectangular unit cells may produce rectangular crystals having two forms, diamond-shaped crystals having only one form, or more complicated crystals displaying three or more forms. Faces of a single crystal form have identical properties because they contain identical atoms in identical arrangements.

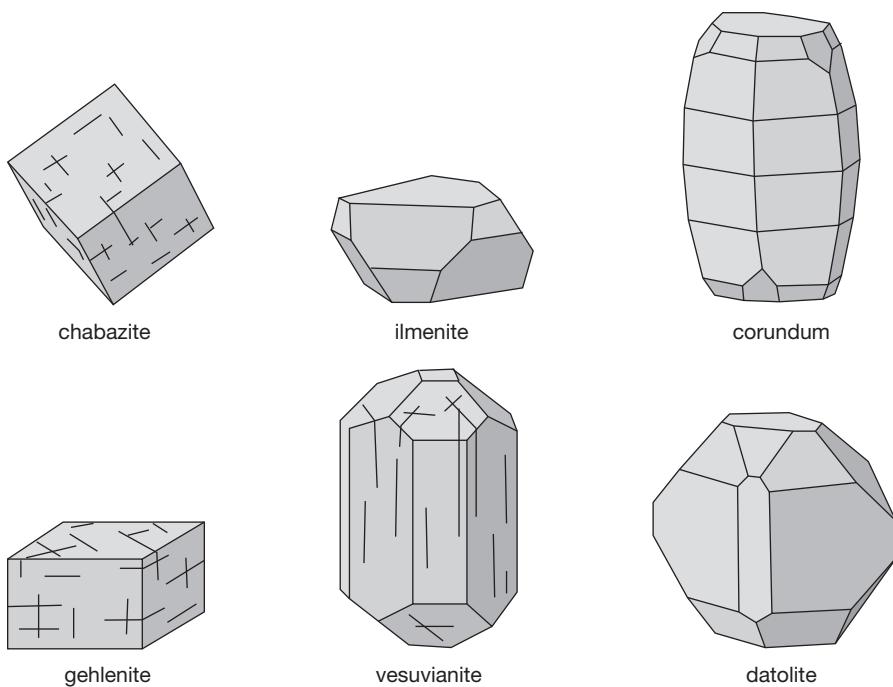
Some minerals, such as chabazite, halite, and garnet, normally contain only one form; others contain more (Figure 4). Chabazite crystals grow as rhombohedrons, cubes "squashed" slightly along one main diagonal. Halite crystals are typically cubic, having six square faces. Garnet crystals commonly have 12 diamond-shaped faces. Other minerals, such as ilmenite, corundum, gehlenite, vesuvianite, and datolite (Figure 4), may contain multiple forms and have more complicated shapes. Some minerals—for example, calcite—have many common forms. But, as we shall see later, they all have a common property called *symmetry*.

A single crystal's habit is controlled by the forms that are present, the way the forms combine, the relative sizes of crystal faces, and other features relating to crystal growth. The most



**FIGURE 3** A two-dimensional example showing how unit cells (in this case shaded rectangles) can stack together in different ways to produce crystals of different shapes: (a) the unit cells are stacked to produce a rectangular crystal with two forms (two kinds of faces); (b) the same unit cell gives a diamond shaped crystal with only one form; (c) this crystal is a combination of the same forms shown in (a) and (b). The size of a unit cell has been greatly exaggerated in these drawings. Real crystals contain many extremely small unit cells, so forms appear as identical smooth crystal faces without the "steps" shown for the diagonal faces in this figure.

**FIGURE 4** Forms and combinations of forms of six minerals. Different samples of the same mineral may crystallize with different forms, but those shown here are typical. The lines on some of the crystal faces show orientations of prominent cleavages. If a crystal contains only one form, all crystal faces are identical. Chabazite crystals, such as the one shown here, typically contain one form and have six identical nearly square faces. The other five drawings show crystals with more than one form. In the ilmenite, corundum, vesuvianite and datolite drawings, the different forms have distinctive different shapes. In the gehlenite drawing, all faces are rectangular but not all are the same size. The crystal contains three forms (pairs of identical rectangular faces) with different sizes and somewhat different cleavage patterns.



useful terms describing habit are self-explanatory (Table 3). Common ones used to describe the habit of single crystals include **equant** (equidimensional), **acicular** (needlelike), **tabular**, and **bladed** (Figure 6). For a group of crystals, habit includes the shape of the crystals and the way they are intergrown. The terms **massive**, **granular**, **radiating**, and **fibrous** are typical of the terms used to describe crystal aggregates (Figure 6).

The color plates in this text show a wide range of crystal habits. The orthoclase crystals in Plate 1.5 are **blocky**; the celestite in Plate 1.6 is **tabular**; the okenite needles in Plate 1.7 and the selenite needles in Plate 3.5 are **acicular**; the smithsonite in Plate 1.8 and pectolite in Plate 3.1 are **botryoidal**. Most of the quartz crystals in Plates 2.1 through 2.8 are **prismatic**, as are the beryl and tourmaline in Plate 3.3. The actinolite in Plate 3.2 and the kyanite in Plate

### BOX 1

#### What's Wrong with This Picture?

In the 1995 movie *Congo*, an exploration team goes to Africa to seek large, flawless diamonds. When the diamonds are shown, the movie immediately loses credibility with mineralogists because the crystals are hexagonal prisms (long crystals with a hexagonal cross section). Mineralogists know that diamond habit does not include hexagonal prisms (Figure 5).

**FIGURE 5** These quartz crystals with hexagonal prismatic habit are not diamonds because diamonds cannot form hexagonal crystals of this sort.



**TABLE 3 Terms Used to Describe Crystal Habit****Terms Generally Used to Describe Individual Crystals (with Example Minerals)**

equant	Having approximately the same dimensions in all directions (garnet, spinel)
blocky	Equant crystals with approximately square cross sections (halite, galena)
acicular	Needle-like (actinolite, sillimanite)
tabular or platy	Appearing to be plates or thick sheets stacked together (gypsum, graphite)
capillary or filiform	Hair-like or thread-like (serpentine, millerite)
bladed	Elongated crystals that are flattened in one direction (kyanite, wollastonite)
prismatic or columnar	Elongated crystals with identical faces parallel to a common direction (apatite, beryl)
Foliated or micaceous	Easily split into sheets (muscovite, biotite)

**Terms Generally Used to Describe Crystal Aggregates**

massive	Solid mass with no distinguishing features
granular	Composed of many individual grains
radiating or divergent	Crystals emanating from a common point
fibrous	Appearing to be composed of fibers
stalactitic	Stalactite shaped
lamellar or tabular	Flat plates or slabs growing together
stellated	Aggregate of crystals giving a star-like appearance
plumose	Having a feathery appearance
arborescent or dendritic	Having a branching tree-like or plant-like appearance
reticulated or laticelike	Slender crystals forming a lattice pattern
colloform or globular	Spherical or hemispherical shapes made of radiating crystals
botryoidal	Having an appearance similar to a bunch of grapes
reniform	Having a kidney-shaped appearance
mammillary	Breast-like
drusy	Having surfaces covered with fine crystals
elliptic or pisolithic	Very small; small spheres

3.6 are **bladed**, while the anthophyllite (Plate 3.4) and chrysotile (Plate 3.7) are **fibrous** aggregates. In Plate 3.8, **drusy** pyrite has grown on top of calcite.

## STRENGTH AND BREAKING OF MINERALS

The color and shape of minerals are obvious to anyone, but there are other, more subtle, properties that a mineralogist will notice. Several relate to the strength of bonds that hold crystals together. These properties are especially reliable for mineral identification because they are not substantially affected by chemical impurities or defects in crystal structure.

### Tenacity

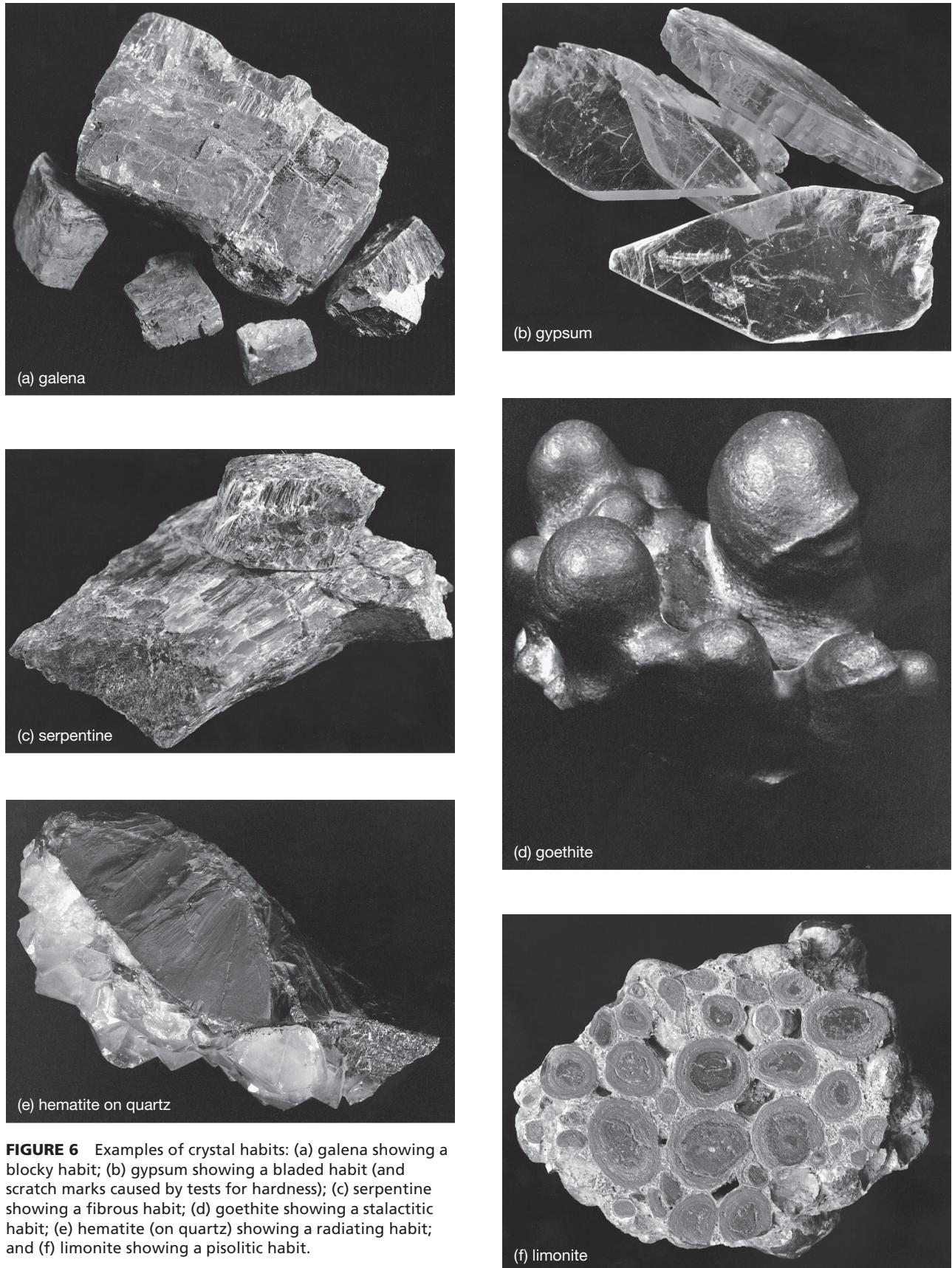
The term *tenacity* refers to a mineral's toughness and its resistance to breaking or deformation. Those that break, bend, or deform easily have little tenacity. In contrast, strong unbreakable

minerals have great tenacity. Jade, composed of either the pyroxene jadeite or the amphibole actinolite, is one of the most tenacious natural materials known. It does not easily break or deform, even when under extreme stress. Table 4 contains some of the terms typically used to describe tenacity.

The tenacity of a mineral is controlled by the nature of its chemical bonds. Ionic bonding often

**TABLE 4 Terms Used to Describe Tenacity**

Flexible	Bendable
elastic	A bendable mineral that returns to its original shape after release
malleable	Capable of being hammered into different shapes
ductile	Capable of being drawn into a wirelike shape
brittle	Easily broken or powdered
sectile	Capable of being cut into shavings with a knife



**FIGURE 6** Examples of crystal habits: (a) galena showing a blocky habit; (b) gypsum showing a bladed habit (and scratch marks caused by tests for hardness); (c) serpentine showing a fibrous habit; (d) goethite showing a stalactitic habit; (e) hematite (on quartz) showing a radiating habit; and (f) limonite showing a pisolithic habit.

**BOX 2****Asbestiform Minerals and Health Risks**

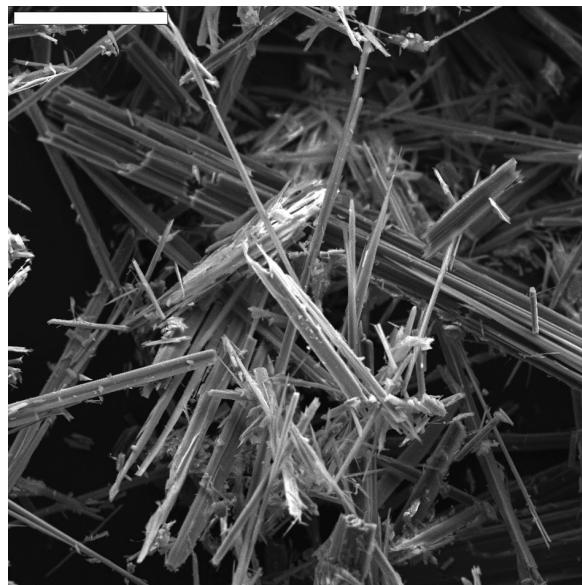
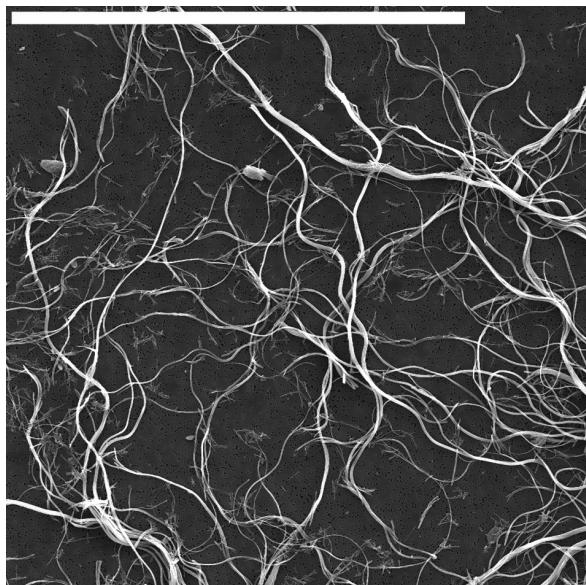
We use the term **asbestiform** to describe a mineral habit characterized by small, strong, and flexible fibers, equivalent to hairs or whiskers (for example, serpentine, as shown in Figure 36c and Plate 3.7; and anthophyllite, as shown in Plate 3.4). **Asbestos** is a commercial name for any marketable asbestiform mineral. Mineralogists have described many asbestiform mineral varieties, but most are rare and only a few are produced for sale. "White asbestos," composed of the mineral chrysotile, accounts for about 95% of the commercial market. Chrysotile, a member of the serpentine group, is a widespread but minor mineral in many altered ultramafic rocks. In North America, production occurs in a few large deposits in Quebec and California. Other forms of commercial asbestos are composed of crocidolite ("blue asbestos") and amosite ("brown asbestos"), varieties of the amphiboles riebeckite and grunerite, respectively. Other minerals with asbestiform varieties include other amphiboles (anthophyllite, tremolite, actinolite), clays (sepiolite, palygorskite), and members of the zeolite group, including roggianite, mazzite, erionite, mordenite, and okenite.

Historically, asbestos has had many uses. Since around 1878, it has been mined in large quantities because it is tough, flexible, and fire and chemical resistant. Between 1900 and 1986, builders sprayed asbestos on walls, ceilings, and pipes in many buildings in the United States. Industries have used asbestos in brake linings, roof shingles, and other applications. Unfortunately, asbestos easily crumbles to make a fine dust that people can inhale. Fibers can become embedded in lung tissue and cause asbestosis (a chronic breathing disorder that may be fatal), lung cancer, or mesothelioma (another form of cancer). For the most part, epidemiologists have documented these diseases in workers exposed to high levels of asbestos over long times.

In 1907 health workers reported the first asbestos-related diseases, but it was not until around 1960 that the threat posed by asbestos was accepted as serious. In 1974 the Environmental Protection Agency (EPA) banned asbestos for most commercial use in the United States, and soon afterward launched a vigorous program to remove asbestos from commercial structures. However, American companies still ship many products containing asbestos to developing countries. Despite the ban and efforts to eliminate asbestos from our environment, it is still common in many buildings and as a component in urban dust.

Although it was originally thought that all asbestos posed a very serious threat, today we know that some kinds are much worse than others (Figure 7). Size and shape of asbestos fibers vary, making some varieties more dangerous. Fortunately, current studies suggest that exposure to low levels of chrysotile, the most common form of asbestos, may not pose as serious a health threat as once thought. In large part this is because chrysotile forms somewhat curly fibers. In contrast, blue asbestos (crocidolite) and brown asbestos (amosite), which commonly have long, straight, needlelike fibers, are thought to be the most dangerous. Blue and brown asbestos also tend to stay airborne longer than other varieties, further increasing their threat.

Adding more complication to the asbestos issue, the EPA found that removing asbestos that is not crumbling or releasing fibers can increase asbestos concentrations in the air and cost a great deal of money without significantly decreasing health threats. For these reasons, Congress modified asbestos laws in 1986.



**FIGURE 7** Two images of asbestos obtained using a scanning electron microscope. The white bars at the top of the images are 0.1 mm long. The image on the left is chrysotile, a variety of serpentine. The mineral on the right is anthophyllite, one of several amphibole minerals that can form asbestos. At one time, all asbestos minerals were thought to pose very significant health risks. Today we know that the amphibole varieties are much more dangerous than chrysotile. These photographs come from the United States Geological Survey Denver Microbeam Laboratory.

leads to rigid, brittle minerals. Halite is an excellent example of a **brittle** mineral. It shatters into many small pieces when struck. Quartz, too, is brittle, although the bonding in quartz is only about 50% ionic. Many metallically bonded minerals, such as native copper, are **malleable**. Other minerals, such as gypsum, are **sectile**. Some minerals, including talc and chlorite, are **flexible** due to weak van der Waals and hydrogen bonds holding well-bonded layers of atoms together. When force is applied, slippage between layers allows bending. When pressure is released, they do not return to their original shape. Still other minerals, notably the micas, are **elastic**. They may be bent but resume their original shape after pressure is released if they were not too badly deformed. In micas and other elastic minerals, the bonds holding layers together are stronger than those in chlorite or clays.

### Fracture, Cleavage, and Parting

*Fracture* is a general term used to describe the way a mineral breaks or cracks. Terms used to describe fracture include *even*, *conchoidal*, and *splintery* (Table 5). Because atomic structure is not the same in all directions and chemical bonds are not all the same strength, most crystals break along preferred directions. The orientation and manner of breaking are important clues to crystal structure. If the fractures are planar and smooth, the mineral is said to have good **cleavage** (Figure 8). Cleavage involves minerals breaking parallel to planes of atoms. There are a few exceptions, such as quartz, that break only along curved surfaces to form **conchoidal fractures** (see Plate 2.1), but the majority of minerals exhibit cleavage.

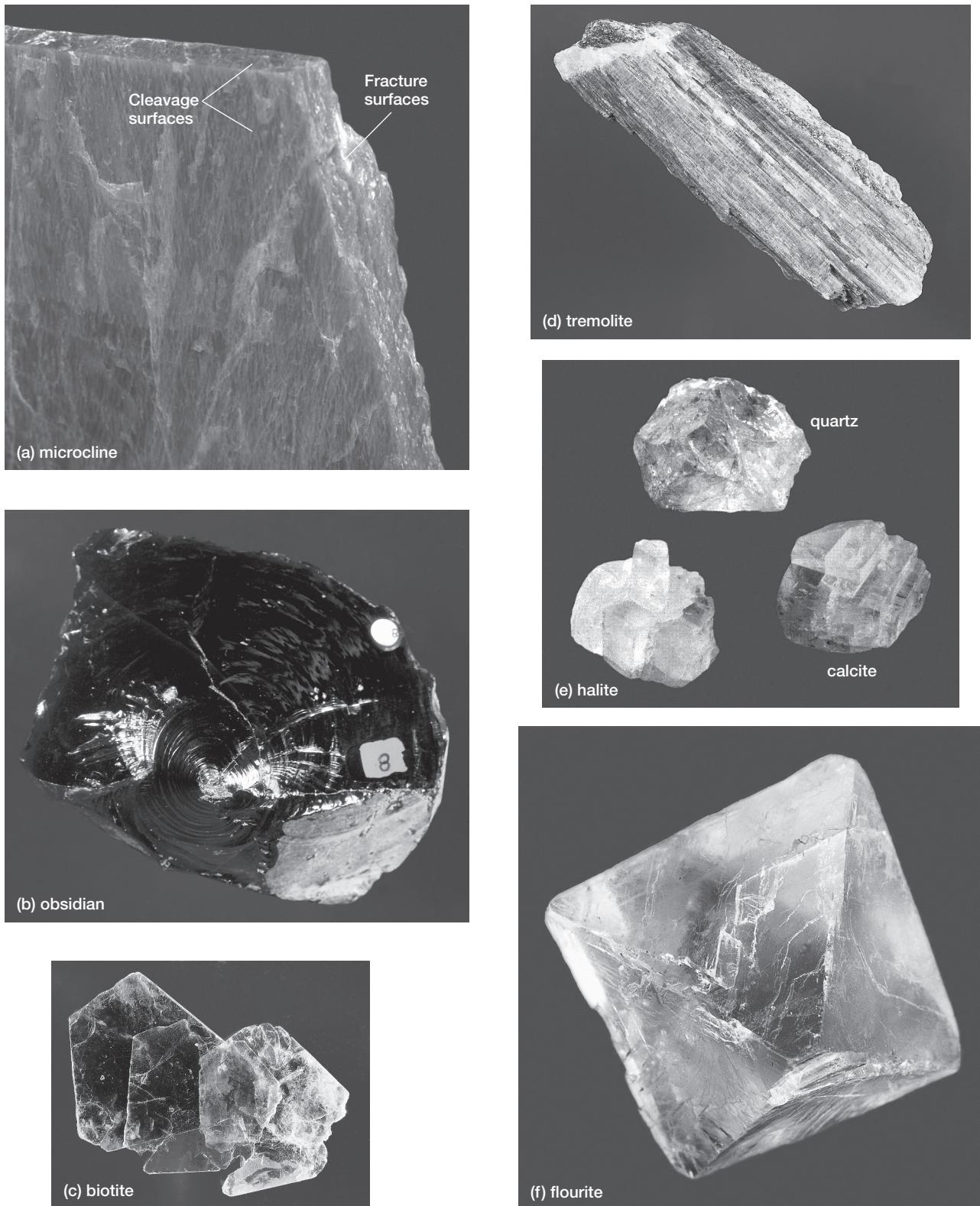
If a mineral cleaves along one particular plane, a nearly infinite number of parallel planes are equally prone to cleavage. This is due to the repetitive arrangement of atoms in atomic structures. The spacing between planes is the repeat distance of the atomic structure, on the order of angstroms ( $1\text{\AA} = 10^{-10}\text{ m}$ ). The whole set of planes, collectively referred to as a cleavage, represents planes of weak bonding in the crystal structure. Biotite (Plate 6.6) is a good example of a mineral with one excellent cleavage. Minerals that have more than one direction of weakness will have more than one cleavage direction (Figure 9). The direction and angular relationships between cleavages, therefore, give valuable hints about atomic structure.

Minerals that are equally strong in all directions, such as quartz, fracture to form irregular surfaces (Plate 2.1). Minerals with only one direction of weakness, such as gypsum and micas, have one direction of cleavage and usually break to form thick slabs or sheets. We say they have *basal cleavage*. Kyanite (Plate 3.6) and anthophyllite, which have two good cleavages, easily break into splintery shapes. Other minerals may have three (halite), four (fluorite), or even six cleavages (Figure 9). We use geometric terms such as cubic, octahedral, or prismatic to describe cleavage when appropriate. The ease with which a mineral cleaves is not the same for all minerals or for all the cleavages in a particular mineral. Mineralogists describe the quality of a particular cleavage with qualitative terms: *perfect*, *good*, *distinct*, *indistinct*, and *poor*. Quartz has poor cleavage in all directions, while micas have one perfect cleavage.

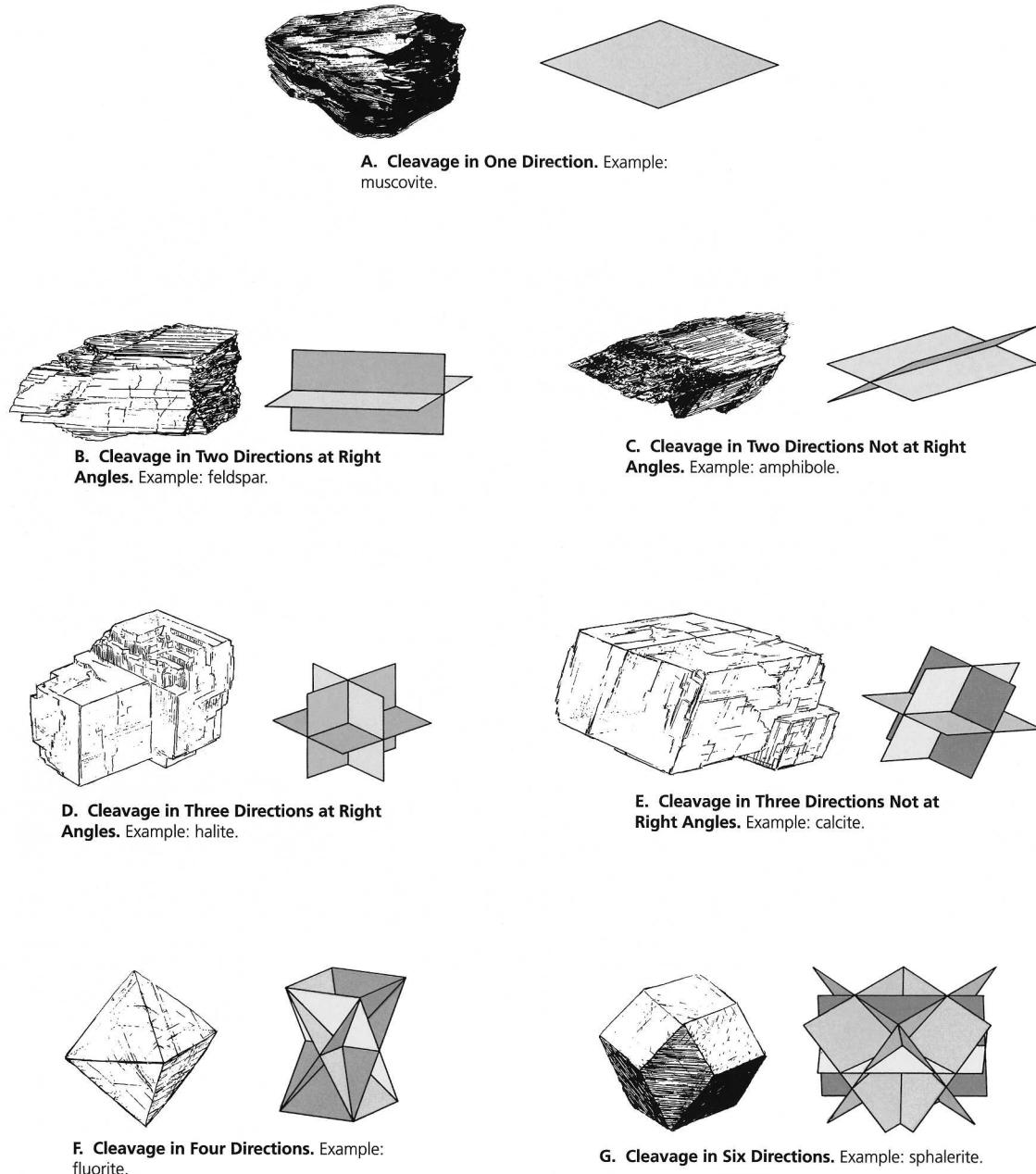
Crystal faces and cleavage surfaces may be difficult to tell apart. A set of parallel fractures indicates a cleavage, but if only one flat surface is visible,

**TABLE 5 Terms Used to Describe Fracture and Cleavage (with Examples)**

Fracture Terms	Description (and Examples)
even	Breaking to produce smooth planar surfaces (halite)
uneven or irregular	Breaking to produce rough and irregular surfaces (rhodonite)
hackly	Jagged fractures with sharp edges (copper)
splintery	Forming sharp splinters (kyanite, pectolite)
fibrous	Forming fibrous material (chrysotile, crocidolite)
conchoidal	Breaking with curved surfaces as in the manner of glass (quartz)
Cleavage Terms	
basal	Also sometimes called <i>platy</i> ; refers to cleavage in minerals such as micas that have one well-developed planar cleavage
cubic	Geometric term used to describe three cleavages at $90^\circ$ to each other (galena)
octahedral	Geometric term used to describe four cleavages that produce octahedral cleavage fragments (fluorite)
prismatic	Multiple directions of good cleavage all parallel to one direction in the crystal



**FIGURE 8** Fracture and cleavage examples: (a) microcline (a K-feldspar variety) typically exhibits two cleavages that intersect at about 90°, it fractures in other directions, and the cleavage surfaces are smoother than the fracture surfaces; (b) obsidian, in contrast with microcline and most minerals, does not cleave because it is not crystalline; instead, it breaks to form conchoidal fractures; (c) micas have only one good cleavage, so they break into sheets; (d) tremolite has two cleavages which allow it to break to form long splintery pieces; (e) quartz (top) has no cleavages and fractures conchoidally; halite (left) has two cleavages that intersect at exactly 90°; calcite (right) has three cleavages, but they do not intersect at 90°; (f) fluorite has four excellent cleavages, allowing it to be broken into octahedra.

**FIGURE 9** Cleavage in minerals. Compare these drawings with the photos in Figure 6.

there can be ambiguity. However, crystal faces often display subtle effects of crystal growth. **Twining** (oriented intergrowths of multiple crystals) and other **striations** (parallel lines on a face), growth rings or layers, pitting, and other imperfections make a face less smooth than a cleavage plane and give it lower reflectivity and a drabber luster. In some minerals, principal cleavage directions are parallel to crystal faces, but in most they are not. Plates 1.3 and 2.7 show pyrite with well-developed striations on its crystal faces.

Cleavage is an excellent property for mineral identification. Often the quality and number of cleavages may be seen in hand specimen. Sometimes a hand lens is used to identify the set of fine parallel cracks more irregular than twinning and striations, which indicate a cleavage that is too poorly developed to be seen with the naked eye. Angles between cleavages may be estimated or, if accurate angular measurements are needed, techniques involving a **petrographic microscope** or a device called a **goniometer** may be used to measure them.

Some mineral specimens exhibit **parting**, a phenomenon that looks like cleavage. Parting is not due to atomic structure weaknesses, but to crystallographic imperfections such as **twin planes** (planes that separate domains with different atomic-structure orientations), stress, or chemical alteration. In contrast with cleavage, parting is restricted to one or a few distinct planes rather than an infinite set. Unlike cleavage, parting will not be present in all specimens of a particular mineral, and parting surfaces are usually less smooth than cleavage planes.

### Hardness

**Hardness** is a mineral's resistance to abrasion or scratching. **Relative hardness** (symbolized by *H*) is determined by trying to scratch a surface of one mineral with an edge or corner of a second mineral. If a scratch or abrasion results, the first mineral is the softer. Although rarely done by mineralogists, absolute values of hardness may be determined in several ways; the easiest is to use an indenting tool similar to ones used to determine the hardness of steel. The indenting tool measures the force necessary to produce a permanent indentation in a flat surface. The results will be almost the same as those determined using scratch tests.

Table 6 gives the relative hardness scale used by mineralogists. Based on 10 well-known minerals, it is called the Mohs hardness scale, named after Austrian mineralogist Friedrich Mohs who developed it in 1812. The Mohs scale ranks minerals by their ability to scratch each other. **Absolute hardness** is the measure of a material's ability to resist permanent deformation.

**TABLE 6** Mohs Hardness Scale and the Hardness of Some Nonmineral Objects

Mineral	<i>H</i>	<i>H</i>	Nonmineral
talc	1		
gypsum	2	2½	fingernail, aluminum
calcite	3	3½	penny, brass
fluorite	4	4½	iron
apatite	5	5½	pocketknife blade, glass
feldspar	6	6½	metal file, streak plate
quartz	7		
topaz	8		
corundum	9		
diamond	10		

The Mohs scale is related to absolute hardness but does not measure the same thing because resistance to scratching depends on additional factors. A simplified comparison to absolute hardness shows that the Mohs hardness scale is not linear and is close to being exponential (Figure 10a). The hardnesses of the softest minerals are more similar than the hardnesses of the four hardest ones (quartz, topaz, corundum, diamond). Gypsum (*H* = 2) is only slightly harder than talc (*H* = 1), but diamond (*H* = 10) has a hardness five times greater than corundum (*H* = 9).

Relative hardness can be determined by conducting scratch tests to compare the hardness of an unknown mineral to the minerals in the Mohs hardness scale. Alternatively, good approximations of hardness may be made by comparing mineral hardness to a

### BOX 3

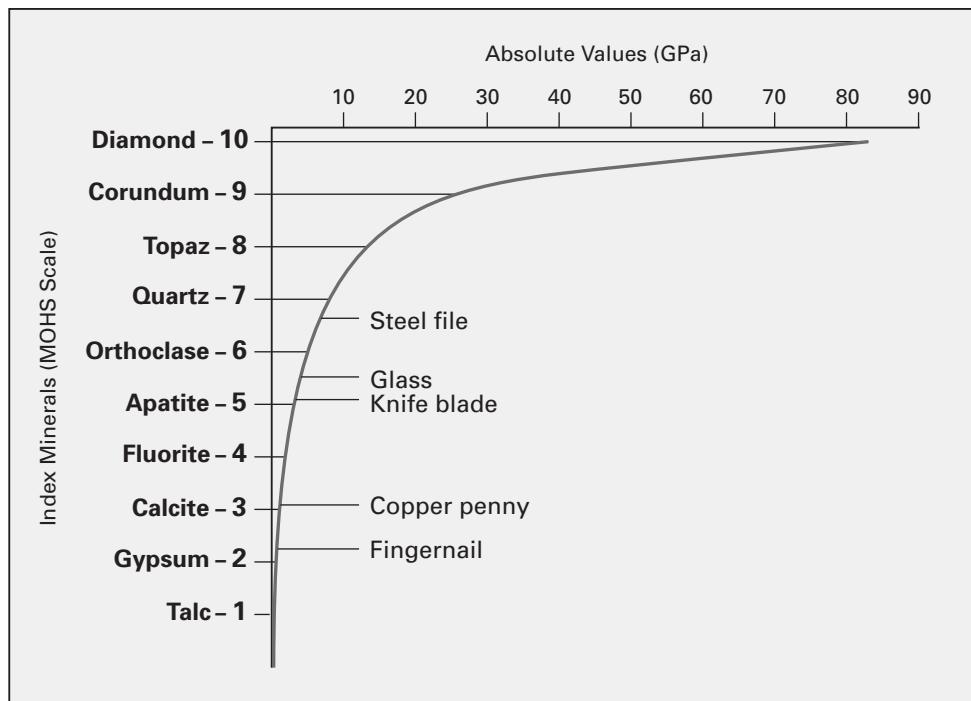
#### Hard and Soft Minerals

Most of the most common minerals have a hardness greater than 2 and less than 7. Following is a list of some of the more common minerals with hardnesses outside this range.

Name	Formula	Hardness
talc	Mg <sub>3</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub>	1
molybdenite	MoS <sub>2</sub>	1 to 1½
graphite	C	1 to 2
pyrophyllite	Al <sub>2</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub>	1½
covellite	CuS	1½ to 2
orpiment	As <sub>2</sub> S <sub>3</sub>	1½ to 2
realgar	AsS	1½ to 2
gypsum	CaSO <sub>4</sub> ·2H <sub>2</sub> O	2
stibnite	Sb <sub>2</sub> S <sub>3</sub>	2
sylvite	KCl	2

#### (Most other minerals have hardness between 2 and 7)

cordierite	(Mg, Fe) <sub>2</sub> Al <sub>4</sub> Si <sub>5</sub> O <sub>18</sub>	7
quartz	SiO <sub>2</sub>	7
andalusite	Al <sub>2</sub> SiO <sub>5</sub>	7½
zircon	ZrSiO <sub>4</sub>	7½
beryl	Be <sub>3</sub> Al <sub>2</sub> Si <sub>6</sub> O <sub>18</sub>	7½ to 8
spinel	MgAl <sub>2</sub> O <sub>4</sub>	7½ to 8
topaz	Al <sub>2</sub> SiO <sub>4</sub> (F, OH) <sub>2</sub>	8
chrysoberyl	BeAl <sub>2</sub> O <sub>4</sub>	8½
corundum	Al <sub>2</sub> O <sub>3</sub>	9
diamond	C	10

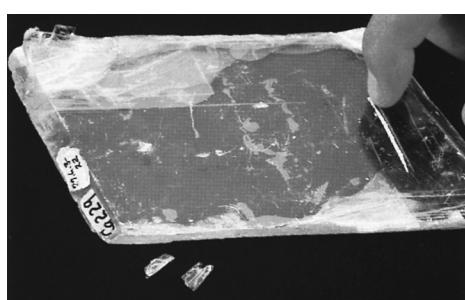


**FIGURE 10A** Mohs hardness scale compared with absolute hardness values and some common everyday objects. Geologists rarely take a complete hardness kit in the field and so often use their fingernail, a penny, or a pocketknife to estimate hardness. This diagram has been simplified to show the general trend; the relationship between Mohs hardness and absolute hardness is more complicated than depicted.

fingernail, penny, pocketknife, glass, or several other common objects (Table 6; Figure 10b). Scratch tests are often straightforward, but there can be complications. Mineral specimens may be too small or too valuable to scratch. Large samples may be made of many grains loosely cemented together so that scratch tests are not possible. Some minerals have different hardnesses depending on the scratch direction. Others may cleave or fracture when tests are performed. In still other cases, the results of scratch tests may be ambiguous, especially if two minerals have the same, or nearly the same, hardness.

The hardness of a mineral relates to its weakest bond strength. Graphite has a hardness of  $1\frac{1}{2}$ , and

diamond has a hardness of 10. Both are made of carbon, but in diamond the carbon atoms are uniformly spaced and tightly bonded together, while in graphite bonding is very weak in one direction (Box 4). Because bonds are usually not the same in all directions in minerals, hardness may vary depending on the direction a mineral is scratched. In kyanite, for example, hardness varies from  $4\frac{1}{2}$  to  $6\frac{1}{2}$  depending on the direction of the scratch test. In most minerals, however, hardness is about the same in all directions. While the general relationship between hardness and bond strength is known, mineralogists have difficulty predicting hardness for complex atomic structures. For some simple ionic compounds, however, theoretical calculations match measurements well. Minerals with high density, highly charged ions, small ions, or covalent bonding tend to be hardest.



**FIGURE 10B** Gypsum has a hardness of 2 on the Mohs hardness scale and so can be scratched with a fingernail to estimate its hardness.

## DENSITY AND SPECIFIC GRAVITY

The Greek letter  $\rho$  (rho) symbolizes **density**. The density of a mineral is usually given in units of grams/centimeter<sup>3</sup> (gm/cm<sup>3</sup>). Density varies slightly depending on pressure or temperature, but most minerals have values between 2 and 8 gm/cm<sup>3</sup>. Accurate determination of density can be difficult or impossible because it requires knowing the volume of a crystal, which can be difficult to measure with

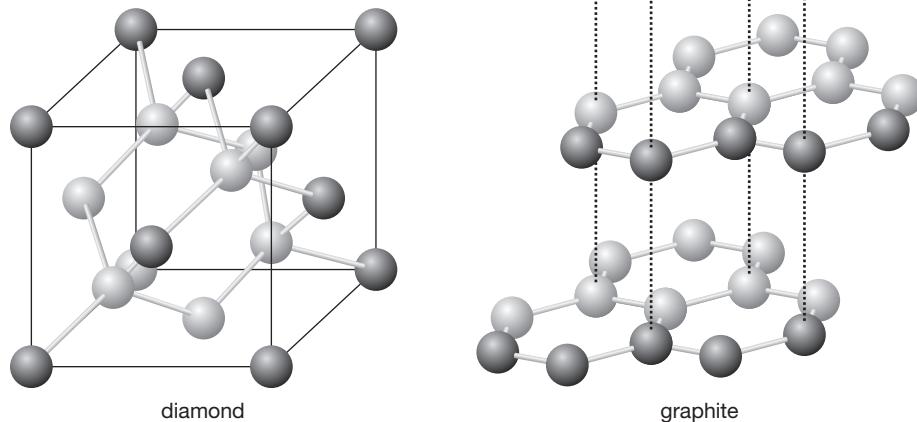
## BOX 4

**Graphite and Diamond Are Made of the Same Thing**

Graphite and diamond are polymorphs; both are made of carbon but have completely different properties and appearances because the carbon atoms are arranged differently in the two minerals (Figure 11). In diamond, each carbon atom is covalently bonded to four others, creating a three-dimensional network that has the same properties in all directions. In graphite, carbon atoms are covalently bonded to form sheets that contain interconnected 6-carbon rings; very weak van der Waals bonds hold the sheets together. As seen in Figure 11, diamond has a denser structure than

graphite. The specific gravity of diamond is about 3.5, and graphite's is 2.1 to 2.3.

Why does carbon have two natural polymorphs? The reason is that, at high pressures, dense minerals are thermodynamically more stable than less dense minerals. Graphite is one of many minerals, including quartz, that react to form more dense species when subjected to extreme pressure. Diamond is only stable at the very high pressures reached more than 100 km (60 mi.) down in the Earth. At Earth's surface it is metastable because it should,



**FIGURE 11** The atomic arrangements in diamond and graphite. Because the atomic arrangements are so different, the two minerals have very different properties. Both minerals contain covalently bonded carbon atoms. In diamond, the bonding forms a three-dimensional network. The overall structure has very high symmetry, is very dense, and is very hard. In graphite, sheets of carbon atoms are held together by covalent bonds, but the sheets themselves are connected by weak van der Waals bonds (dashed lines). So, graphite is soft, deforms easily, and has excellent cleavage in one direction.

accuracy. A related property, **specific gravity (*G*)**, is often used instead. Specific gravity is the ratio of the mass of a mineral to the mass of an equal volume of water at 1 atm pressure and 4 °C (39 °F). Because mass and weight are proportional, we normally determine specific gravity by comparing weights. If a mineral is at 4 °C(39 °F), density (gm/cm<sup>3</sup>) and specific gravity (unitless) have identical values because the density of water is 1 gm/cm<sup>3</sup>:

$$\begin{aligned} G_{4\text{ }^{\circ}\text{C}} &= \frac{\text{weight}_{\text{mineral}}}{\text{weight}_{\text{water}}} = \frac{\text{volume} \times r_{\text{mineral}}}{\text{volume} \times r_{\text{water}}} \\ &= \frac{r_{\text{mineral}}}{r_{\text{water}}} = r_{\text{mineral}} \end{aligned} \quad (1)$$

At room temperature, the density of water is still approximately 1, and most scientists ignore the minor differences between density and specific gravity. In general, borates, halides, sulfates, and some other mineral classes have lower densities than silicates or carbonates, which are of moderate density. Native metals, oxides, and sulfides, in contrast, are denser than most other minerals. There are many exceptions to these generalizations, some of which are apparent from the list of values in Table 7.

The specific gravity of a mineral depends on the atoms within it and how closely packed they are. The polymorphs diamond and graphite are both made of

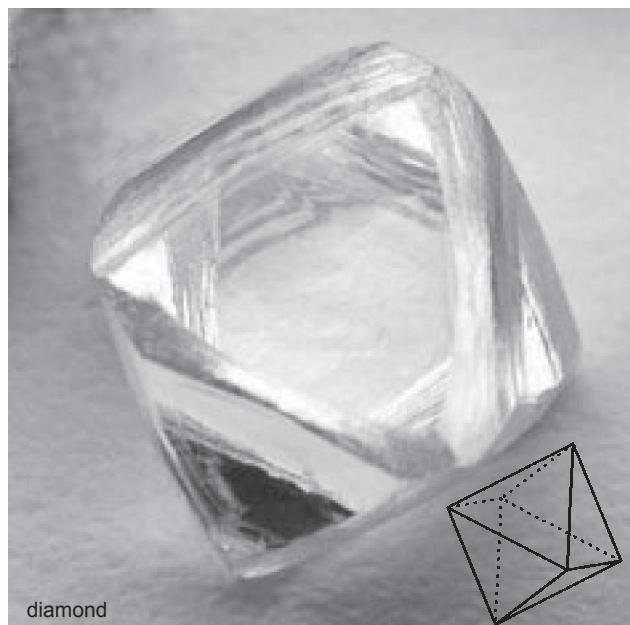
in principle, react to form graphite. However, the reaction of diamond to graphite has a very high activation energy and so does not take place under natural conditions.

Because bonding is the same in all directions, diamond tends to crystallize to form crystals with high symmetry (Figure 12). Octahedra (crystals having eight identical triangular faces) are most common, but cubes, dodecahedra (12-sided crystals) and more complicated crystals are known. Graphite is typically anhedral, and so shows no crystal faces. When it is euhedral, it forms hexagonal crystals, often appearing as shiny six-sided thin tablets (Figure 12).

The tight covalently bonding means that diamond is very hard ( $H = 10$ ). It is strong, rigid, and has no cleavage. It is, in fact, the hardest known natural substance and is used as a grinding and cutting agent in many applications. Diamond is also the least compressible material and the

best thermal conductor. Graphite, in contrast, is very soft ( $H = 1$  to 2) and deforms easily. The weak bonds between layers easily break, giving graphite an excellent cleavage. Because the layers slip past each other easily, graphite is "greasy" and is used as an industrial lubricant. The softness and good cleavage also make it work as pencil lead.

Carbon has four valence electrons. All are tied up in covalent bonds in diamond, but one is "left over" in graphite. It is free to move about the structure and, consequently, graphite can conduct electricity while diamond cannot. Graphite is sometimes used to make heating elements or welding rods. The covalent bonding also means that both diamond and graphite have very high melting and boiling points. Diamond melts at  $3,800\text{ }^{\circ}\text{C}$  ( $6,872\text{ }^{\circ}\text{F}$ ), a few hundred degrees higher than graphite. The boiling point of carbon is  $4,830\text{--}4,830\text{ }^{\circ}\text{C}$  ( $8730\text{--}8730\text{ }^{\circ}\text{F}$ ). Neither mineral is soluble in water.



**FIGURE 12** Examples of natural graphite and diamond crystals. These crystals are euhedral but are not perfect; both are about 7 mm (a quarter-inch) in longest dimension. The small drawings show idealized sketches. Note the cleavage in the graphite crystal.

carbon (C). Diamond has specific gravity of 3.5, while graphite's is 2.2, due to differences in atomic structure (Box 4). Graphite forms under Earth surface conditions, but diamond, with its high specific gravity, only forms deep in the Earth where pressures are great. The laws of thermodynamics tell us that high pressures favor dense minerals, which makes sense because at high pressure things are squeezed together. Table 8 compares the specific gravities of  $\text{SiO}_2$  and of  $\text{Al}_2\text{SiO}_5$  polymorphs. For both the  $\text{SiO}_2$  and  $\text{Al}_2\text{SiO}_5$  minerals, the densest polymorphs are stable at highest pressures.

The effect of composition on  $G$  can be seen by comparing values for **isostuctural minerals**, minerals with identical atomic structures but different

compositions. Minerals in the garnet group are isostructural. They are often divided into two subgroups, the **pyralspites** (*pyrope-almandine-spessartine*) with composition  $(\text{Mg},\text{Fe},\text{Mn})_3\text{Al}_2\text{Si}_3\text{O}_{12}$ , and the **ugrandites** (*uvarovite-grossular-andradite*) with composition  $\text{Ca}_3(\text{Cr},\text{Al},\text{Fe})_2\text{Si}_3\text{O}_{12}$ . The names of the two groups are based on the names of garnet species within the groups.

Table 9 compares the specific gravities of garnets within the two groups. (For comparison, grossular has been included with the pyralspite garnets, although it is not normally considered a member of that group.) Within the pyralspite series, the increase in  $G$  from pyrope to grossular to spessartine to almandine is consistent with the different atomic

**TABLE 7 Specific Gravity of Selected Minerals**

**Values shown are the average specific gravities at 1 atm, 25°C.**

borax	$\text{Na}_2\text{B}_4\text{O}_5(\text{OH})_4 \cdot 8\text{H}_2\text{O}$	1.8
sylvite	KCl	2.0
sulfur	S	2.1
graphite	C	2.1
halite	NaCl	2.2
gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	2.3
orthoclase	$\text{KAlSi}_3\text{O}_8$	2.6
kaolinite	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	2.6
albite	$\text{NaAlSi}_3\text{O}_8$	2.6
quartz	$\text{SiO}_2$	2.6
calcite	$\text{CaCO}_3$	2.7
anorthite	$\text{CaAl}_2\text{Si}_2\text{O}_8$	2.8
muscovite	$\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$	2.8
talc	$\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$	2.8
dolomite	$\text{CaMg}(\text{CO}_3)_2$	2.8
biotite	$\text{K}(\text{Mg},\text{Fe})_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2$	3.0
chlorite	talc + brucite combinations	3.0
andalusite	$\text{Al}_2\text{SiO}_5$	3.2
fluorite	$\text{CaF}_2$	3.2
apatite	$\text{Ca}_5(\text{PO}_4)_3(\text{OH},\text{F},\text{Cl})$	3.2
olivine	$(\text{Mg},\text{Fe})_2\text{SiO}_4$	3.3
diopside	$\text{CaMgSi}_2\text{O}_6$	3.4
sillimanite	$\text{Al}_2\text{SiO}_5$	3.2
diamond	C	3.5
kyanite	$\text{Al}_2\text{SiO}_5$	3.6
staurolite	$\text{Fe}_2\text{Al}_9\text{Si}_4\text{O}_{23}(\text{OH})$	3.7
corundum	$\text{Al}_2\text{O}_3$	4.0
sphalerite	ZnS	4.0
chalcocite	$\text{CuFeS}_2$	4.2
rutile	$\text{TiO}_2$	4.2
goethite	$\text{FeO}(\text{OH})$	4.3
smithsonite	$\text{ZnCO}_3$	4.4
barite	$\text{BaSO}_4$	4.5
ilmenite	$\text{FeTiO}_3$	4.5
pyrolusite	$\text{MnO}_2$	4.5
covellite	CuS	4.6
pyrrhotite	$\text{Fe}_{1-x}\text{S}$	4.6
zircon	$\text{ZrSiO}_4$	4.7
hematite	$\text{Fe}_2\text{O}_3$	5.0
pyrite	$\text{FeS}_2$	5.1
magnetite	$\text{Fe}_3\text{O}_4$	5.2
chalcocite	$\text{Cu}_2\text{S}$	5.8
cuprite	$\text{Cu}_2\text{O}$	6.0
bornite	$\text{Cu}_5\text{FeS}_4$	6.0
scheelite	$\text{CaWO}_4$	6.1
cobaltite	$(\text{Co},\text{Fe})\text{Ass}$	6.3
anglesite	$\text{PbSO}_4$	6.4
cerussite	$\text{PbCO}_3$	6.5
cassiterite	$\text{SnO}_2$	7.0
galena	PbS	7.6
cinnabar	HgS	8.1
copper	Cu	8.8
silver	Ag	10.3
platinum	Pt	16.5
gold	Au	17.2

weights of magnesium (Mg), calcium (Ca), manganese (Mn), and iron (Fe). Similarly, the increase in  $G$  from grossular to uvarovite to andradite of the ugrandite series mirrors the increase in atomic weight from Ca to Cr to Fe.

Some minerals have specific gravity less than 2.0. Others have values greater than 10 (Table 7). Because of great variability, it is possible to distinguish between minerals with high, moderate, or low specific gravity simply by holding a specimen in your hand. We use the term **heft** for estimations of  $G$  made by holding hand specimens; heft can be very useful in mineral identification. For example, the mineral barite ( $\text{BaSO}_4$ ) sometimes exists as massive white material that is easy to confuse with feldspars. Its high density, easily discerned by picking it up, helps identify it. Similarly, cerussite ( $\text{PbCO}_3$ ) can be distinguished from other carbonate minerals by its heft.

Density differences can also help in the separation of minerals. In the laboratory, crushed rock is often separated into mineral components by “floating” samples in liquids of different densities. In these **heavy liquids**, which are much denser than water, minerals separate as some float and others sink according to their specific gravities. In mining operations, ore minerals are often separated from uneconomical minerals by using gravity separation techniques that depend on density differences. This occurs in natural systems, too. Placer gold deposits are formed when gold from weathered rock, because of its high specific gravity, concentrates in streambeds.

A number of techniques can be used to determine a mineral's specific gravity. High-precision measuring devices, including a **Jolly balance** or a **Berman balance**, can be used to determine a mineral's weight when suspended in air and when suspended in water. The specific gravity is then calculated:

$$G = \frac{\text{weight}_{\text{air}}}{\text{weight}_{\text{air}} - \text{weight}_{\text{water}}} \quad (2)$$

Balance techniques require relatively large samples, at least  $0.5 \text{ cm}^3$  or more, to be accurate. The samples must also be homogeneous. When such material is not available, an alternative method, which uses a powdered sample and a small bottle called a **pycnometer**, is employed (Box 5; Figure 13).

## MAGNETISM OF MINERALS

Magnetism derives from a property of electrons called the *magnetic moment* that results from their spinning and orbiting motions. The sum of all the magnetic moments of all the atoms in a mineral gives it magnetism. Minerals are classified as **ferromagnetic**, **diamagnetic**, or **paramagnetic**. If the moments of a

**TABLE 8 Specific Gravity (G) and Occurrence for SiO<sub>2</sub> and Al<sub>2</sub>SiO<sub>5</sub> Polymorphs**

Mineral	Composition	Specific Gravity	Occurrence
tridymite	SiO <sub>2</sub>	2.26	Volcanic rocks
cristobalite	SiO <sub>2</sub>	2.32	Volcanic rocks
quartz	SiO <sub>2</sub>	2.65	Many Earth surface rocks
coesite	SiO <sub>2</sub>	3.01	Meteor impact craters and rare high-pressure metamorphic rocks
stishovite	SiO <sub>2</sub>	4.35	Meteor impact craters
andalusite	Al <sub>2</sub> SiO <sub>5</sub>	3.18	Low-pressure metamorphic rocks
sillimanite	Al <sub>2</sub> SiO <sub>5</sub>	3.23	Low- to high-pressure metamorphic rocks
kyanite	Al <sub>2</sub> SiO <sub>5</sub>	3.60	High-pressure metamorphic rocks

mineral's atoms interact in a constructive way, the mineral will have properties similar to those of a magnet. Such is the case for a few minerals, including magnetite and pyrrhotite. Magnetite, pyrrhotite, and other magnetic minerals are called *ferromagnetic* because they have the same magnetic properties as metallic iron. Most minerals exhibit little magnetic character but may be weakly repelled by a strong magnetic field; they are *diamagnetic*. Pure feldspars, halite, and quartz all exhibit weak diamagnetism. An impure feldspar, however, may contain iron (Fe), which results in *paramagnetism*, attraction to a strong magnet. Other paramagnetic minerals include garnet, hornblende, and many pyroxenes.

For a few minerals, magnetic properties aid in identification. In the field, ferromagnetic minerals, such as magnetite, may be identified because a magnet will be attracted to them. In the laboratory, subtle differences in the magnetic properties of minerals are used to separate different minerals in crushed rock samples (Figure 14).

## ELECTRICAL PROPERTIES

Some minerals may conduct electricity. Electrical conduction occurs when a mineral's electrons can move

throughout its structure. Such will be the case in structures containing metallic bonds. The native metals, such as copper, are the best examples. Small amounts of electrical conduction may also occur in minerals with defects or other imperfections in their structures. Other minerals, while being unable to conduct electricity, may hold static charges for brief periods of time. They may be charged by exposure to a strong electric field, a change in temperature, or an application of pressure. A mineral charged by temperature change is **pyroelectric**; a mineral charged by pressure change is **piezoelectric**. Because they are difficult to measure, electrical properties are not often used for mineral identification.

## REACTION TO DILUTE HYDROCHLORIC ACID

One chemical property, the reaction of minerals to dilute (5%) hydrochloric acid (HCl), is included here because it is diagnostic for calcite, one of the most common minerals of the Earth's crust. Drops of acid placed on coarse samples of calcite cause obvious bubbling or fizzing, called *effervescence* (Figure 15). Dolomite, a closely related carbonate

**TABLE 9 Specific Gravity (G) Values for Pyralspite and Ugrandite Garnets**

Mineral	Composition	Key Element	Atomic Weight of Key Element	G of Mineral
<i>Pyralspites</i>				
pyrope	Mg <sub>3</sub> Al <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>	Ma	24.304	3.54
grossular	Ca <sub>3</sub> Al <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>	Ca	40.080	3.56
spessartine	Mn <sub>3</sub> Al <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>	Mn	54.938	4.19
almandine	Fe <sub>3</sub> Al <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>	Fe	55.847	4.33
<i>Ugrandites</i>				
grossular	Ca <sub>3</sub> Al <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>	Al	26.982	3.56
uvarovite	Ca <sub>3</sub> Cr <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>	Cr	51.996	3.80
andradite	Ca <sub>3</sub> Fe <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>	Fe	55.847	3.86

**BOX 5****What Is a Pycnometer?**

A pycnometer (Figure 13) is a small bottle fitted with a ground-glass stopper containing a small hole. The bottle is filled with water and the top placed on it. It is carefully wiped dry after excess water squeezes out of the hole, and then weighed. A small amount of mineral of known weight is put in the bottle with the water. The top is replaced and excess water is wiped off. It is weighed again and the mineral's specific gravity is calculated:

$$G = \frac{weight_{mineral}}{weight_{bottle+water} + weight_{mineral} - weight_{bottle+water+mineral}} \quad (3)$$



**FIGURE 13**  
Pycnometer.

mineral, effervesces when finely powdered but not when coarse. Other carbonate minerals (smithsonite, aragonite, strontianite) effervesce to different degrees. They are distinguished by crystal form, color, and other properties. Although acid tests have limited use, most mineralogy labs are equipped with small bottles of HCl and eyedroppers to aid in carbonate identification. Many geologists carry a small bottle of dilute hydrochloric acid when they go in the field so they may distinguish

between rocks that contain calcite and rocks that do not.

**OTHER PROPERTIES**

Minerals possess many other properties (for example, solubility, radioactivity, or thermal conduction). Because they are of little use for mineral identification in most cases, they will not be discussed individually here.



**FIGURE 14** Magnetic separator. A fine-grained sample is fed slowly through the hopper funnel. As it slides downhill, a magnetic field separates the grains based on how magnetic they are.



**FIGURE 15** A drop of dilute hydrochloric acid on calcite causes it, and a few other minerals, to effervesce.

## Questions for Thought

*Some of these questions have no specific correct answers; they are intended to promote thought and discussion.*

1. Why do all samples of a given mineral (for example, quartz) have similar physical properties?
2. One systematic approach to mineral identification would be to fill out a table that has columns for luster, color, streak, cleavage, hardness, and so on. Mineralogists rarely do this. Why?
3. When identifying an unknown mineral, color is often a poor property to use. Form and habit, however, are often good properties. What makes color unreliable? What controls a crystal's form? Are there additional things that control its habit?
4. We know that asbestos minerals lead to health problems if they get in our lungs. Why don't all minerals cause the same sort of health problems?
5. Why do different minerals break in different ways? Quartz has a conchoidal fracture; biotite has one excellent cleavage. What does this tell you about the difference between quartz and biotite?
6. If you look in the table in Appendix E you will find that only a few minerals have hardnesses greater than 8. Why?
7. Many of the least dense minerals are evaporite minerals (they form by precipitation from water). Why? Many of the densest minerals are metals. Why?

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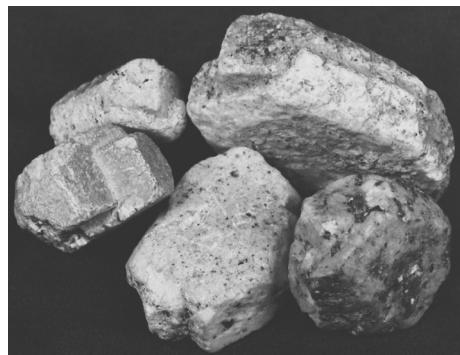
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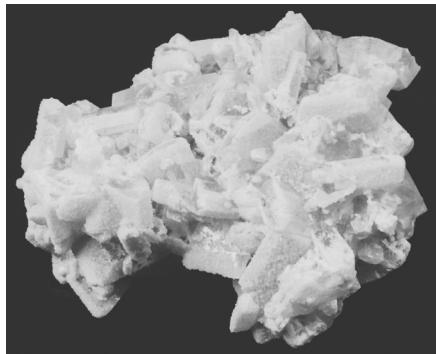
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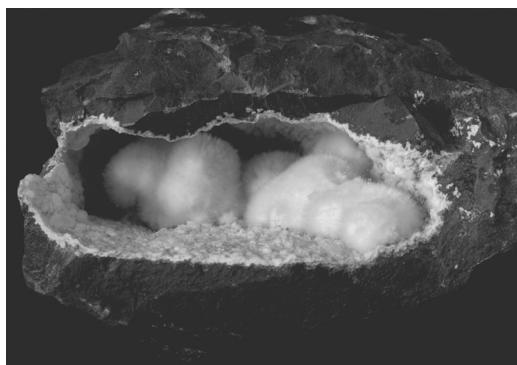
**PLATE 1.3** Pyrite crystals with pyritohedron form showing growth striations on faces.



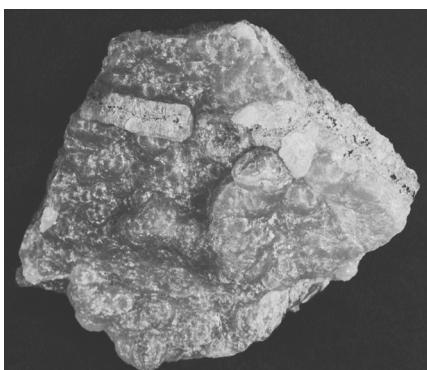
**PLATE 1.5** Orthoclase from Petschau, Bohemia, showing penetration twins.



**PLATE 1.6** Celestite from Lime City, Ohio.



**PLATE 1.7** Acicular okenite in a geode from Bombay, India.



**PLATE 1.8** Botryoidal purple smithsonite from Choix, Mexico.



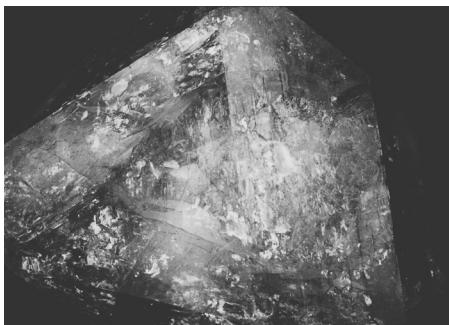
**PLATE 2.1** Rutile needles in quartz from Brazil showing conchoidal fractures.



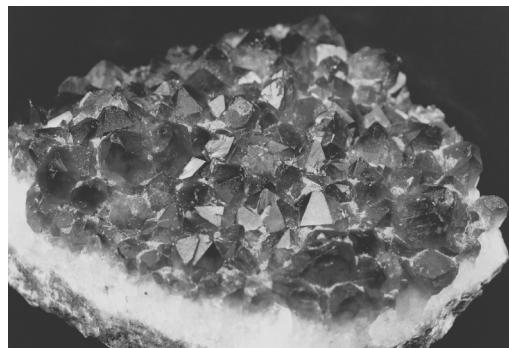
**PLATE 2.2** Rose quartz from Custer, South Dakota.



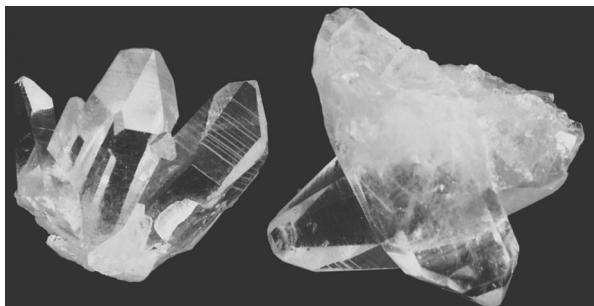
**PLATE 2.3** Amethyst, a purple variety of quartz.



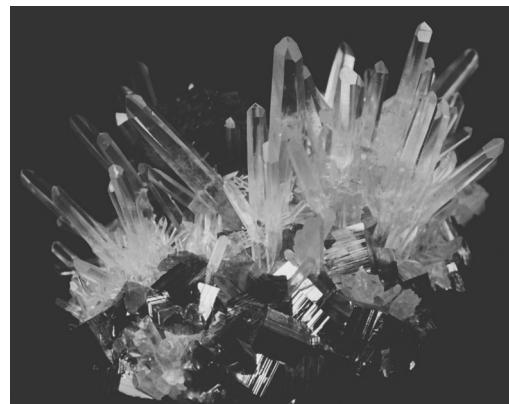
**PLATE 2.4** Quartz showing play of colors and internal reflection due to internal fractures.



**PLATE 2.5** Brown quartz from California.



**PLATE 2.6** Clear quartz crystals from Hot Springs, Arkansas, showing growth striations.



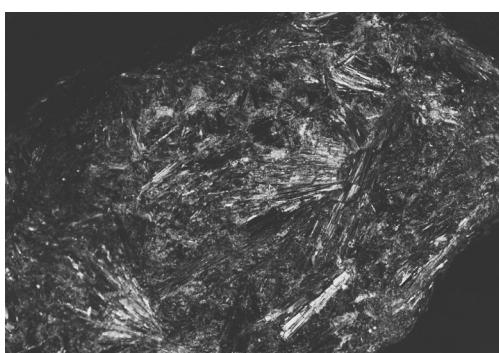
**PLATE 2.7** Prismatic quartz crystals on pyrite; sphalerite is the dark mineral behind the quartz crystals (sample from Huaron, Peru).



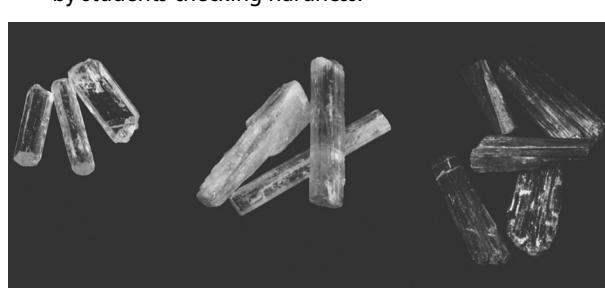
**PLATE 2.8** Herkimer diamonds (in reality, quartz crystals) from Herkimer, New York.



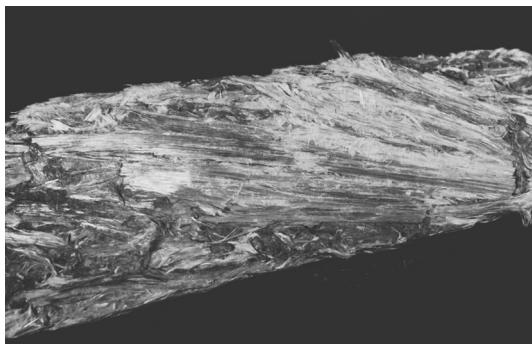
**PLATE 3.1** Pectolite from Patterson, New Jersey, showing radiating habit and scratch marks caused by students checking hardness.



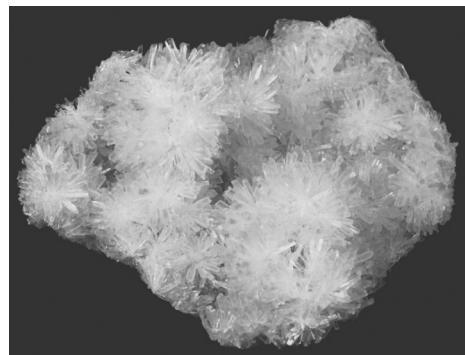
**PLATE 3.2** Actinolite from the Adirondack Mountains, New York, showing bladed habit.



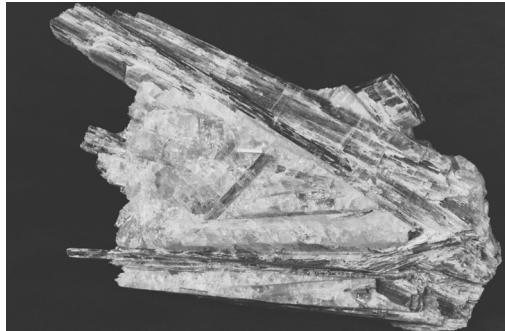
**PLATE 3.3** Prismatic crystals: beryl from Nigeria (left); rubellite, a pink variety of tourmaline, from San Diego County, California (center); green tourmaline from Minas Gerais, Brazil (right).



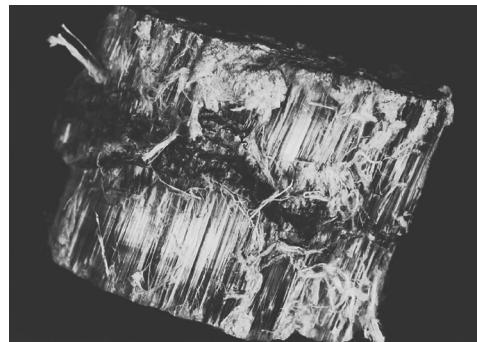
**PLATE 3.4** Fibrous anthophyllite from Gainesville, Georgia.



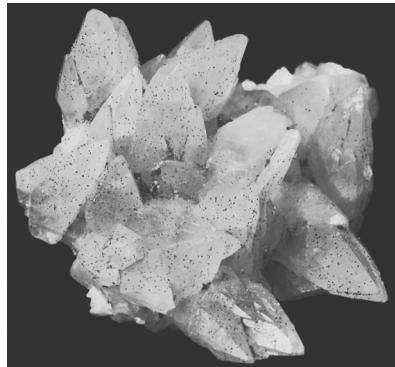
**PLATE 3.5** Green selenite, a variety of gypsum, from Mt. Gudson, South Australia.



**PLATE 3.6** Bladed blue kyanite from Minas Gerais, Brazil.



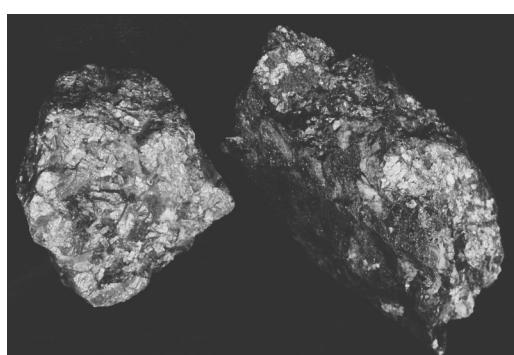
**PLATE 3.7** Chrysotile, the asbestosiform variety of serpentine, from Waldheim, Saxony.



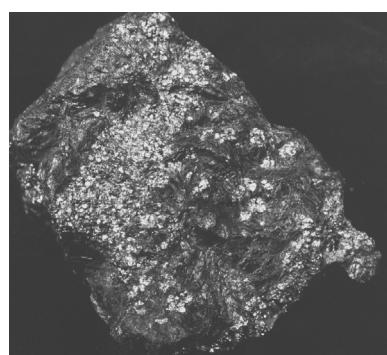
**PLATE 3.8** Calcite with drusy pyrite from the Campbell Mine, Red Lake, Ontario, Canada.



**PLATE 7.1** Acicular boulangerite from the Noche Buena Mine, Zacatecas, Mexico.



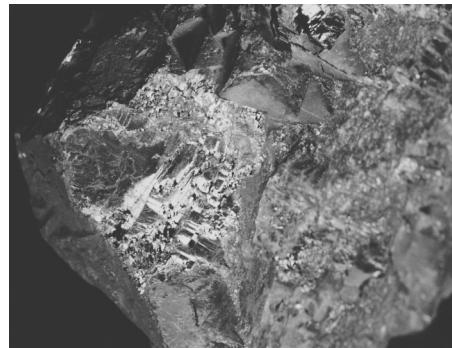
**PLATE 7.2** Arsenopyrite in a biotite schist from the Homestake Mine, Lead, South Dakota.



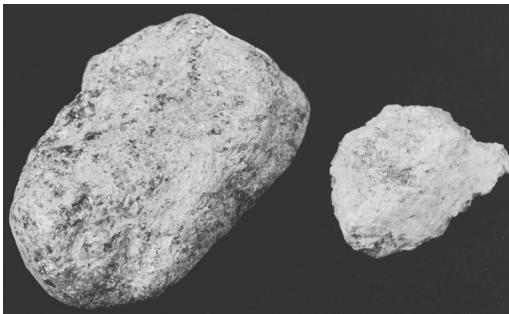
**PLATE 7.3** Covellite (purple tarnish) and pyrite (gold) from Sudbury, Ontario, Canada.



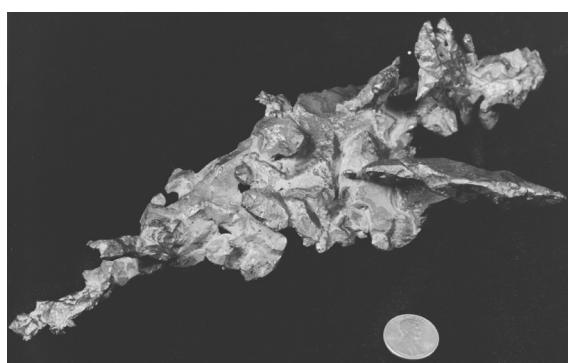
**PLATE 7.4** Sphalerite from Tennessee.



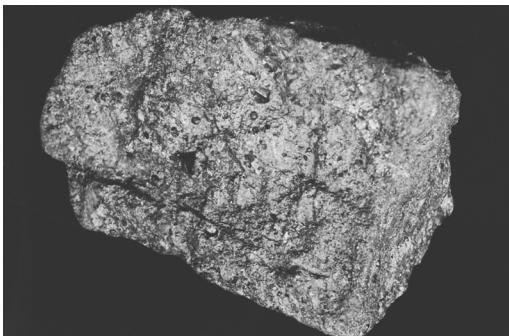
**PLATE 7.5** Galena in ore from Joplin, Missouri.



**PLATE 7.6** Orpiment (yellow) and realgar (orange-pink).



**PLATE 7.7** Native copper from the Keweenaw Peninsula, Michigan.



**PLATE 7.8** Chalcopyrite from Timmins, Ontario, Canada.



**PLATE 8.1** Pentlandite (silver) with minor pyrrhotite (yellow-gold) from Cobalt, Ontario, Canada.



**PLATE 8.2** Molybdenite in quartz.

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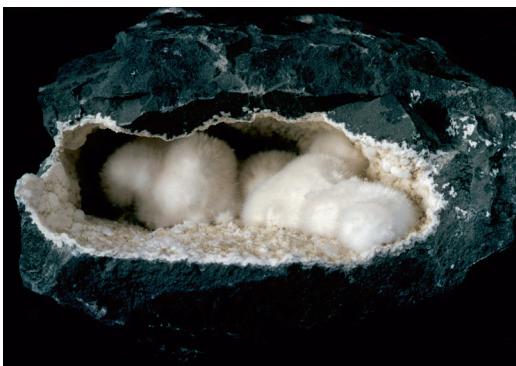
# Mineral Properties: Hand Specimen Mineralogy Color Plates



**PLATE 1.3** Pyrite crystals with pyritohedron form showing growth striations on faces.



**PLATE 1.6** Celestite from Lime City, Ohio.



**PLATE 1.7** Acicular okenite in a geode from Bombay, India.



**PLATE 1.8** Botryoidal purple smithsonite from Choix, Mexico.



**PLATE 2.1** Rutile needles in quartz from Brazil showing conchoidal fractures.



**PLATE 2.2** Rose quartz from Custer, South Dakota.



**PLATE 2.3** Amethyst, a purple variety of quartz.



**PLATE 2.4** Quartz showing play of colors and internal reflection due to internal fractures.



**PLATE 2.5** Brown quartz from California.



**PLATE 2.6** Clear quartz crystals from Hot Springs, Arkansas, showing growth striations.



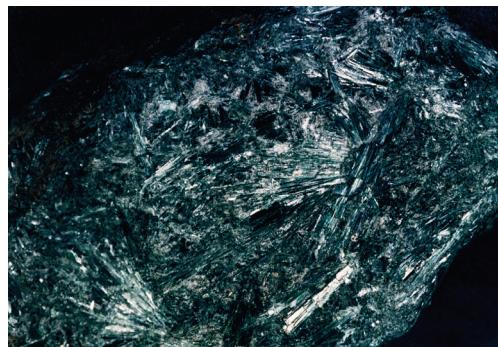
**PLATE 2.7** Prismatic quartz crystals on pyrite; sphalerite is the dark mineral behind the quartz crystals (sample from Huaron, Peru).



**PLATE 2.8** Herkimer diamonds (in reality, quartz crystals) from Herkimer, New York.



**PLATE 3.1** Pectolite from Patterson, New Jersey, showing radiating habit and scratch marks caused by students checking hardness.



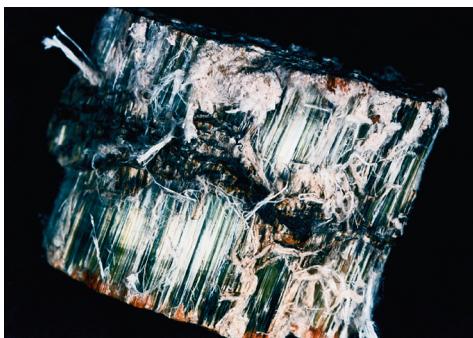
**PLATE 3.2** Actinolite from the Adirondack Mountains, New York, showing bladed habit.



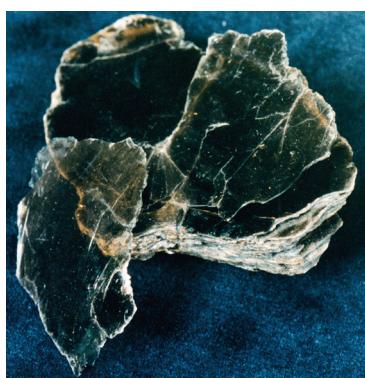
**PLATE 3.3** Prismatic crystals: beryl from Nigeria (left); rubellite, a pink variety of tourmaline, from San Diego County, California (center); green tourmaline from Minas Gerais, Brazil (right).



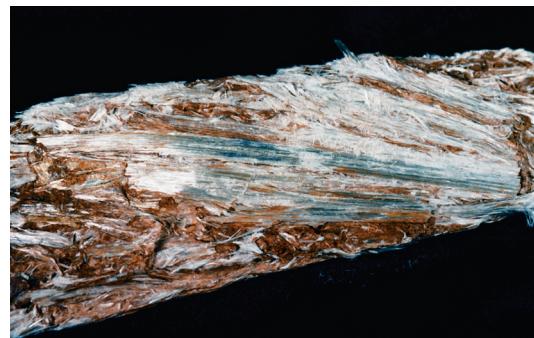
**PLATE 3.5** Green selenite, a variety of gypsum, from Mt. Gudson, South Australia.



**PLATE 3.7** Chrysotile, the asbestosiform variety of serpentine, from Waldheim, Saxony.



**PLATE 6.6** A book of biotite from Sioux Lookout, Ontario, Canada.



**PLATE 3.4** Fibrous anthophyllite from Gainesville, Georgia.



**PLATE 3.6** Bladed blue kyanite from Minas Gerais, Brazil.



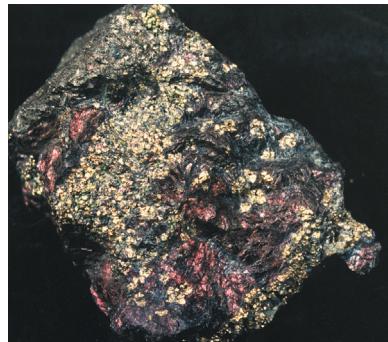
**PLATE 3.8** Calcite with drusy pyrite from the Campbell Mine, Red Lake, Ontario, Canada.



**PLATE 7.1** Acicular boulangerite from the Noche Buena Mine, Zacatecas, Mexico.



**PLATE 7.2** Arsenopyrite in a biotite schist from the Homestake Mine, Lead, South Dakota.



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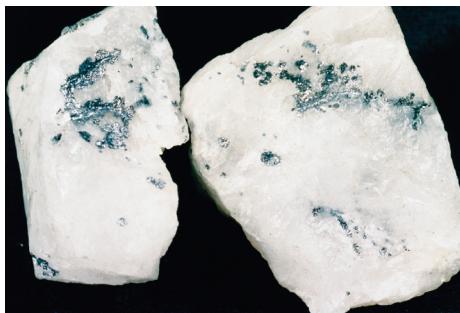
**PLATE 7.7** Native copper from the Keweenaw Peninsula, Michigan.



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**PLATE 8.1** Pentlandite (silver) with minor pyrrhotite (yellow-gold) from Cobalt, Ontario, Canada.



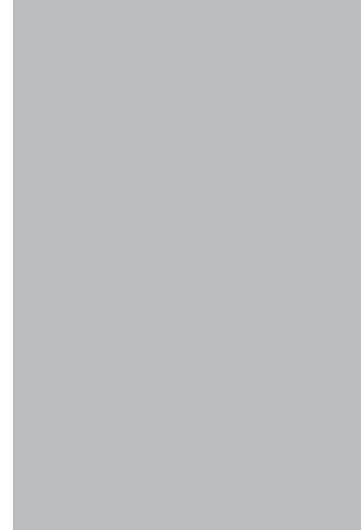
**PLATE 8.2** Molybdenite in quartz.



**PLATE 8.5** A collection of gem minerals. Back row, left to right: blue aquamarine (beryl), topaz, pink tourmaline; middle row: yellow beryl, blue-green tourmaline, red ruby (corundum); front row: emerald (beryl), kunzite (a variety of spodumene), yellow sapphire, blue sapphire.

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# Optical Mineralogy



# Optical Mineralogy

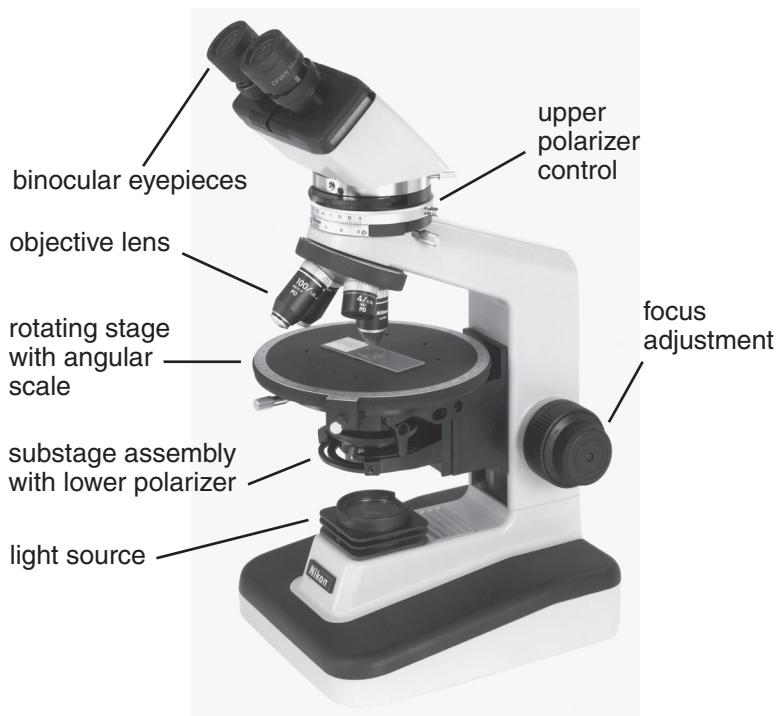
This chapter discusses the interaction of minerals and light, and the properties of minerals in thin section. It discusses the most practical aspects of *optical mineralogy*, which is the branch of mineralogy that deals with the optical properties of minerals.

A fundamental principle of optical mineralogy is that most minerals—even dark-colored minerals and others that appear opaque in hand specimens—transmit light if we slice them thinly enough. We use a *polarizing microscope* to examine them by **transmitted light microscopy** (Figure 1). We look at small mineral grains (powdered samples) or specially prepared thin sections (0.03-mm-thick specimens of minerals or rocks mounted on glass slides) to determine properties that are otherwise not discernible. Minerals with metallic luster and a few others are termed *opaque minerals*. They don't transmit light even if they are thin-section thickness. For these minerals, transmitted light microscopy is of no use. **Reflected light microscopy**, a related technique, can reveal some of the same properties. It is an important technique for economic geologists who deal with metallic ores but is not used by most mineralogists or petrologists, so we discuss it only briefly in this text.

Most minerals can be identified when examined with a polarizing microscope, even if unidentifiable in hand specimen. Optical properties also allow a mineralogist to estimate the composition of some minerals. For example, the magnesium-to-iron ratio of olivine,  $(\text{Mg},\text{Fe})_2\text{SiO}_4$ , can be distinguished based on optical properties. The composition of plagioclase feldspar,  $\text{CaAl}_2\text{Si}_2\text{O}_8 - \text{NaAlSi}_3\text{O}_8$ , can be similarly distinguished. Box 1 summarizes the

optical properties used for mineral identification and gives the properties of some common minerals. We divide minerals into those that will not transmit light unless the sections are much thinner than normal thin sections (*opaque minerals*) and those that will (*nonopaque minerals*). Nonopaque minerals are further divided into those that are **isotropic** (having the same properties in all directions) and those that are **anisotropic** (having different optical properties in different directions). Finally, the anisotropic minerals are divided according to whether they are **uniaxial** or **biaxial**, and according to whether they have a positive or negative **optic sign**. The details of these and other diagnostic properties will be discussed later.

Besides mineral identification, the polarizing microscope reveals important information about rock-forming processes (**petrogenesis**). When we use thin sections, distinguishing igneous, sedimentary, and metamorphic rocks is often easier than when we use hand specimens. More significantly, it is possible to identify minerals and distinguish among different types of igneous, sedimentary, and metamorphic rocks. The microscope allows us to see textural relationships in a specimen that give clues about when and how different minerals in the rock formed. Microscopic relationships between mineral grains allow us to determine the order in which minerals crystallized from magma, and we can identify minerals produced by alteration or



**FIGURE 1** A polarizing microscope with main features labeled. From Nikon, Inc., Melville, New York. Photo used with permission.

weathering long after magma cooling. Similar observations are possible for sedimentary or metamorphic rocks. Only the microscope can give us such information, information that is essential if rocks are to be used to interpret geological processes and environments.

## WHAT IS LIGHT?

### The Properties of Light

Before starting a discussion of optical mineralogy, it is helpful to take a closer look at light and its properties. Light is one form of **electromagnetic**

### BOX 1

#### Optical Classification of Minerals

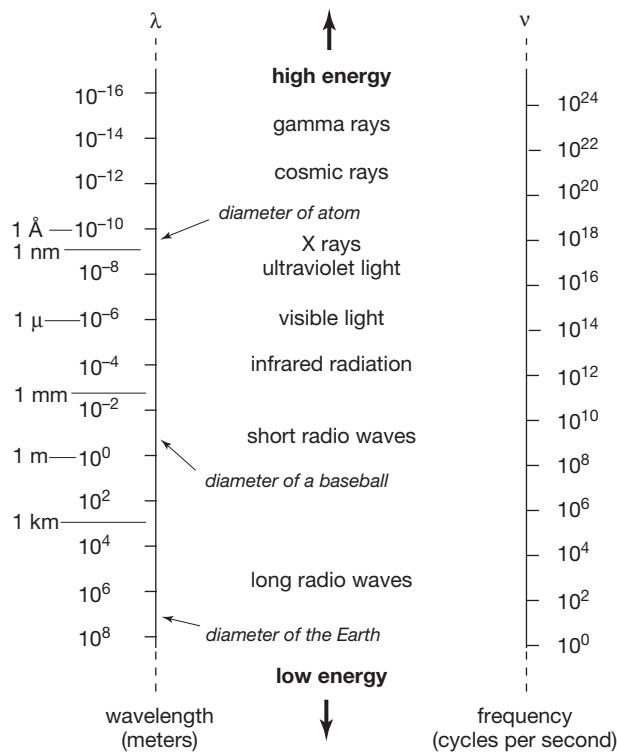
Mineralogists often classify minerals according to the mineral's optical properties. The table below shows the basic classification scheme and gives examples of minerals belonging to each of six categories. At the highest level, we divide minerals into two groups: opaque minerals and nonopaque minerals. We further divide the nonopaque minerals into those that are isotropic and anisotropic, and then we divide the anisotropic minerals by other properties discussed later—all of which can be determined using a polarizing microscope (see Box 2).

Opacity	Isotropy	Optic Class	Optic Sign	Examples of Common Minerals
opaque				→ gold, copper, pyrite, pyrrhotite, magnetite, ilmenite
nonopaque	{ isotropic	uniaxial	{ (+)	→ garnet, diamond, halite, fluorite, periclase, spinel
	{ anisotropic	biaxial	{ (-)	→ quartz, zircon, ice, brucite, rutile, leucite
			{ (+)	→ apatite, calcite, dolomite, beryl, tourmaline, corundum, nepheline
			{ (-)	→ enstatite, diopside, sillimanite, gypsum, plagioclase, barite
				→ K-feldspar, muscovite, hornblende, plagioclase, fayalite, epidote

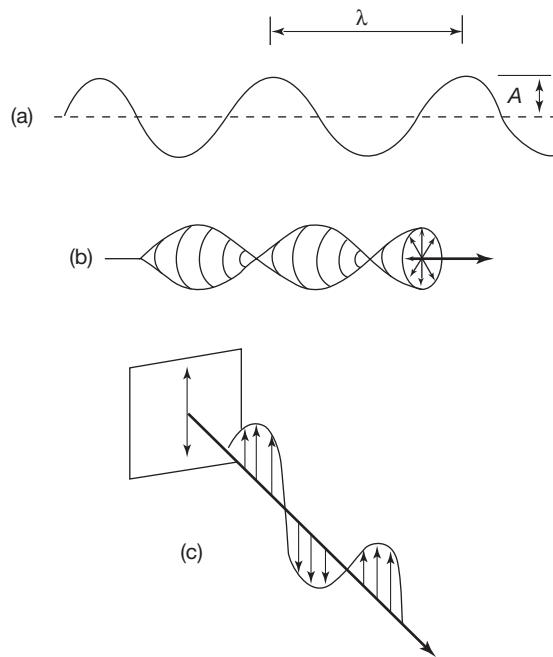
**radiation** (Figure 2). Radio waves, ultraviolet light, and X-rays are other forms of electromagnetic radiation. All consist of propagating (moving through space) electric and magnetic waves. The interactions between electric waves and crystals are normally much stronger than the interactions between magnetic waves and crystals (unless the crystals are metallic). Consequently, this text only discusses the electrical waves of light. In principle, however, much of the discussion applies to the magnetic waves as well. Light waves, like all electromagnetic radiation, are characterized by a particular wavelength,  $\lambda$ , a frequency,  $v$ , and a polarization state (Figure 3). The velocity,  $v$ , of the wave is the product of  $\lambda$  and  $v$ :

$$v = \lambda v \quad (1)$$

In a vacuum, the velocity of light is  $3 \times 10^8$  meters per second. Light velocity is slightly less when passing through air, and can be considerably less when passing through crystals. When the velocity of light is altered as it passes from one medium (for example, air) to another (perhaps a mineral), the wavelength changes, but the frequency remains the same.



**FIGURE 2** The electromagnetic spectrum. Visible light is a form of electromagnetic radiation with wavelengths and energies that fall in the middle of the spectrum.

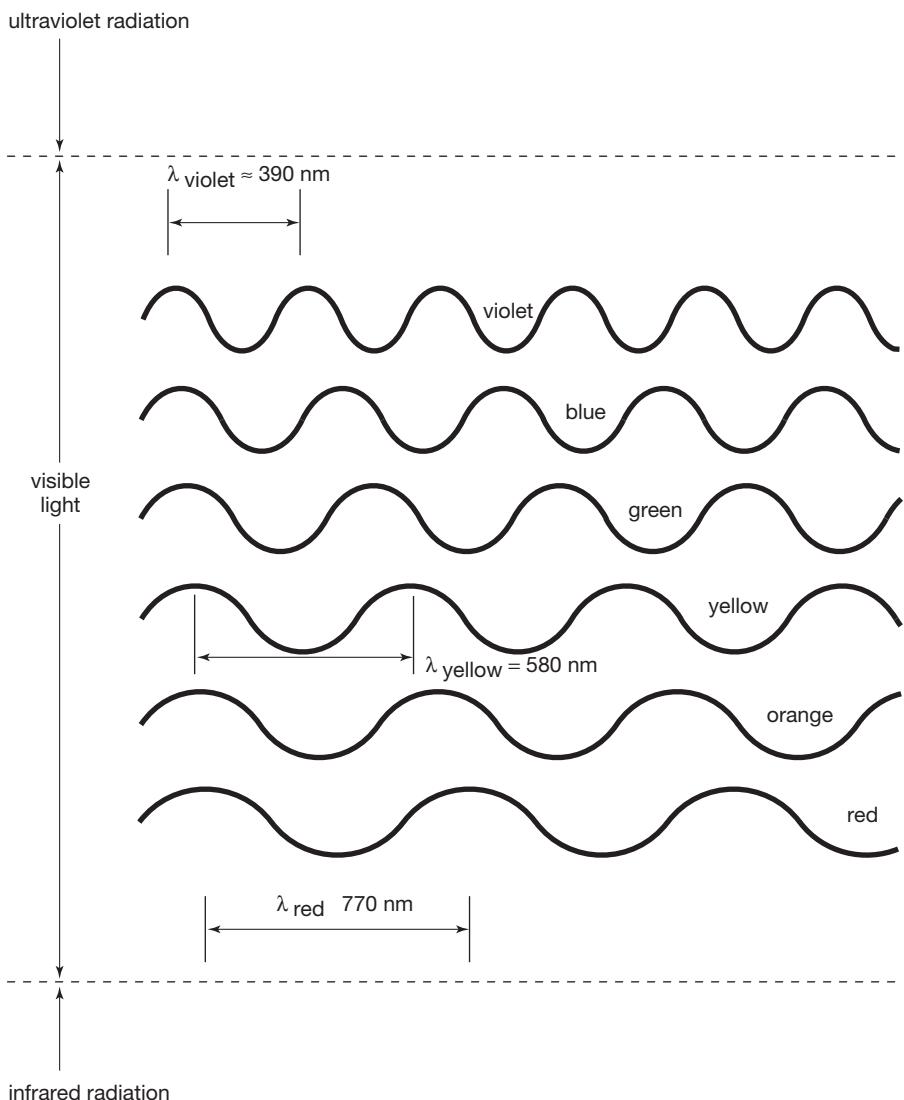


**FIGURE 3** Properties of light rays: (a) different colors of light are characterized by different wavelengths ( $\lambda$ ); the intensity of a wave is proportional to its amplitude ( $A$ ); (b) the electric vectors of unpolarized light (arrows) vibrate in all directions perpendicular to the direction of travel; (c) the electric vectors of plane polarized light are constrained to vibrate in a plane.

Visible light has wavelengths of 390 to 770 nm, which is equivalent to 3,900 to 7,700 Å, or  $10^{-6.1}$  to  $10^{-6.4}$  m ( $10^{-5.6}$  to  $10^{-5.9}$  ft.). Different wavelengths correspond to different colors of light (Figure 4). The shortest wavelengths, corresponding to violet light, grade into invisible ultraviolet radiation. The longest wavelengths, corresponding to red light, grade into invisible infrared radiation. Light composed of multiple wavelengths appears as one color to the human eye. If wavelengths corresponding to all the primary colors are present with nearly equal intensities, the light appears white. White light is **polychromatic** (many colored), containing a range, or spectrum, of wavelengths. Polychromatic light can be separated into different wavelengths in many ways. When one wavelength is isolated, the light is **monochromatic** (single colored).

### Interference

Besides wavelength ( $\lambda$ ) and frequency ( $v$ ) an amplitude and a phase characterize all waves. *Amplitude* ( $A$ ) refers to the height of a wave. *Phase* refers to whether a wave is moving up or down at a particular time. If two waves move up and down at the same time, they are *in phase*; if not, they are *out of phase*. When two waves interact, traveling in the same



**FIGURE 4** The wavelengths of visible light. The wavelength of violet light is about half that of red light. The boundaries between visible light and invisible radiation are not precisely defined, but visible light grades into ultraviolet radiation at short wavelengths and into infrared radiation at long wavelengths.

direction simultaneously, they interfere with each other. The nature of the interference depends on the relationships between their wavelengths, amplitudes, and phases. Light waves passing through crystals can have a variety of wavelengths, amplitudes, and phases that are affected by atomic structure in different ways. They yield interference phenomena, giving minerals distinctive optical properties.

In Figure 5a, two in-phase waves of the same wavelength are going in the same direction. If we could measure the intensity of the two waves together, we would find that it is about twice the intensity of each individual wave. When waves are in phase, no energy is lost; this is **constructive interference**. In contrast, Figure 5b shows two waves that are partially out of phase, and Figure 5c shows two waves that are completely out of phase. When waves are out of phase, wave peaks and valleys do not correspond. If they are completely out of phase, the peaks of one wave correspond to the valleys of the other.

Consequently, addition of out-of-phase waves can result in **destructive interference**, a condition in which the waves “consume” some or all of each other’s energy. For perfect constructive or destructive interference to occur, waves must be of the same wavelength. Interaction of waves with different wavelengths is more complicated.

## POLARIZATION OF LIGHT AND THE POLARIZING MICROSCOPE

### Polarized Light

The vibration motion of a light wave is perpendicular, or nearly perpendicular, to the direction it is propagating. In normal unpolarized beams of light, waves vibrate in many different directions, shown by arrows in Figure 3b. However, we can filter or alter a light beam to make all the waves vibrate in one direction parallel to a particular plane (shown by arrows in

**FIGURE 5** Waves in phase and out of phase, and the results when they combined: (a) waves are in phase if their peaks and wavelengths correspond, so they interfere constructively to produce one wave with greater amplitude; (b) when waves are partially in phase, their peaks do not exactly correspond; so combination results in some loss of energy; (c) when waves are completely out of phase, they interfere destructively, their motions cancel, and addition leads to complete energy loss.

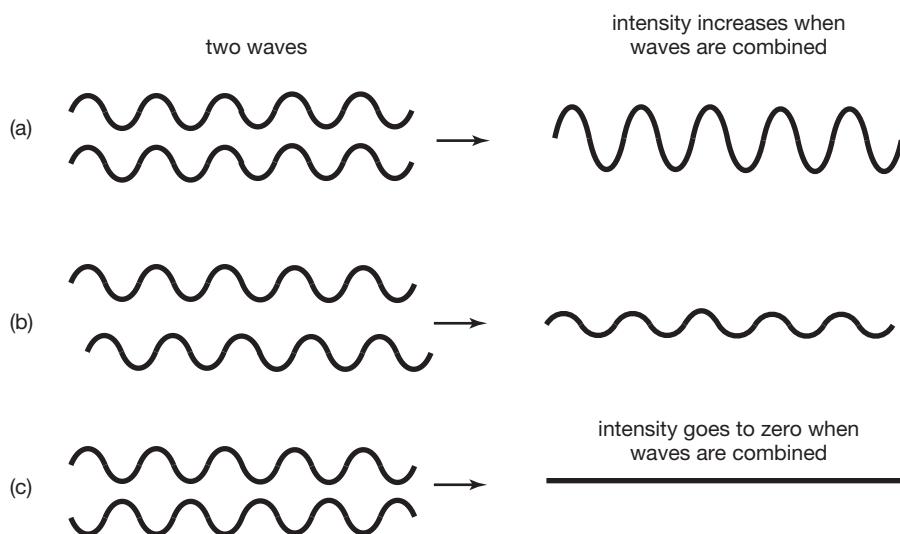


Figure 3c). The light is then **plane polarized**, sometimes called just *polarized*. Light becomes polarized in different ways. Reflection from a shiny surface can partially or completely polarize light because light vibrating in planes parallel to the reflecting surface is especially well reflected, while light vibrating in other directions is absorbed. This is why sunglasses with polarizing lenses help eliminate glare.

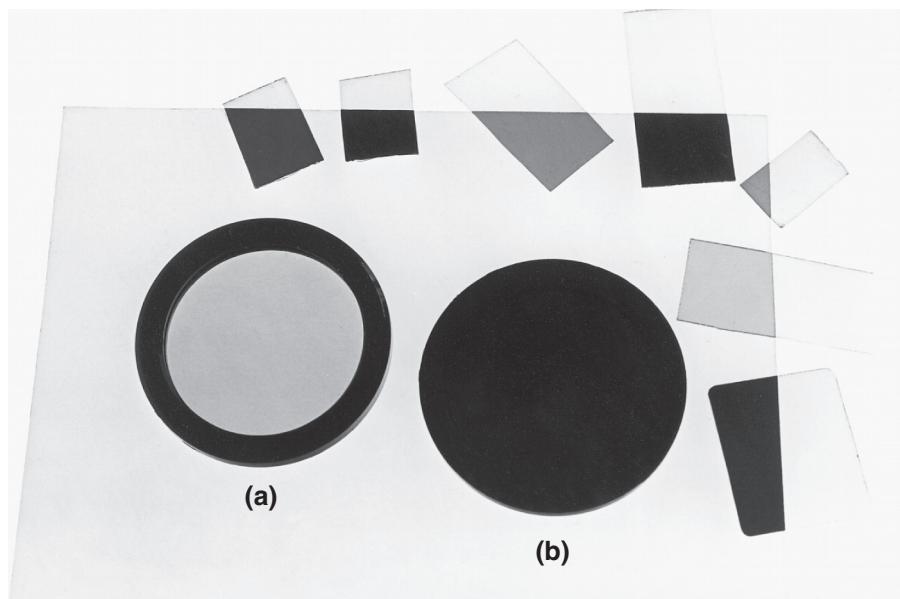
Suppose light passes through a polarizing filter that constrains it to vibrate in a north-south (up-down) direction. The polarized beam, although perhaps decreased in intensity, appears the same to our eyes because human eyes cannot determine whether light is polarized. If, however, another polarizing filter is in the path of the beam, we can easily determine that the beam is polarized (Figure 6). If the second filter allows only light

vibrating in a north-south direction to pass, the polarized beam will pass through it (Figure 6a). If we slowly rotate the second filter to an east-west direction, it will gradually transmit less light, and eventually no light (Figure 6b).

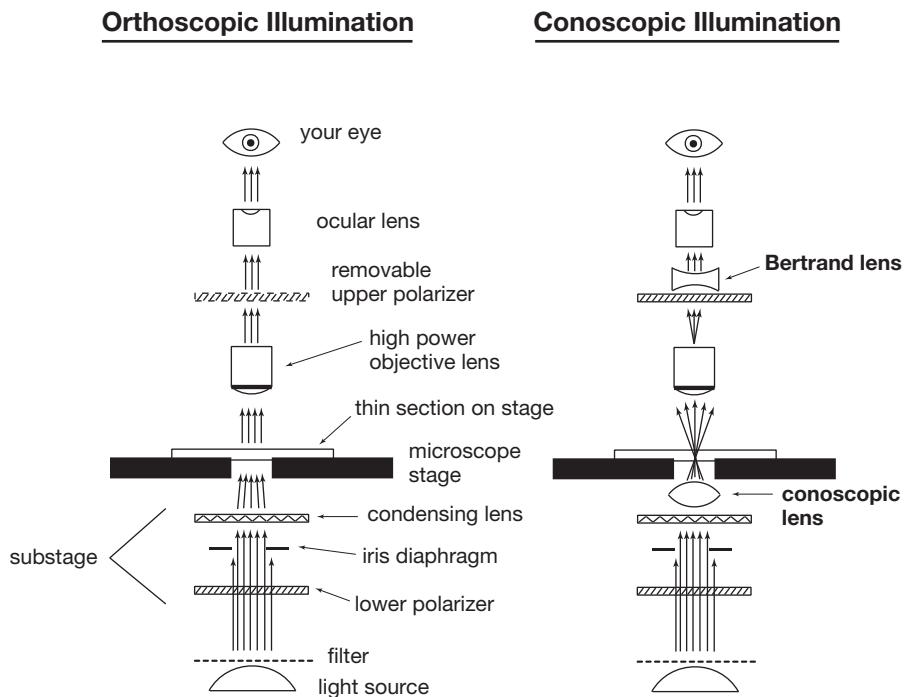
### Polarizing Microscopes

*Polarizing microscopes*, also called **petrographic microscopes**, are in many respects the same as other microscopes (Figures 1 and 7). They magnify small objects so we can see them in greater detail. A bulb provides a white light source. The light passes through several filters and diaphragms before it reaches the stage and interacts with the material being observed. One of the most important filters is the lower polarizer, which ensures that all

**FIGURE 6** Several small polarizing filters on top of a large polarizing sheet. The amount of light transmitted depends on the relative orientations of the polarization of the sheet and the small filter: (a) when polarization directions of the two are parallel, the maximum amount of light possible is transmitted; (b) when polarization directions are perpendicular, no light is transmitted. At other orientations, the two filters transmit intermediate amounts of light.



**FIGURE 7** The most important components of a polarizing microscope. For normal orthoscopic illumination, light from a bulb passes through a filter, the lower polarizer, a diaphragm, and a condensing lens in the substage before it hits the sample on the stage. Above the stage the objective and ocular lenses magnify and focus the light. The upper polarizer, Bertrand lens, and conoscopic lens are inserted to view a sample using conoscopic illumination. Conoscopic illumination has the same components as orthoscopic illumination with two additional lenses: a conoscopic lens below the stage and a Bertrand lens above the upper polarizer. In some microscopes, the conoscopic lens is permanently in place; for others it is necessary to insert it when needed.



light striking samples on the stage is plane polarized (vibrating, or having wave motion, in only one plane). The presence of a lower polarizer sets polarizing microscopes apart from others. In most modern polarizing microscopes, the lower polarizer only allows light vibrating in an east-west direction to reach the stage. Older microscopes, however, have the lower polarizer oriented in a north-south direction. A fixed condensing lens and a diaphragm in the substage help concentrate light on the sample. For most purposes, we use **orthoscopic illumination**, in which an unfocused beam travels from the substage through the sample and straight up the microscope tube. The light rays travel orthogonal to the stage and to a sample or thin section on the stage. However, we can insert a special lens—a *conoscopic lens*—between the lower polarizer and stage to produce *conoscopic illumination* when needed (Figure 7). The conoscopic lens, also called a **condenser lens**, causes the light beam to converge (focus) on a small spot on the sample and illuminates the sample with a cone of nonparallel rays.

We can rotate the microscope stage to change the orientation of the sample relative to the polarized light. Because most minerals are anisotropic, the interaction of the light with a mineral varies with stage rotation. A calibrated angular scale allows us to make precise measurements of crystal orientation. The scale is also useful for measuring angles between cleavages, crystal faces, and twin orientations, and for measuring other optical properties.

Above the stage, a rotating turret holds several **objective lenses**. They usually range in magnification from about  $2\times$  to  $5\times$ . Different objective lenses can have different **numerical apertures** (N.A.), a value that describes the angles at which light can enter a lens, which is an important consideration when making certain measurements. *In the discussion of interference figures. We have assumed that the objective lens being used has an N.A. of 0.85, since this is by far the most common today. If you use a lens with a different N.A., some of the given angular values may be in error.* The **ocular**, an additional lens usually providing  $8\times$  or  $10\times$  magnification, is in the eyepiece. Binocular microscopes, such as the one in Figure 1, have two eyepieces and two oculars. Oculars have crosshairs that aid in making angular measurements when we rotate the stage. The total magnification, which is the product of the objective lens magnification and the ocular magnification, varies from about  $16\times$  to  $500\times$ , depending on the lenses used.

We can insert several other filters and lenses between the objective lens and the ocular when needed (Figure 7). The **upper polarizer**, sometimes called the **analyzer**, is a polarizing filter oriented at  $90^\circ$  to the lower polarizer, which we can insert or remove from the path of the light beam. If no sample is on the stage, light that passes through the lower polarizer cannot pass through the upper polarizer. If a sample is on the stage, it usually changes the polarization of the light so that some can pass through the upper polarizer. We can also

insert an **accessory plate** above the upper polarizer. The most common kind of accessory plate used today is called a “full wave” plate. In the past, all full wave plates were made of gypsum and are still often referred to as “gypsum plates,” but today they are made of quartz. Above the accessory plate, most polarizing microscopes have a **Bertrand lens** and diaphragm. We use them with the **substage** conoscopic lens to view minerals in conoscopic illumination, allowing us to make some special kinds of measurements.

Petrologists and mineralogists use polarizing microscopes with or without the upper polarizer inserted (Box 2). Without the upper polarizer, we see the sample in **plane polarized light (PP light)**; with the upper polarizer, we see it in **crossed polars (XP light)**. Grain size, shape, color, cleavage, and other physical properties are best revealed in PP light. The optical properties refractive index and pleochroism are also determined using PP light. We use XP light, sometimes focused with conoscopic

and Bertrand lenses, to determine properties including retardation, optic sign, and  **$2V$** . These properties are discussed in detail later.

We examine minerals or rocks in **grain mounts** or in **thin sections** (Figure 8). For determining some mineral properties, a small amount of a powdered mineral sample is placed on a glass slide to produce a grain mount. The grains must be thin enough so that light can pass through them without a significant loss of intensity, usually 0.10 to 0.15 mm in longest dimension. A small amount of liquid (often referred to as a **refractive index oil**) surrounds them, and a thin piece of glass, called a cover slip, is placed over the grains and liquid. Grain mounts and refractive index oils are absolutely necessary for making some types of measurements. Petrologists use thin sections, however, for routine mineral identification and other petrographic work. For more information about studying minerals in grain mounts, see the optical mineralogy texts listed in the references at the end of this chapter.

## BOX 2

### Identifying Minerals and Mineral Properties with a Polarizing Microscope

You will often find diagnostic properties or shortcuts that help speed mineral identification, but the process below covers all the key properties. You may wish to look at a number of different grains, and you should get used to changing back and forth between plane polarized (PP) and crossed polarized (XP) light. For routine mineral identification, it is often unnecessary to obtain an interference figure and identification can be quite rapid.

#### **Look at the whole thin section (and at a hand specimen if available):**

If you are looking at a thin section of a rock: What kind of rock is it?

How many different major minerals does it contain?

What are the associated minerals?

#### **Examine several grains of the same mineral under PP light:**

Is the mineral opaque or nonopaque?

What color is the mineral? Rotate the stage. Is it pleochroic? What is the color variation?

What is the crystal shape and habit?

What cleavage does it display, if any?

What is its apparent relief?

#### **Now cross the polars to examine several grains of the mineral under XP light:**

Rotate the stage. Is it isotropic or anisotropic?

#### **If anisotropic:**

Rotate the stage. What is the range of interference colors? Estimate the maximum birefringence by looking at grains with the highest order of interference colors.

For minerals with a long dimension of principal cleavage: What is the maximum extinction angle? Is it length fast or length slow?

Is the mineral twinned? If so, what kinds of twins?

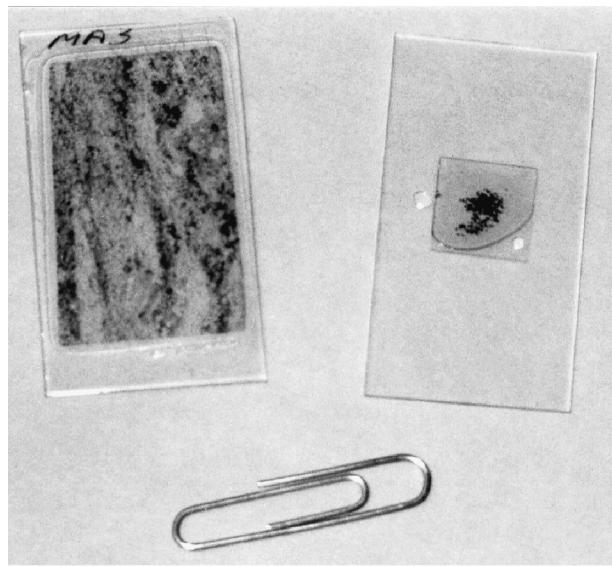
#### **If necessary, obtain an interference figure. You may have to try several different grains to get one that is useful:**

Is the mineral uniaxial or biaxial?

What is its optic sign?

#### **If biaxial:**

Estimate  $2V$ .



**FIGURE 8** Thin section and grain mount.

### Colors in Plane Polarized (PP) Light and Crossed Polarized (XP) Light

In hand specimens, many minerals appear strongly colored, but minerals viewed with a microscope using PP light generally display a weak color or appear colorless. Many minerals in thin section or in grain mount are not thick enough to significantly absorb or enhance specific wavelengths of light. If minerals do appear colored, the color may change when we rotate the microscope stage because rotating the stage changes the orientation of the mineral's crystal structure with respect to the polarized light. Some minerals absorb different wavelengths of light depending on light vibration direction. We call this property **pleochroism**. Biotite is an example of a mineral that normally displays marked pleochroism (Plates 5.3 and 5.4).

Pleochroism is an especially useful diagnostic property when identifying some minerals, but it can be overlooked. In thin sections, orthopyroxenes are commonly colorless, but some show a faint pleochroism from pink to green. Pleochroism of pyroxenes is an important property because it distinguishes the two major pyroxene subgroups: orthopyroxene and clinopyroxene. For minerals with noticeable pleochroism, reference tables describe the property by listing colors seen when looking at the mineral in different directions. For pleochroic uniaxial minerals, color varies between two hues. For biaxial minerals, color varies between three hues.

In contrast with pyroxenes, many amphiboles display strong colors and a very noticeable pleochroism in thin section. The biaxial mineral glaucophane (an amphibole) has pleochroism described by its *pleochroic formula*:

X = colorless or pale blue

Y = lavender-blue or bluish green

Z = blue, greenish blue, or violet

X, Y, and Z refer to light vibrating parallel to each of three mutually perpendicular vibration directions in the crystal. In thin sections, glaucophane's colors vary within the limits described for X, Y, and Z, depending on the crystal orientation, as we rotate the microscope stage. The biotite in Plates 5.3 and 5.4 is pleochroic in green and brown, but the standard pleochroic formula for biotite might be:

X = colorless, light tan, pale greenish brown, or pale green

Y  $\cong$  Z = brown, olive brown, dark green, or dark red-brown

When we insert the upper polarizer, we see minerals in crossed polarized (XP) light, and we may see colors that are brighter and more pronounced than when we view the same grain in PP light. These are **interference colors**. They do not result from absorption of different wavelengths by the mineral (which is how minerals get their normal color). Instead, they result from the interference of light rays passing through the upper polarizer. They rarely resemble the true color of the mineral. Interference colors depend on grain orientation, so different grains of the same mineral in one thin section normally display a range of interference colors. Because different minerals can display different ranges of interference colors, interference colors are useful for mineral identification. Interference colors also vary with the thickness of the grains, so it is important that thin sections be of uniform thickness. Additionally, the edges of some grains, grains near the edge of a thin section, or grains adjacent to holes in a thin section (places where the sample is thin), may display abnormal interference colors.

### THE VELOCITY OF LIGHT IN CRYSTALS AND THE REFRACTIVE INDEX

When electromagnetic radiation passes near an atom, the electric wave causes electrons to oscillate. The oscillations absorb energy from the light, and the wave slows down. A wave's velocity through a crystal is described by the crystal's refractive index ( $n$ ), which depends on chemical composition, crystal structure, and bond type in the crystal. The refractive

index ( $n$ ) is the ratio of the velocity (v) of light in a vacuum to the velocity in the crystal:

$$n = v_{\text{vacuum}}/v_{\text{crystal}} \quad (2)$$

Because light passes through a vacuum faster than through any other medium,  $n$  always has a value greater than 1. High values of  $n$  correspond to materials that transmit light slowly. Under normal conditions, the refractive index of air is 1.00029. Because it is much easier to work with air than with a vacuum, this is a common reference value.

As light passes from air into most nonopaque minerals, its velocity decreases by a third or a half. Because the frequency of the light remains unchanged, we know that the wavelength must decrease by a similar fraction (Equation 1). Most minerals have refractive indices between 1.5 and 2.0. Fluorite, borax, and sodalite are examples of minerals that have a very low (<1.5) index of refraction. At the other extreme, zincite, diamond, and rutile have very high indices (>2.0). The refractive index is one of the most useful properties for identifying minerals in grains mounts but is less valuable when we examine minerals in thin sections.

The refractive index of most materials varies with the wavelength of light. In other words, the velocity of light in a crystal varies with the light's color. This property, called **dispersion**, is a property of minerals that can sometimes be seen in thin sections but is not discussed in detail in this text. An excellent but nonmineralogical example of dispersion is the separation of white light into colored "rainbows" when refracted by a glass prism. When a beam of white light enters a prism, different wavelengths (colors) are refracted at different angles, resulting in the production of the "rainbow." For a mineralogical example, we may consider diamond. Diamond's extreme dispersion accounts, in part, for the play of colors ("fire") that diamonds display. Minerals with low dispersion, such as fluorite, appear dull no matter how well cut or faceted. They may, however, be useful as lenses when dispersion causes unwanted effects.

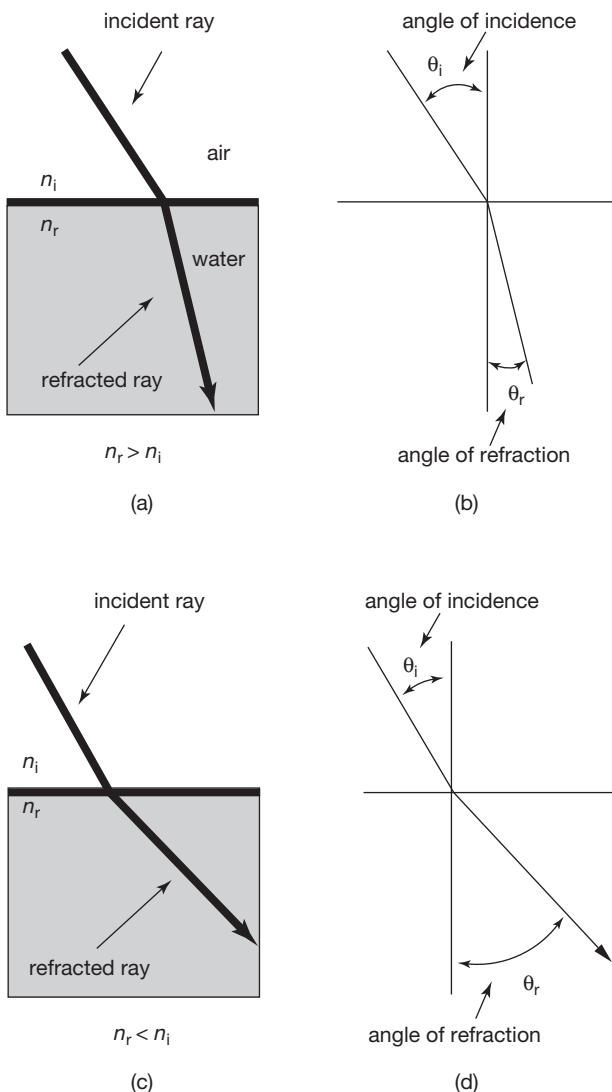
A mineral's refractive index and dispersion profoundly affect its *luster*. Minerals with a very high refractive index and dispersion, such as diamond or cuprite, appear to sparkle and are termed *adamantine*. Minerals with a moderate refractive index, such as spinel and garnet ( $n = 1.5 - 1.8$ ), may appear vitreous (glassy) or shiny; those with a low refractive index, such as borax, will appear drab because they do not reflect or refract as much incident light. Refractive index depends on many things, but a high  $n$  value suggests minerals composed of atoms with high atomic numbers, or of atoms packed closely together.

Most minerals are anisotropic, so their refractive index varies with direction. In contrast, a glass, such as window glass or obsidian, is isotropic because it has a random atomic structure. Randomness means that, on the average, the structure and refractive index are the same in all directions. Isotropic minerals are relatively easy to spot in thin sections. When viewed with a polarizing microscope and XP light, they remain **extinct**, appearing black as the stage rotates, no matter what their orientation is on the microscope stage. There are few common isotropic minerals, but the most common are garnet, sphalerite, and fluorite. Sometimes thin sections contain holes, places with no mineral and only epoxy. They appear isotropic and can occasionally be mistaken for isotropic minerals. Usually we can tell isotropic minerals apart by looking at color, relief, habit, and cleavage.

Anisotropic minerals normally do not appear extinct under XP light, but as the microscope stage rotates, they go extinct briefly every 90°. However, if we orient an anisotropic crystal so that light passes through it parallel to a special direction called an **optic axis**, it will appear isotropic. It remains extinct when we rotate the stage. Fortunately, the number of optic axes in anisotropic minerals is limited to one (uniaxial minerals) or two (biaxial minerals); the odds of the optic axis being exactly parallel to the light beam are small, and confusing isotropic and anisotropic minerals is rarely a problem. When in doubt, we can distinguish them using conoscopic illumination because anisotropic minerals will transmit some conoscopic light and display interference figures (discussed later), while isotropic minerals do not.

### Snell's Law and Light Refraction

We have all seen objects that appear to bend as they pass from air into water. A straw in a glass of soda, or an oar in the water, seem bent when we know they are not. We call this phenomenon **refraction**. Refraction occurs when a beam of light passes from one medium to another with a different refractive index (Figure 9). If the light strikes the interface at an angle other than 90°, it changes direction. Consider a beam traveling from air into water (Figure 9a and b). The side of the beam that reaches the interface first will be slowed as it enters the water. The beam bends toward the water, the medium with a higher refractive index, because one side of the beam moves faster than the other. Figures 9c and d show the opposite case: a beam traveling from a medium with a high refractive index to another with a lower refractive index. The beam refracts toward the medium with a higher index, as in Figure 9a. A beam traveling at 90° to an interface, whether from a medium with a high refractive index to a low or vice versa, is not refracted at all.



**FIGURE 9** Refraction of a beam of light: (a) a light ray is bent as it crosses the boundary from air into water (or from any medium to another with higher refractive index); (b) the geometry of refraction shown in (a); (c) a light ray is bent as it crosses the boundary from one medium to another with a lower refractive index; (d) the geometry of refraction shown in (c).

The angle between the incoming beam and a perpendicular to the interface is the **angle of incidence** ( $\theta_i$ ). The angle between the outgoing beam and a perpendicular to the interface is the **angle of refraction** ( $\theta_r$ ). The relationship between the angle of incidence ( $\theta_i$ ) and the angle of refraction ( $\theta_r$ ) is

$$\sin \theta_i / \sin \theta_r = v_i / v_r = n_r / n_i \quad (3)$$

where  $v_i$  and  $v_r$  are the velocities of light through two media, and  $n_r$  and  $n_i$  are the indices of refraction of the two media. This relationship, **Snell's Law**, is named after Willebrod Snell, the Dutch scientist who first derived it in 1621.

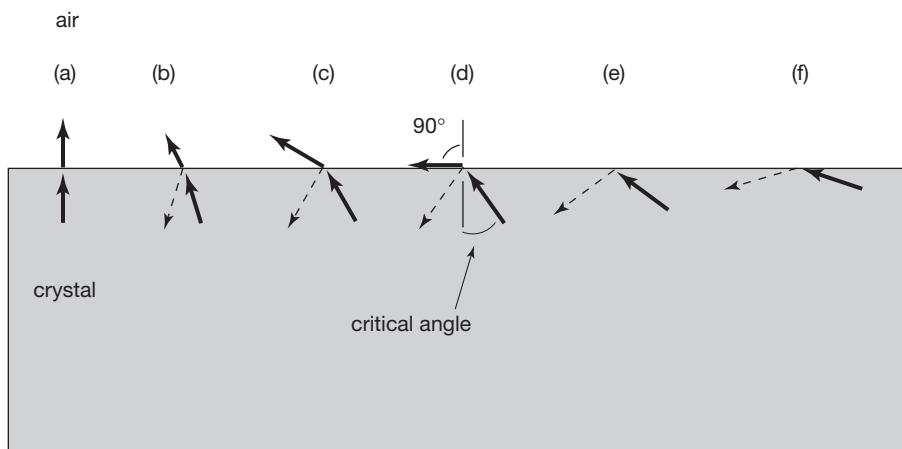
Rearranging Snell's Law tells us that we can calculate the angle of refraction:

$$\theta_r = \sin^{-1}[n_i/n_r \times \sin \theta_i] \quad (4)$$

By definition, sine values can never be greater than 1.0. Suppose a light beam is traveling from a crystal into air. In this case,  $n_i > n_r$ , and because the term in square brackets on the right-hand side of Equation 4 must be less than or equal to 1.0, for some large values of  $\theta_i$  there is no solution. The limiting value of  $\theta_i$  is the **critical angle** of refraction. If the angle of incidence is greater, none of the light will escape; the entire beam will be reflected inside the crystal (Figure 10). This is the reason crystals with a high refractive index, such as diamond, exhibit internal reflection that gives them a sparkling appearance. Measuring the critical angle of refraction is a common method for determining refractive index of a mineral. Instruments called **refractometers** simplify such measurements.

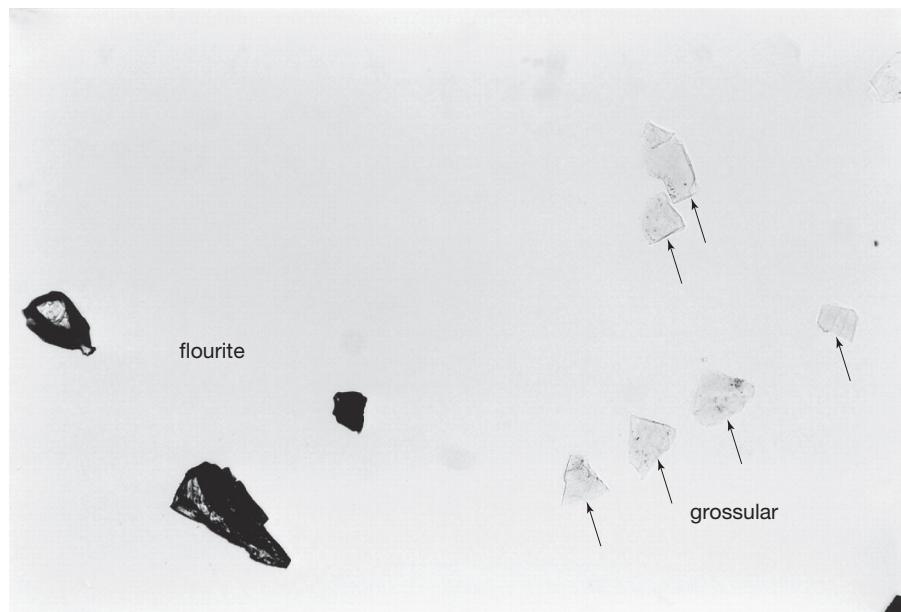
### Relief and Beke Lines

If we immerse an isotropic mineral grain in a liquid with the same refractive index, we will have difficulty seeing it unless it is one of the few minerals



**FIGURE 10** Refraction and reflection of a beam of light passing from a crystal into air for various angles of incidence. The solid rays show the incident and refracted beams; the dashed rays are the reflected beams. In (a), (b), and (c), the angle of incidence is less than the critical angle, so a refracted beam escapes the crystal. In (e) and (f), the angle of incidence is greater than the critical angle, so all the light is reflected back into the crystal.

**FIGURE 11** Minerals appear to have high relief when in a liquid if their index of refraction differs greatly from that of the liquid. Minerals have low relief, and may nearly disappear, if the mineral and the liquid have similar indices of refraction. This figure shows grossular (low relief,  $n = 1.750$ ) and fluorite (high relief,  $n = 1.430$ ) in a liquid with  $n = 1.720$ . The grossular (arrows) is very difficult to see because its index of refraction is almost the same as the surrounding liquid.



with very strong coloration. The edges of the mineral grain will not stand out. However, if a grain has an index of refraction that is significantly different from the liquid, light refracts and reflects at the edges of the grains. As the difference between the index of the liquid and the mineral increases, the boundary between the two becomes more pronounced (Plate 4.1). The term **relief** describes the contrast between the mineral and its surroundings (in this case, liquid). Grains with low relief are barely visible, while those with high relief stand out clearly (Figure 11; Plates 4.1 and 4.2).

Minerals in thin sections also show relief. The relief depends on the difference in the indices of refraction of the mineral and the material (today usually a special type of epoxy) in which it is mounted. As the difference in indices increases, relief becomes more noticeable. Minerals with high refractive indices show high ("positive") relief because their index of refraction is *greater* than that of the epoxy. They also tend to show structural flaws, such as scratches, cracks, or pits, more than those with low refractive indices. Some minerals (fluorite, for example) with very low refractive indices also show high relief (termed "negative" relief) because their index of refraction is *lower* than that of the epoxy. We do not differentiate between positive and negative relief for most purposes, we need only to know whether a mineral displays high, medium, or low relief. A few minerals (such as calcite) display variable relief with stage rotation; variable relief is a useful diagnostic property. We can see relief with either a monocular or a binocular microscope, but more easily with the latter.

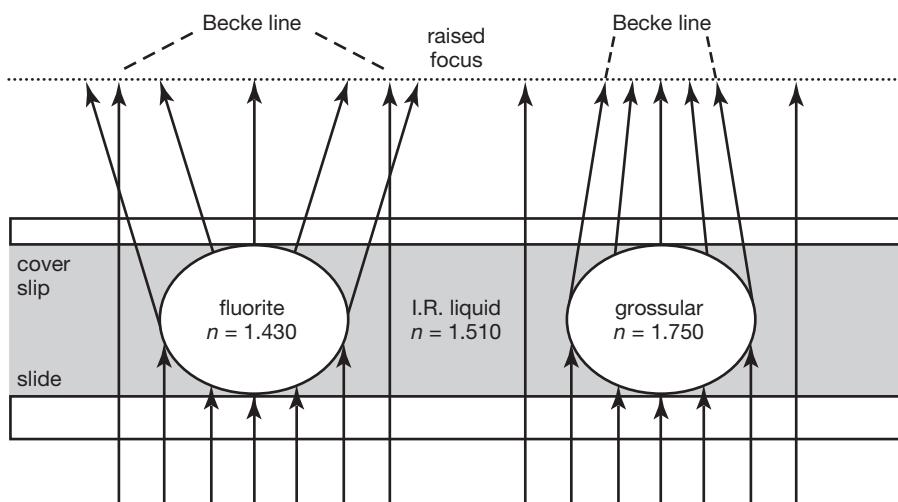
As pointed out before, when we immerse a grain in liquid, some light rays bend toward the medium with the refractive higher index. Other light rays are completely reflected because they hit the mineral-liquid interface at an angle greater than the critical angle of refraction. The light interacts with the grain as if it were a small lens (Figure 12). If  $n_{\text{mineral}} > n_{\text{liquid}}$ , light rays are refracted and converge after passing through the grain. If  $n_{\text{mineral}} < n_{\text{liquid}}$ , light rays are refracted and diverge after passing through the grain. If we slowly lower the microscope stage, shifting the focus to a point above the mineral grain, a bright narrow band of light called a **Becke line** appears at the interface and moves toward the material with higher refractive index (Figure 12 and Plate 4.3). A complementary but more difficult to see dark band moves toward the material with lower refractive index. Although not as straightforward, we can also use Becke lines to compare the relief of minerals in thin sections by purposely focusing and defocusing the microscope while we examine a grain boundary. We also compare relief by noting how well a mineral appears to stand out above another.

## INTERACTION OF LIGHT AND CRYSTALS

### Double Refraction

In most modern polarizing microscopes, polarized light leaves the lower polarizer vibrating in the east-west direction. If it encounters an isotropic mineral on the stage, it slows as it passes through the mineral, but is still east-west polarized when it emerges. Upon entering an anisotropic crystal,

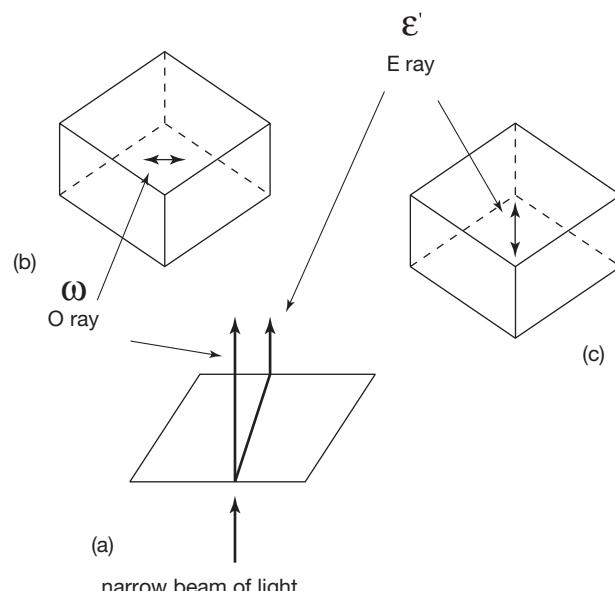
**FIGURE 12** Mineral grains behave like lenses when immersed in a liquid of a different index of refraction, causing light to converge or diverge. In this figure, the fluorite grains (left) cause light to diverge and the grossular grains (right) cause light to converge because  $n_{\text{fluorite}} < n_{\text{liquid}} < n_{\text{grossular}}$ . Consequently, if the microscope stage is lowered so the focus is raised to a plane above the grains, narrow, bright Becke lines move out into the liquid from the fluorite-liquid boundary, and in toward the center of the grain from the grossular-liquid boundary. When the stage is lowered, Becke lines always move toward the crystal or liquid with the greater index of refraction.



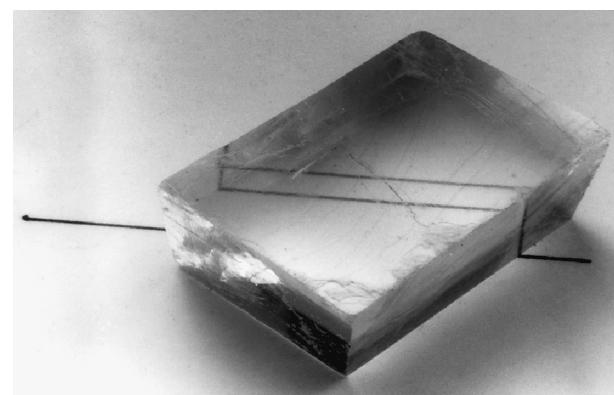
however, light is normally split into two polarized rays, each traveling through the crystal along a slightly different path with a slightly different velocity and refractive index (Figure 13a). For uniaxial minerals, we call the two rays the **ordinary ray (O ray)**, symbolized by  $\omega$ , and the **extraordinary ray (E ray)**, symbolized by  $\epsilon'$ . The O ray travels a path predicted by Snell's Law, while the E ray does not. The directions of the O-ray and E-ray vibrations depend on the direction the light is traveling

through the crystal structure, but the vibration directions of the two rays are always perpendicular to each other (Figure 13b and c).

We call the splitting of a light beam into two perpendicularly polarized rays **double refraction**. All randomly oriented anisotropic minerals cause double refraction. We can easily observe it by placing clear calcite over a piece of paper on which a line, dot, or other image has been drawn (Figure 14). Two images appear, one corresponding to each of the two rays. A thin piece of polarizing film placed over the calcite crystal would verify that the two rays are polarized and vibrating perpendicular to each other. If we rotate either the film or the crystal, every 90° one ray becomes extinct, and we will see only one image. Calcite is one of the few common minerals that exhibit double refraction easily seen without a microscope, but even minerals that exhibit subtler double refraction can be tested using polarizing filters. Gemologists use this technique to tell gems from



**FIGURE 13** Splitting of polarized light into an ordinary (O) ray and an extraordinary (E) ray by calcite: (a) a side view showing that the paths of the two rays are different; (b) the O ray vibrates parallel to the long axis of the calcite rhomb; (c) the E ray vibrates perpendicular to the long axis of the calcite rhomb.



**FIGURE 14** Calcite crystal showing double refraction.

imitations made of glass. Glass, like all isotropic substances, does not exhibit double refraction.

As the two rays pass through an anisotropic crystal, they travel at different velocities unless they are traveling parallel to an optic axis. We call the two rays the **slow ray** and the **fast ray**. Because the rays travel at different velocities, their refractive indices must be different. The difference in the indices of the fast ray and the slow ray ( $n_{\text{slow}} - n_{\text{fast}}$ ) is the apparent **birefringence** ( $\delta'$ ). It varies depending on the direction light is traveling through the crystal and ranges from zero to some maximum value ( $\delta$ ) determined by the crystal structure. The maximum birefringence ( $\delta$ ) is a diagnostic property of minerals.

When the slow ray emerges from an anisotropic crystal, the fast ray has already emerged and traveled some distance. This distance is the **retardation**,  $\Delta$ . Retardation is proportional to both the thickness ( $t$ ) of the crystal and to the birefringence in the direction the light is traveling ( $\delta'$ ):

$$\Delta = t \times \delta' = t \times (n_s - n_f) \quad (5)$$

The birefringence and retardation of isotropic crystals are always zero. No double refraction occurs, and all light passes through isotropic crystals with the same velocity because the refractive index is equal in all directions. Most anisotropic minerals have birefringence between 0.01 and 0.20. Interference colors are a function of birefringence.

### Crystals Between Crossed Polars

When viewed with the upper polarizer in place (under crossed polar (XP) light), we can differentiate isotropic and anisotropic crystals. Suppose we are viewing an isotropic crystal using XP light. It will remain dark through  $360^\circ$  of stage rotation. This is because the light emerging from the mineral retains the polarization it had on entering and will always be east-west polarized. It cannot pass through the upper polarizer, oriented at  $90^\circ$  to the lower polarizer. The effect is the same as if no mineral were on the stage.

When we view an anisotropic crystal with XP light, light is split into two rays unless we are looking down an optic axis. The two rays, after emerging from the crystal, travel on to the upper polarizer where they are resolved into one ray with north-south polarization. Because the vibration directions of both the rays are normally not perpendicular to the upper polarizer, components of both pass through the upper polarizer and combine to produce the light reaching our eye. As we rotate the microscope stage, however, the relative intensities of the

two rays emerging from the crystal vary. Every  $90^\circ$ , the intensity of one is zero, and the other is vibrating perpendicular to the upper polarizer. Consequently, no light passes through the upper polarizer and the crystal appears extinct every  $90^\circ$ .

If we used a monochromatic light (one wavelength) source in our microscope and looked at an anisotropic crystal under XP light, it would go from light to complete darkness as we rotate the stage. Extinction would occur every  $90^\circ$ , and maximum brightness would be at  $45^\circ$  to the extinction positions. However, most polarizing microscopes use polychromatic light. Because of dispersion, double refraction is slightly different for different wavelengths. Minerals with high dispersion may never appear completely dark, but most come close.

### Interference Colors

When white light passes through an anisotropic mineral, all wavelengths are split into two polarized rays vibrating at  $90^\circ$  to each other. Different colors have different wavelengths, so when the rays leave the crystal, some colors may be retarded an even number of wavelengths, but most will not. Consequently, when the north-south components of the two rays are combined at the upper polarizer, constructive interference occurs for some colors, and destructive interference for others. If we look at a mineral of uniform thickness under XP light, we see one color, the **interference color**. Interference colors depend on the retardation of different wavelengths, which in turn depends on the orientation, birefringence, and thickness of a crystal. Interference colors change intensity and hue as we rotate the stage; they disappear every  $90^\circ$ , when the mineral goes extinct.

Normal interference colors are shown in a *Michel-Lévy Color Chart* (see Plate 4.11). Very low-order interference colors, corresponding to a retardation of less than 200 nm, are gray and white. The interference color of a mineral with very low birefringence, then, changes from white (or gray) to black every  $90^\circ$  as we rotate the microscope stage. For minerals with slightly greater birefringence, yellow, orange, or red interference colors will appear when we rotate the stage. These colors, corresponding to retardation of 200 nm to 550 nm, are called *first-order* colors. As retardation increases further, colors repeat every 550 nm. They go from violet to red (*second order*) and then from violet to red again (*third order*). They become more pastel (washed out) in appearance as order increases. Fourth-order colors are often so weak that they appear “pearl” white and may occasionally be confused with first-order white. When describing an

interference color, it is important to state both the color and the order; for mineral identification, the order is often more important than the color. The difference in retardation between “orders” is 550 nm, the average wavelength of visible light.

Plates 5.1 and 5.2 show calcite ( $\delta = 0.172$ ) viewed under crossed polars; the interference colors are pastels of high order. In contrast, Plate 5.8 shows plagioclase ( $\delta = 0.011$ ) with first-order gray and white interference colors. Other minerals in Plates 5.6 and 5.8 show interference colors between those of plagioclase and calcite. The interference colors in Plates 5.6 and 5.8 can be compared with the actual colors of the mineral grains viewed under PP light (Plates 5.5 and 5.7).

Interference colors are often a key property for identifying minerals in thin section. Minerals with very low birefringence that display first-order white, gray, or yellow interference colors in thin section include leucite, nepheline, apatite, beryl, quartz, and feldspar. At the other extreme, minerals such as titanite (sphene), calcite, dolomite, and rutile display extreme retardation; interference colors are light pastels of high order. They may have such weak colors that it is hard to determine the retardation and birefringence with certainty.

Anisotropic minerals have different refractive indices depending on the path light travels when passing through them. Their optical properties, including birefringence, and thus interference colors, depend on their orientation. For identification purposes, the maximum birefringence ( $\delta$ ), corresponding to the highest-order interference colors, is diagnostic. This may be hard to estimate in grain mounts because mineral thickness varies, making it difficult or impossible to estimate birefringence from interference colors. In thin sections, the task is easier because thickness is known (0.03 mm), so we can use the Michel-Lévy Chart to determine birefringence from interference color. Randomly oriented mineral grains may not show maximum interference colors; often we must rotate the stage and look at many grains of the same mineral. Because it is difficult to be exact, we normally use qualitative terms such as “low,” “moderate,” “high,” or “extreme” to describe retardation and birefringence.

Some minerals have **anomalous interference colors**, colors that are not represented on the Michel-Lévy Color Chart. Anomalous interference colors may result if minerals have highly abnormal dispersion, if they are deeply colored, or for a number of other reasons. Minerals that commonly display anomalous interference colors include chlorite, epidote, zoisite, jadeite, tourmaline, and sodic amphiboles.

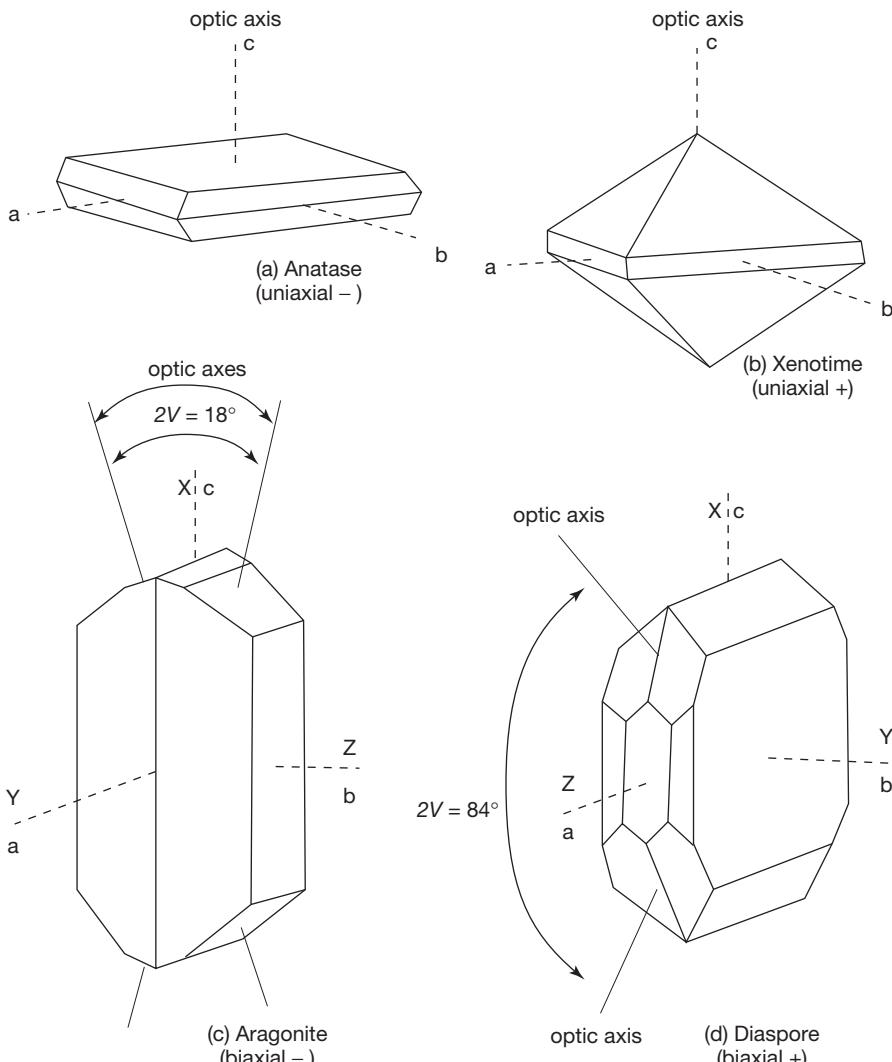
## Uniaxial and Biaxial Minerals

Isotropic minerals have the same light velocity and therefore the same refractive index ( $n$ ) in all directions. This is not true for anisotropic minerals, whether they are uniaxial or biaxial. For uniaxial minerals, we need two indices of refraction ( $\epsilon$  and  $\omega$ ) to describe the mineral’s refractive index. For biaxial minerals, we need three ( $\alpha$ ,  $\beta$ , and  $\gamma$ ).

*Optic axes* are directions that light can travel through a crystal without being split into two rays (Figure 15). In some uniaxial minerals, the optic axis is parallel or perpendicular to crystal faces; in biaxial minerals, the two optic axes rarely are. Light traveling parallel to the single optic axis of a uniaxial mineral travels as an ordinary ray and has a unique refractive index, designated  $\omega$ . Light traveling in other directions is doubly refracted, splitting into two rays with one having refractive index  $\omega$ . The other has refractive index  $\epsilon'$ , which varies depending on the direction of travel.  $\epsilon'$  may have any value between  $\omega$  and  $\epsilon$ , a limiting value corresponding to light traveling perpendicular to the optic axis. If  $\omega < \epsilon$ , the mineral is uniaxial positive (+). If  $\omega > \epsilon$ , the mineral is uniaxial negative (-). We sometimes use the mnemonics POLE (positive = omega less than epsilon) and NOME (negative = omega more than epsilon) to remember these relationships. The maximum possible value of birefringence in uniaxial crystals,  $\delta$ , is  $|\omega - \epsilon|$  (Table 1). We can only see maximum birefringence if the optic axis is parallel to the microscope stage.

Most minerals are biaxial, having two optic axes (Figures 15c and 15d). Light passing through a biaxial crystal experiences double refraction unless it travels parallel to an optic axis. We describe the optical properties of biaxial minerals in terms of three mutually perpendicular directions: X, Y, and Z (Figure 16). The vibration direction of the fastest possible ray is designated X, and that of the slowest is designated Z. The indices of refraction for light vibrating parallel to X, Y, and Z are  $\alpha$ ,  $\beta$ , and  $\gamma$ .  $\alpha$  is therefore the lowest refractive index, and  $\gamma$  is the highest.  $\beta$ , having an intermediate value, is the refractive index of light vibrating perpendicular to an optic axis.

Normally, light passing through a randomly oriented biaxial crystal is split into two rays, neither of which is constrained to vibrate parallel to X, Y, or Z, so their refractive indices will be some values between  $\alpha$  and  $\gamma$ . However, if the light is traveling parallel to Y, the two rays have refractive indices equal to  $\alpha$  and  $\gamma$ , vibrate parallel to X and Z, and the crystal will display maximum retardation. If the light travels parallel to an optic axis, no double refraction



**FIGURE 15** Sketches of crystals showing orientation of optic axes: (a) anatase,  $\text{TiO}_2$ , uniaxial (-); (b) xenotime,  $\text{YPO}_4$ , uniaxial (+); (c) aragonite,  $\text{CaCO}_3$ , biaxial (-); (d) diaspore,  $\text{AlO(OH)}$ , biaxial (+).

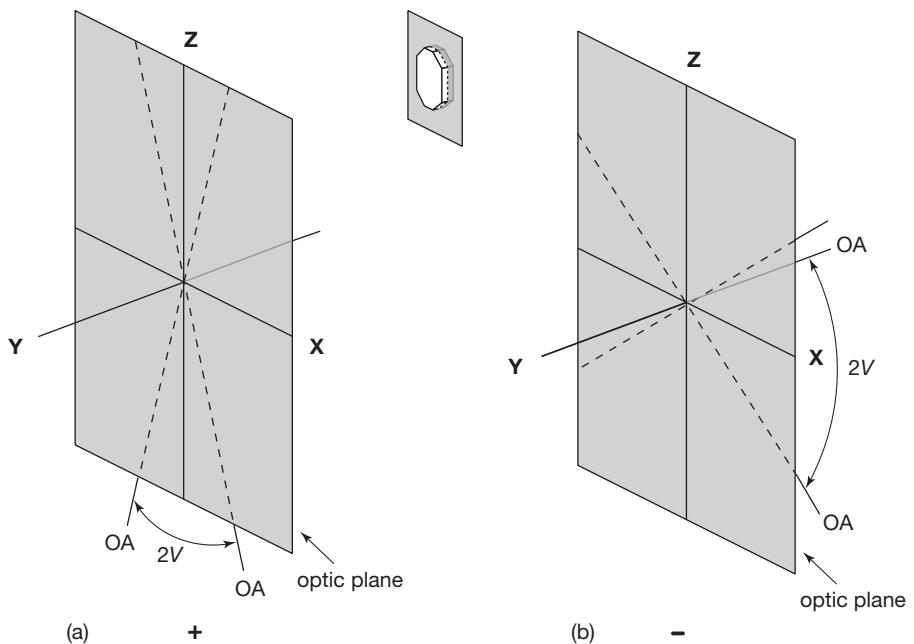
occurs, and it has a single refractive index,  $\beta$ . There is no birefringence or retardation, and the mineral appears extinct.

In biaxial minerals, we call the plane that contains X, Z, and the two optic axes the **optic plane** (Figure 16). The acute angle between the optic axes is  $2V$ . A line bisecting the acute angle must parallel either Z (in *biaxial positive* crystals) or X (in

*biaxial negative* crystals). In biaxial positive minerals, the intermediate refractive index  $\beta$  is closer in value to  $\alpha$  than to  $\gamma$ . In biaxial negative minerals, it is closer in value to  $\gamma$ . Retardation and **apparent birefringence** vary with the direction light travels through a crystal, but the maximum possible value of birefringence ( $\delta$ ) in biaxial crystals is always  $\gamma - \alpha$ .

**TABLE 1** Indices of Refraction and Birefringence for Light Passing through Isotropic and Anisotropic Minerals

	Principal Indices of Refraction	Index of Refraction for Light Traveling Parallel to an Optic Axis	Indices of Refraction in a Random Direction	Birefringence in a Random Direction	Maximum Possible Birefringence
Isotropic crystals	$n$	$n$	$n$	0	0
Uniaxial crystals	$\omega, \varepsilon$	$\omega$	$\omega, \varepsilon'$	$\delta' =  \omega - \varepsilon' $	$\delta =  \omega - \varepsilon $
Biaxial crystals	$\alpha, \beta, \gamma$	$\beta$	$\alpha', \gamma'$	$\delta' = \gamma' - \alpha'$	$\delta = \gamma - \alpha$



**FIGURE 16** Geometric relationships between X, Y, and Z; optic plane; optic axes (OA); and  $2V$  in biaxial positive and negative crystals. The small inset shows the optic plane for a hypothetical crystal. Both optic axes lie in the optic plane, but it is impossible to tell their orientations from the shape of the crystal: (a) in positive crystals, the acute angle between the optic axes is bisected by Z; (b) in negative crystals, the acute angle between the optic axes is bisected by X.

### Accessory Plates and the Sign of Elongation

Polarizing microscopes have accessory plates we can insert above the objective lens. When inserted, the slow and fast vibration directions of the plate are at  $45^\circ$  to the lower and upper polarizers. A double-headed arrow on accessory plates usually marks the slow direction. A standard full-wave plate has a retardation of 550 nm (equal to the average wavelength of visible light), equivalent to first-order red interference colors. A quartz wedge is sometimes a useful alternative to a full-wave plate. The wedge has a variable thickness, with retardation ranging from 0 nm to 3,500 nm.

By inserting a plate when we are viewing a crystal on the microscope stage, we can add or subtract retardation. Accessory plates make it possible to learn which vibration direction in the crystal permits polarized light to travel the fastest. If crystals have a long dimension, we can learn whether the mineral is length fast (also sometimes called “negative elongation”) or length slow (“positive elongation”). Determining the sign of elongation is often straightforward and can be helpful when identifying a mineral (Box 3).

### Uniaxial Interference Figures

Optic sign (positive or negative) is another useful characteristic for identifying anisotropic minerals. The easiest way to learn whether a uniaxial mineral is positive or negative is to examine an interference figure. Examples are shown in Plates 4.5

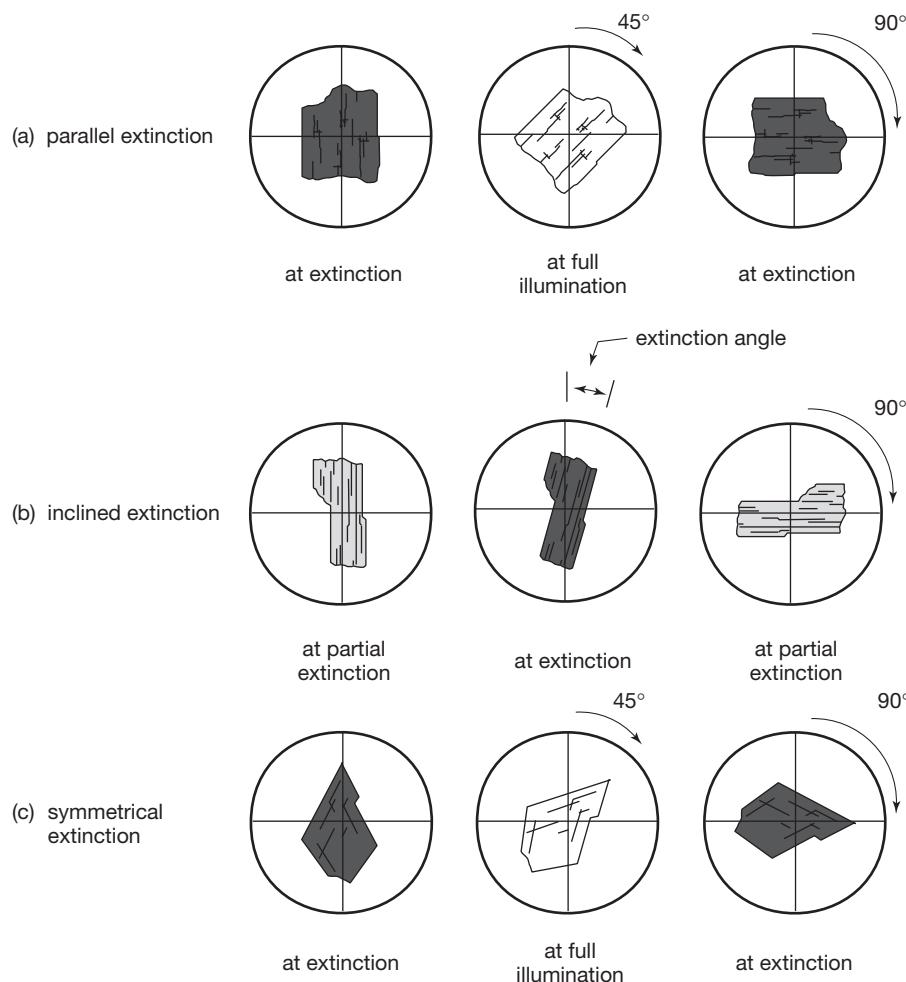
through 4.10. We obtain interference figures by passing conoscopic light through a mineral (Box 4). The **conoscopic lens** focuses light into the crystal from many different converging directions. After the light leaves the crystal and passes through the upper polarizer, we can insert a Bertrand lens to refocus the rays and magnify the interference figure.

To determine the optic sign of a uniaxial mineral, it is best to look down, or nearly down, the optic axis (Box 5). The figure obtained is an **optic axis (OA) figure**. Finding grains that give an OA figure is normally not difficult. Grains oriented with the optic axis vertical appear isotropic because they have no retardation when being viewed down an optic axis. Grains oriented with the optic axis close to vertical have low birefringence and, therefore, low-order interference colors. An ideal uniaxial OA figure has a black cross that does not move much when the stage rotates (Figures 19a–c; Plates 4.8 and 4.9). Even if the cross is somewhat off center, we can use it to determine the optic sign. The center of the cross, called the **melatope**, corresponds to the direction of emergence of the optic axis. We call the dark bands forming the cross **isogynes**. The surrounding colored rings, if present, are **isochromes** (Plate 4.8). They are bands of equal retardation caused by the light entering the crystal at slightly different angles. Minerals with low birefringence, like quartz, may not show isochromes (Plate 4.9). When viewing an OA figure, we use an accessory plate to learn whether a uniaxial mineral is positive or negative (Box 5).

## BOX 3

## Determining the Extinction Angle and the Sign of Elongation

Viewed with crossed polars, anisotropic grains go extinct every  $90^\circ$  as we rotate the microscope stage. We can measure the **extinction angle**, the angle between a principal cleavage or direction of elongation and extinction (Figure 17). Minerals with cleavages that exhibit **parallel extinction** go extinct when their cleavages or directions of elongation are parallel to the upper or lower polarizer (Figure 17a). Many monoclinic and all triclinic crystals exhibit **inclined extinction** and go extinct when their cleavages or directions of elongation are at angles to the upper and lower polarizer (Figure 17b). Some minerals exhibit **symmetrical extinction**; they go extinct at angles symmetrical with respect to cleavages or crystal faces (Figure 17c). Because an extinction angle depends on grain orientation, determining an extinction angle for minerals in thin sections requires measurements on a number of different grains, or on one grain in the correct orientation (determined by looking at interference figures, discussed later). If the grains are randomly oriented in the thin section and if the sample size is large enough, the maximum value of the measurements should approximate the actual extinction angle of the mineral.



**FIGURE 17** Extinction of minerals viewed with XP light in this section: (a) parallel extinction of minerals such as orthopyroxene occurs every  $90^\circ$  when the long axis of grains or the cleavage are perpendicular to either polarizer; (b) inclined extinction in many minerals, including most micas, occurs when the cleavage is at an angle to both polarizers; (c) symmetrical extinction of minerals, such as calcite, occurs when cleavages are oriented symmetrically to cross hairs and polarizers.

Most uniaxial mineral grains do not exhibit a perfectly centered OA figure when viewed in conoscopic light. The optic axis is only one direction in the crystal and grains are unlikely to be oriented with the optic axis vertical. If we choose a random grain, we typically get an off-center figure (Figures 19d–g). If the optic axis of a grain lies parallel to the stage of the microscope, we get an **optic normal** figure, also called a

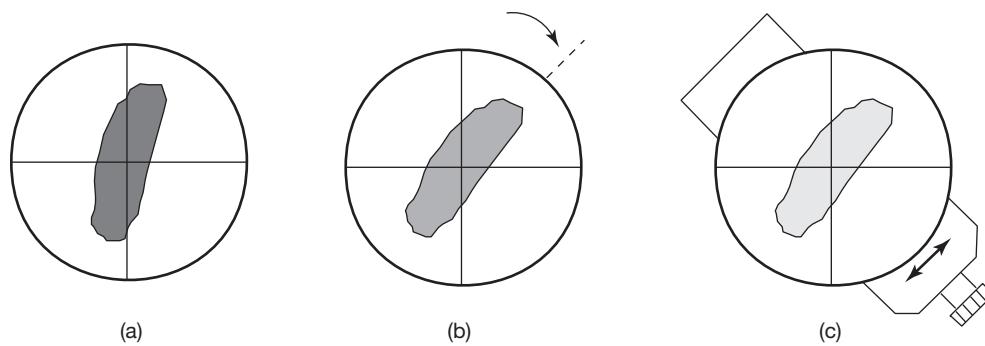
**flash figure.** The flash figure appears as a vague cross or blob that nearly fills the field of view when the grain is at extinction (when the optic axis is perpendicular to one of the polarizers). Upon stage rotation, it splits into two curved isogyres flashing in and out of the field of view with a few degrees of stage rotation. Uniaxial flash figures have the same general appearance.

Some anisotropic crystals have a prismatic habit or a well-developed cleavage that causes them to break into elongated fragments. Polarized light passing through an anisotropic prismatic crystal with polarization parallel to the long dimension will not travel at the same velocity as light polarized in other directions. This distinction allows the prismatic minerals to be divided into two **signs of elongation: length fast** (faster light vibrates parallel to the long dimension) and **length slow** (slower light vibrates parallel to the long dimension). The sign of elongation cannot be determined on anisotropic crystals that cleave to produce equidimensional fragments.

Determining the sign of elongation (length fast or length slow) is usually straightforward for tetragonal and hexagonal prismatic crystals (all of which are uniaxial). We orient the long dimension of a grain in a southwest-northeast direction ( $45^\circ$  to the lower polarizer) and note the interference colors. Many minerals, especially if grains are small, exhibit low first-order interference colors (grays). We can insert a full-wave accessory plate (having a retardation of 550 nm, equivalent to first-order red interference colors). After insertion, the slow direction of most accessory plates will be oriented southwest-northeast. If gray interference colors are added to first-order red, first-order blue results. If gray interference colors are subtracted from first-order red, first-order yellow results. For a grain oriented in the southwest-northeast direction, addition or subtraction is often just a matter of looking for blue or yellow. If we see blue or other higher-order interference colors when the plate is inserted, the mineral is length slow. If we see yellow or other lower-order colors, it is length fast (Figure 18).

If the interference colors for a mineral grain are not mostly gray, determining addition or subtraction may not be quite so simple. Sometimes it will be necessary to rotate the stage  $90^\circ$  to see the colors that appear when the mineral is oriented northwest-southeast. The effects in that orientation will be opposite to those seen when the mineral is oriented southwest-northeast. When oriented northwest-southeast, higher-order colors correspond to length fast, lower-order to length slow. A quartz wedge can be useful in determining the sign of elongation if a grain contains several color bands rather than just gray. As the wedge is inserted into the accessory slot, the color bands on a southwest-northeast-oriented grain will move toward the thicker portions of the grain (usually the center of the grain) if the retardation is being subtracted (length fast). If the bands move away from the thicker portions of the grain, the retardation is being added (length slow).

Determining the sign of elongation for an orthorhombic, monoclinic, or triclinic mineral can be problematic or impossible. We can sometimes determine it for orthorhombic or monoclinic minerals with parallel extinctions, but it may vary with the orientation of the mineral. Mineral identification tables sometimes list whether a given mineral is likely to provide a sign of elongation and whether the sign may vary with the mineral's orientation. If the extinction angle of the monoclinic or triclinic grain is only a few degrees, we can often determine a sign of elongation. If they have inclined extinction, we often cannot because the sign may vary in a complicated way with the orientation of the grain, and because determining the orientation of the grain on the microscope stage is difficult.



**FIGURE 18** Determining the sign of elongation: (a) An elongated grain at extinction position (XP light); (b) the grain is rotated until it is at  $45^\circ$  to the crosshairs and oriented southwest-northeast; (c) the accessory plate (slow direction marked with a double arrow) is inserted to determine whether the interference colors add or subtract. If they add, producing blue or other higher order interference colors, the grain is "length slow"; if they subtract, producing yellow or other lower order interference colors, the grain is "length fast."

## Biaxial Interference Figures

We obtain *biaxial interference figures* in the same way as uniaxial interference figures. However, complications arise with biaxial minerals because it is more difficult to find and identify grains oriented in a useful way. We can get interference figures from all grains, but interpreting them can be difficult or impossible. Four types of interference figures are

commonly identified (Box 6). When we observe an acute bisectric figure (Bxa) for a grain in an extinction orientation (Y perpendicular to one of the polarizers), it appears as a black cross, similar in some respects to a uniaxial interference figure. When we rotate the stage, the cross splits into two isogyres that move apart and may leave the field of view (Figure 20; Plates 4.5, 4.6, and 4.7). After a rotation

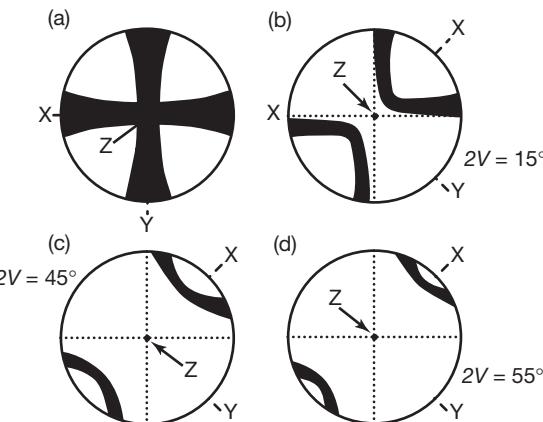
**BOX 4****Obtaining an Interference Figure**

Any uniaxial or biaxial mineral (whether in a grain mount or a thin section) will, in principle, produce a visible interference figure; isotropic minerals will not. Care must be taken to choose grains without cracks or other flaws so light can pass through without disruption. In addition, some purposes require grains with a specific orientation.

Having chosen an appropriate grain, obtaining an interference figure is relatively straightforward. Carefully focus the microscope using PP light and high magnification. (If perfect focus is ambiguous, it may help to focus first at low magnification.) Insert the upper polarizer to get XP light; if the microscope is properly aligned, the grain will still be in focus. Fully open the substage diaphragm, insert the substage conoscopic lens if it is not already in place, and then insert the Bertrand lens above the upper polarizer. You will now see an interference figure, perhaps similar to one of those shown in Plates 4.5 to 4.10.

The conoscopic lens focuses light so it enters the crystal from many different angles simultaneously. The Bertrand lens focuses the light so it is parallel again when it reaches the eyepiece. In effect, the two lenses together permit the examination of light traveling through a crystal in many different directions. Without the lenses, we would have to look at many different crystals of known optical orientation to obtain the same information. Some older microscopes do not have Bertrand lenses, but interference figures can still be obtained by removing an ocular and inserting a peep sight, or by just peering down the tube. The figures, however, will be quite small.

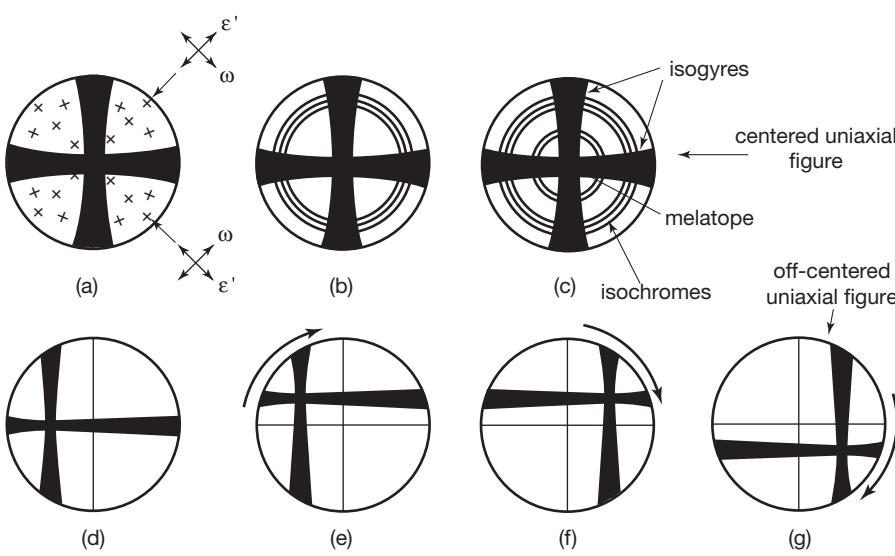
of  $45^\circ$ , the isogynes are at maximum separation; they come back together to reform the cross with further stage rotation. The maximum amount of isogyne



**FIGURE 20** Biaxial acute bisectrix (Bxa) interference figures for a biaxial (+) crystal: In (a) the crystal is oriented with X and Y parallel to the polarizers; in (b), (c), and (d) the stage has been rotated  $45^\circ$  so that X (the trace of the optic plane) is oriented northwest-southeast and the isogynes are at maximum separation. The amount of separation is proportional to  $2V$ . Similar relationships apply to biaxial (-) crystals except that X and Z are interchanged.

separation depends on  $2V$  (Box 7). If  $2V$  is less than about  $60^\circ$ , the isogynes stay in the field of view as we rotate the stage. If  $2V$  is greater than  $60^\circ$ , the isogynes completely leave the field of view. Plate 4.10 shows an interference figure for biotite;  $2V$  is  $20^\circ$ , to  $25^\circ$ .

The points on the isogynes closest to the center of a Bxa or Bxo, the melatopes, are points corresponding to the orientations of the optic axes (Figure 24) of different colors. If the retardation of the crystal is great, isochromes circle the melatopes; none are apparent in Plate 4.10. Interference colors



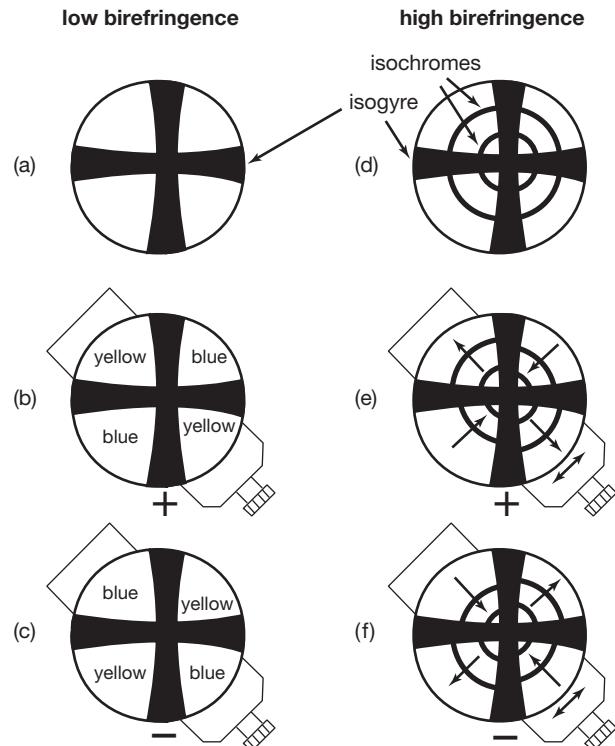
**FIGURE 19** Uniaxial interference figures: In (a), (b), and (c) the figure is centered; in (d), (e), (f), and (g) it is off center but the cross is visible. In (a), the small crosses show the vibration directions of  $\epsilon'$  and  $\omega$ ;  $\epsilon'$  always vibrates radially and  $\omega$  vibrates perpendicular to  $\epsilon'$ . In (b), one set of isochromes is shown, while in (c) there are two sets due to higher birefringence. Figures (d) through (g) show how the melatope (the center of the cross) of an off-centered figure precesses as the microscope stage is rotated. See also Plates 4.8 and 4.9.

## BOX 5

## Determining the Optic Sign of a Uniaxial Mineral

To determine the optic sign of a uniaxial mineral, it is necessary to know whether  $\omega > \varepsilon$  or  $\varepsilon > \omega$ . We do this by examining an optic axis figure and using an accessory plate with known orientation of the fast and slow rays. Standard accessory plates have their slow direction oriented southwest-northeast at 45° to both polarizers. The plate is inserted, and we observe interference color changes or isochrome (color ring) movements in the southwest and northeast quadrants of the interference figure (Figure 21).

Uniaxial optic axis figures appear as black crosses (Figures 19 and 21; Plates 4.8 and 4.9). In all parts of a uniaxial optic axis interference figure  $\varepsilon'$  vibrates radially (along the radius of the interference figure) and  $\omega$  vibrates tangent to isochromes (see Figure 4.19a). One way to remember these relationships is with the acronym WITTI for the mnemonic “ $\omega$  Is Tangent To Isochrome.” If interference colors in the southwest and northeast quadrants shift to higher orders when the plate (or wedge) is inserted, addition of retardation has occurred.  $\varepsilon'$  is the slow ray and the crystal is uniaxial positive. Subtraction (lower-order interference colors) in the southwest and northeast quadrants indicates that  $\varepsilon'$  is the fast ray, and the crystal is optically negative. Because  $\varepsilon'$  vibrates parallel to the prism axis (*c*-axis) in prismatic uniaxial minerals, the optic sign is the same as the sign of elongation.



**FIGURE 21** Determining the sign of a uniaxial mineral: (a) a slightly off-center uniaxial interference figure showing no isochromes (low birefringence); (b) and (c) when we insert the accessory plate, yellow and blue colors seen in different quadrants allow us to determine whether the mineral is positive or negative; (d) a slightly off-center uniaxial interference figure with isochromes (due to high birefringence); (e) and (f) when we insert a quartz wedge the isochromes move in and out in different quadrants depending on optic sign.

increase in order moving away from the melatopes because retardation is greater as the angle to the optic axes increases.

The isogyes in a Bxo figure always leave the field of view because, by definition, an obtuse angle separates the optic axes in the Bxo direction. Thus, if the isogyes remain in view, the figure is a Bxa figure. For standard lenses, if they leave the field of view, the

mnemonic “ $\omega$  Is Tangent To Isochrome.” If interference colors in the southwest and northeast quadrants shift to higher orders when the plate (or wedge) is inserted, addition of retardation has occurred.  $\varepsilon'$  is the slow ray and the crystal is uniaxial positive. Subtraction (lower-order interference colors) in the southwest and northeast quadrants indicates that  $\varepsilon'$  is the fast ray, and the crystal is optically negative. Because  $\varepsilon'$  vibrates parallel to the prism axis (*c*-axis) in prismatic uniaxial minerals, the optic sign is the same as the sign of elongation.

Although we could use a quartz wedge, we normally use a full-wave accessory plate when the optic axis figure shows low-order interference colors. In positive crystals, addition produces blue in the southwest and northeast quadrants of the interference figure, while subtraction produces yellow in the northwest and southeast quadrants. In negative crystals, the effect is the opposite. If several different color rings (isochromes) are visible, the blue and yellow colors will only appear on the innermost rings near the melatope (the center of the black cross).

We can sometimes use a full-wave plate, but normally use a quartz wedge, to determine an optic sign for minerals that exhibit high-order interference colors. The retardation of the quartz will add to the retardation of the unknown mineral in two quadrants as the wedge is inserted. It will also subtract from the retardation in the other two. The result will be color rings (isochromes) moving inward in quadrants where addition occurs, and outward in quadrants where subtraction occurs (Figure 21). For positive minerals, this means that colors move inward in the southwest and northeast quadrants and outward in the northwest and southeast quadrants. For negative minerals, the motion is opposite.

figure may be a Bxo or a Bxa for a mineral with high  $2V$  (greater than about 60°). Getting a perfectly centered Bxo or Bxa figure is difficult. It may only be possible to see one isogye clearly. Experienced mineralogists can tell a Bxa from a Bxo figure by the speed with which the isogye leaves the field of view on rotation. For the rest of us, it is probably best to search for another grain with a better orientation.

## BOX 6

## The Four Kinds of Oriented Biaxial Interference Figures

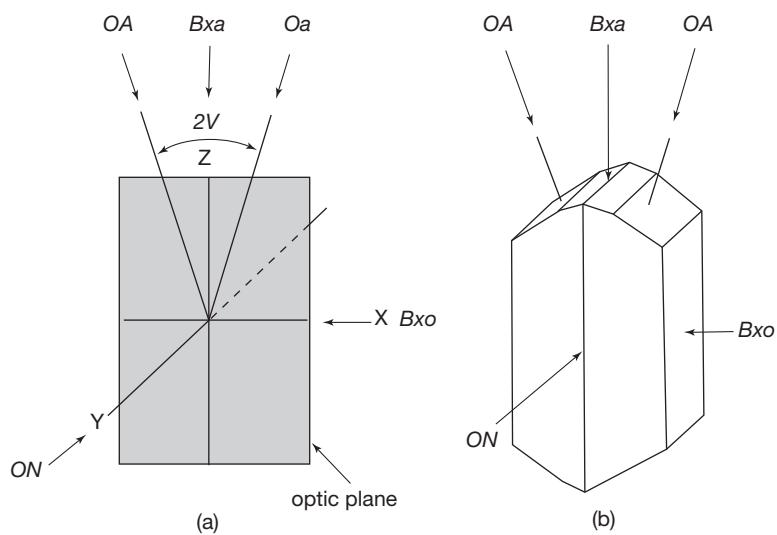
Biaxial interference figures are more difficult to interpret than uniaxial interference figures. With care, however, it is possible to identify three different kinds of useful figures: optic axes, acute bisectrix, and optic normal. Each corresponds to a different light path through the crystal, relative to the orientation of the optic axes (Figure 22). A fourth type of figure—Bxo—is generally of limited use but is included in the interests of thoroughness.

**Optic axis figure (OA):** We obtain an OA figure by looking down an optic axis (Figures 22 and 23). We can locate grains oriented to give an OA figure because they have zero or extremely low retardation. Under orthoscopic XP light, they remain dark even if the microscope stage is rotated. An interference figure will show only one isogyre unless  $2V$  is quite small (less than  $30^\circ$ ). We can use the curvature of the isogyre to estimate  $2V$  (see Box 8 and Figure 23).

**Acute bisectrix figure (Bxa):** We obtain Bxa figures, such as those in Figures 21 and 24 and Plate 4.10, by looking down the **acute bisectrix**, the line bisecting the acute angle between the two optic axes (Figure 22). In biaxial positive crystals, Bxa corresponds to a view along Z; in biaxial negative crystals, it corresponds to a view along X. For small values of  $2V$ , the isogyes form a black cross similar to a uniaxial interference figure when Y is parallel to the lower polarizer or upper polarizer. On rotation of the stage, the isogyes will split into hyperbolas, reforming the cross every  $90^\circ$  (Figure 24). For  $2V$  values greater than about  $60^\circ$ , the isogyes will completely leave the field of view before coming back together to re-form the cross.

**Optic normal figure (ON):** An ON is the figure obtained when looking down Y, normal to the plane of the two optic axes (Figure 22). Grains that yield an optic normal figure are those that have maximum retardation. The interference figure resembles a poorly resolved Bxa, but the isogyes leave the field of view with only a slight rotation of the stage. Biaxial optic normal figures appear similar to uniaxial flash figures.

**Obtuse bisectrix figure (Bxo):** Bxo figures are generally not useful for mineral identification, but they can be confused with other, more useful figures. A Bxo is the figure obtained when looking down the **obtuse bisectrix**, a line bisecting the obtuse angle between the optic axes (Figure 22). A Bxo looks superficially like a Bxa, but the isogyes will always leave the field of view on a stage rotation (because the angle between the optic axes is greater than  $90^\circ$  along the Bxo). Distinguishing a Bxo from a Bxa is difficult or impossible for large values of  $2V$  (greater than  $70^\circ$ ). Bxo figures are also easily confused with ON figures in minerals with small  $2V$ .

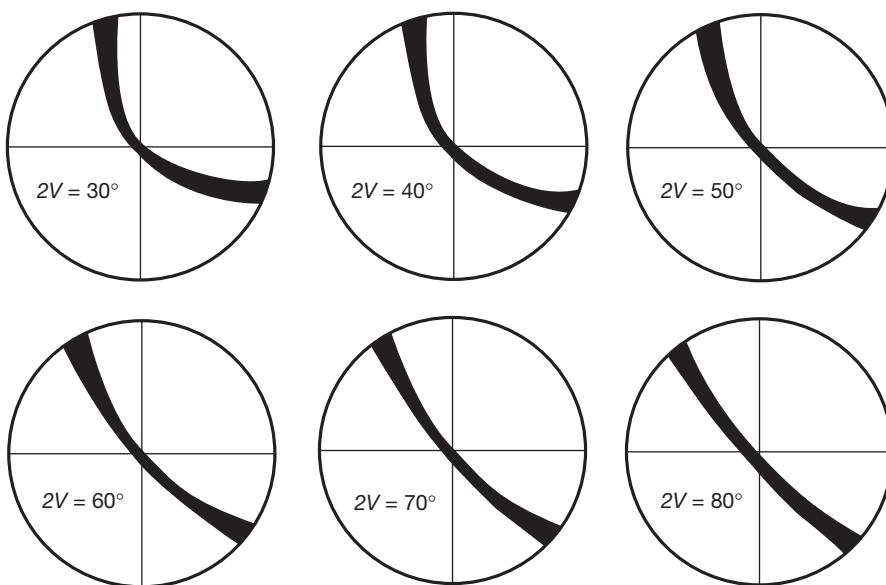


**FIGURE 22** Relative orientations of optic axis (OA), Bxa, Bxo, and optic normal (ON) directions in a biaxial (+) crystal: (a) schematic showing optic axes and optic plane; (b) drawing of a crystal in a similar orientation. In biaxial (-) crystals the relationships are similar but the X and Z axes are interchanged.

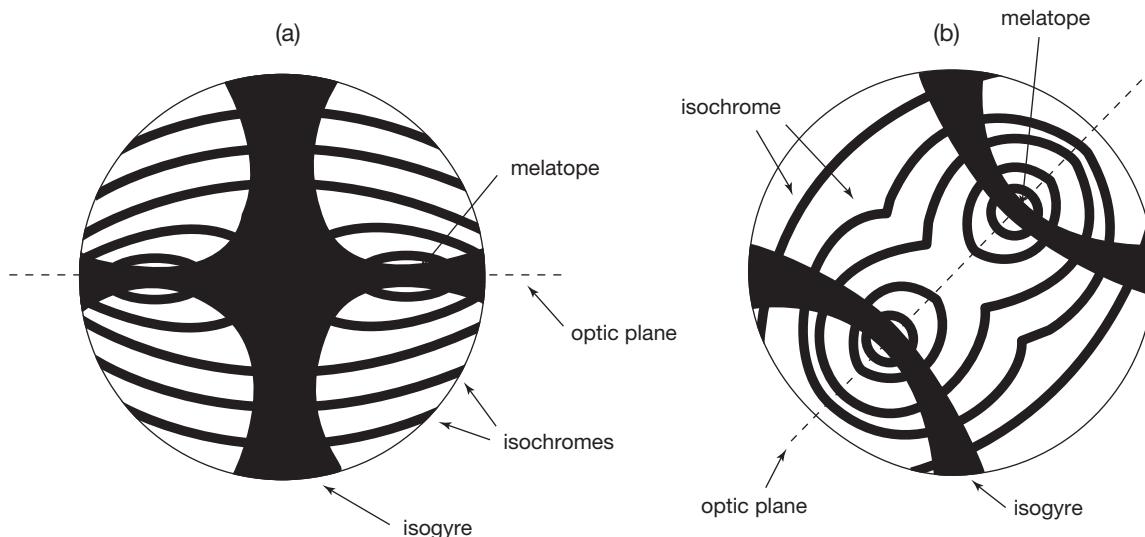
Determining optic sign from a Bxa figure is equivalent to asking whether the Bxa corresponds to the fast direction (biaxial negative crystals) or to the slow direction (biaxial positive crystals). We can make the determination in much the same manner as for a uniaxial interference figure (Box 7). However, for figures where the isogyes leave the field of view, this is not the recommended way to

learn optic sign because Bxa and Bxo figures are so easily confused when  $2V$  is greater than  $70^\circ$  to  $80^\circ$ .

An alternative way to determine optic sign and  $2V$  is to find a grain that yields a centered optic axis figure (Box 8). Finding such grains is often not difficult because they show very low-order interference colors, or may appear isotropic under crossed polars.



**FIGURE 23** Biaxial optic axis (OA) figure. These figures show the isogyes that would be seen when looking down an optic axis for crystals with various  $2V$  values. The microscope stage has been rotated so the isogyre is concave to the northeast. We use the curvature to estimate  $2V$ .



**FIGURE 24** Two views of a Bxa interference figure: (a) a black cross, with or without isochromes, is seen when the optic plane is parallel to a polarizer; (b) the cross separates into two curved isogyes when the optic plane is parallel to neither polarizer. The optic plane is oriented northeast-southwest. See also Plate 4.10.

## OTHER MINERAL CHARACTERISTICS IN THIN SECTIONS

Besides the optical properties already discussed, we can use several other mineral characteristics to aid mineral identification. These characteristics give certain minerals a distinctive property in thin section. An experienced microscopist can, for example, often identify amphibole because of its cleavage and plagioclase feldspar because of its twinning. Besides

cleavage and twinning, other important characteristics include alteration, compositional zonation, exsolution, anomalous extinction, or the presence of inclusions. They are, however, beyond the scope of this text.

### Cleavage

Many minerals exhibit cleavage; when it can be seen with a microscope, it can be an important diagnostic tool. We use qualitative terms such as perfect, good,

**BOX 7****Determining Sign and  $2V$  from a Bxa Figure**

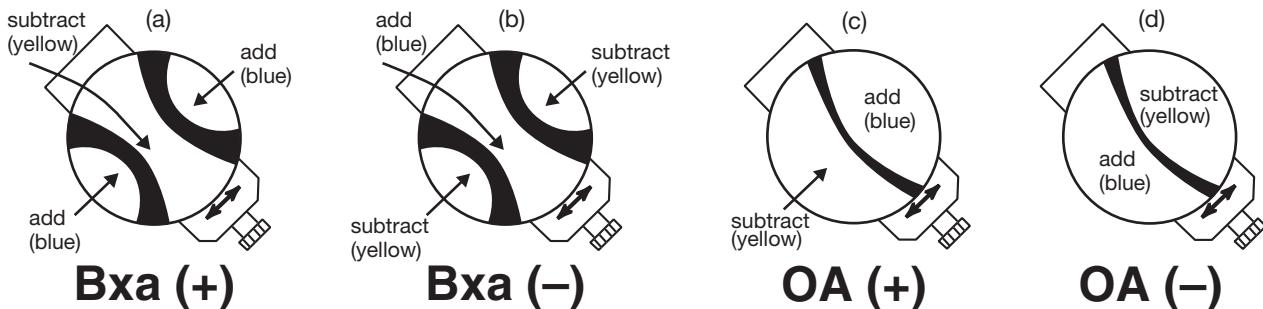
Finding a grain that yields a Bxa is easiest for minerals with a small  $2V$ . You can begin by searching for a grain that has minimal retardation. Such a grain will be oriented with one of the optical axes near vertical. Then obtain an interference figure, rotate the stage, and note how the isogyes behave. After checking several grains, you should find a Bxa. For minerals with low-to-moderate  $2V$  ( $0^\circ$  to  $60^\circ$ ), both isogyes will stay in the field of view, but the interference figure may not be perfectly centered (Plate 4.10). If one of the isogyes leaves the field of view, check other grains until you are sure you are looking at a nearly centered Bxa. For minerals with high  $2V$ , the search for a Bxa sometimes becomes frustrating. It may be difficult or impossible to distinguish a Bxa from a Bxo. For this reason, the optic sign often is best determined using an OA figure (Box 8).

Having found a Bxa, rotate the stage so the isogyes are in the southwest and northeast quadrants (Figure 24b; 25a–b). The Y direction in the crystal is now oriented northwest-southeast. The points corresponding to the optic axes (the melatopes) are the points on the isogyes closest to each other, and either X or Z is vertical, depending on optic sign.

To determine optic sign, we must know which direction (X or Z) is vertical, corresponding to Bxa. If the slow direction (Z) corresponds to Bxa, the crystal is positive. If the fast direction (X) is Bxa, the crystal is negative. To make the determination, insert the full-wave accessory plate (with slow-oriented direction southwest-northeast) and note any changes in interference colors on the concave sides of the isogyes. If the interference colors add on the concave sides of the isogyes (and subtract on the convex sides), the mineral is positive (Figure 25a–b). In positive minerals with low to moderate retardation, the colors in the center of the figure will be yellow (subtraction), and those on the concave side of the isogyes will be blue (addition). In a negative mineral, the color changes will be the opposite.

For minerals with high retardation, it may be difficult to determine whether a full-wave accessory plate adds or subtracts retardation because isochromes of many repeating colors circle the melatopes. A quartz wedge facilitates determination. As the wedge is inserted, color rings move toward the melatopes if there is addition of retardation, or the rings move away from the melatopes if there is subtraction. If the interference colors move toward the optic axes from the concave side of the isogyes, and away on the convex side, the mineral is positive. The opposite effect is seen for a negative mineral.

You can estimate  $2V$  from a Bxa figure by noting the degree of separation of the isogyes when you rotate the stage. For standard lenses, if the isogyes just leave the field of view when they are at maximum separation,  $2V$  is  $60^\circ$  to  $65^\circ$ . If the isogyes barely separate,  $2V$  is greater than about  $10^\circ$ .



**FIGURE 25** Determining optic sign from Bxa and OA figures: The accessory plate (with slow direction oriented southwest-northeast) is inserted and interference color changes are noted. For a biaxial positive mineral, interference colors add (increase to higher order) on the concave side of the isogyes; for a biaxial negative mineral, they subtract. For grains with low retardation, addition produces blue interference colors and subtraction produces yellow. (a) Bxa figure for a biaxial positive mineral; (b) Bxa figure for a biaxial negative mineral; (c) OA figure for a biaxial positive mineral; (d) OA figure for a biaxial negative mineral.

fair, and poor to describe the ease with which a mineral cleaves in different directions. Cleavage appears as fine parallel cracks in mineral grains when viewed with a microscope. Minerals with one or more good or perfect cleavages can be expected to show cleavage most of the time, while those with only poor cleavage may not. Additionally, minerals with low relief do not show cleavage as readily as those with high relief. This problem can be overcome somewhat by closing down the substage diaphragm, which narrows the cone of light hitting the thin section and increases contrast.

Minerals may have zero, one, two, three, four, or even more cleavages, but because thin sections provide a view of only one plane through a mineral grain, we rarely see more than three at a time. Minerals that have elongate habits generally exhibit different cleavage patterns when viewed in a cross section than they do when viewed in a longitudinal section. Amphibole, for example, shows two good cleavages intersecting at about  $60^\circ$  and  $120^\circ$  in a cross section, but only one good cleavage in a long section. The number of different

**BOX 8****Determining Sign and  $2V$  from an Optic Axis Figure for a Biaxial Mineral**

Determining the optic sign from an optic axis figure can often be simpler than looking for a Bxa. To find an OA figure, look for a grain displaying zero or very low retardation. Obtain an interference figure and rotate the stage. It should be an OA figure, showing one centered or nearly centered isogyre (Figures 23 and 25c–d). If you see two isogories that stay in the field of view when you rotate the stage, you are looking at a Bxa for a mineral with low  $2V$ . Rotate the stage so the isogyre (or the most nearly centered if there are two) is concave to the northeast (Figure 25). Note that the isogyre rotates in the opposite sense from the stage. Insert the full-wave accessory plate. If the retardation increases on the concave side of the isogyre (and decreases on the convex side), the mineral is positive (Figures 25c–d). In minerals with low to moderate retardation, it is often necessary only to look for yellow and blue. Blue indicates an increase and yellow a decrease in retardation. The increase or decrease of retardation will be opposite if the mineral is negative.

You can estimate  $2V$  by noting the curvature of the isogyre. If  $2V$  is less than  $10^\circ$  to  $15^\circ$ , the isogyre will seem to make a  $90^\circ$  bend. If  $2V$  is  $90^\circ$ , it will be straight. For other values, it will have curvature between  $90^\circ$  and  $0^\circ$  (Figure 23).

cleavages and the angles between them aid mineral identification. Hornblende and other amphibole cross sections often show a typical diamond cleavage pattern (Plate 5.5), which serves to distinguish amphiboles from other similar minerals. However, it is important to remember that cleavage angles depend on grain orientation. If a mineral has two cleavages at  $60^\circ$  to each other, the cleavages will appear to intersect at any angle from  $0^\circ$  to  $60^\circ$  depending on grain orientation. So we must often examine many grains (or one with a known orientation determined by examining an interference figure) to determine the maximum, and true, cleavage angle.

**Twinning**

Many minerals twin, and sometimes we can see the twins with a microscope (see the feldspars in Plate 5.8, for example). They manifest themselves as different regions of a grain that have different crystallographic orientations, so they do not go extinct at the same time when the microscope stage is rotated. Contact twin domains are separated by a

sharp line, the trace of the twin plane. Penetration twins generally have irregular domain boundaries. Simple twins consist of two individual **domains**, but **lamellar** twins are characterized by multiple parallel bands called **twin lamellae**. The plagioclase in Plate 5.8 shows well-developed twin lamellae. Some minerals, such as plagioclase, exhibit polysynthetic twinning caused by many parallel twin lamellae, often quite narrow, related by parallel twin planes. Still others, such as andalusite may exhibit cyclic twinning, although it is rarely seen in thin sections. The feldspars are excellent examples of minerals that twin. Plagioclase is characterized by polysynthetic twinning, orthoclase often by simple penetration or contact twins, and microcline by two types of lamellar twins with different orientations (that combine to produce “Scotch plaid” twinning). Calcite is characterized by polysynthetic twins parallel to the long diagonal of its rhombohedral shape (Plate 5.2). Other carbonates have no twins or have twins parallel to the short diagonal. Thus, for the feldspars, the carbonates, and for other minerals, twinning can be a key to identification.

**Questions for Thought**

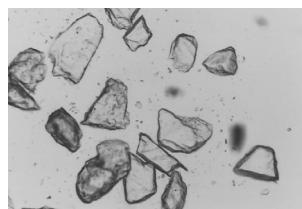
*Some of these questions have no specific correct answers; they are intended to promote thought and discussion.*

1. Why do we use a polarizing light microscope to examine minerals? Why not use a standard microscope?
2. Minerals that grow cubic crystals are isotropic when viewed under a polarizing microscope. What does isotropic mean? What is the connection between crystal shape and optical properties?
3. When calcite is viewed with polarized light and a petrographic microscope, its relief may vary as the stage is rotated. Why?
4. In general, high-density minerals have high refractive index compared to low-density minerals. Why do density and refractive index correlate?
5. Minerals that do not cause double refraction are not birefringent. What do we call such minerals? What is the connection between double refraction and birefringence?
6. Some anisotropic minerals are uniaxial and some are biaxial. What is the difference between them? Do you suppose it is possible to distinguish uniaxial and biaxial minerals simply by looking at their crystal forms? What would we look for? Must we always use a microscope?

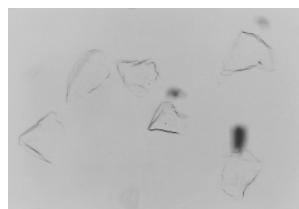
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## Resources

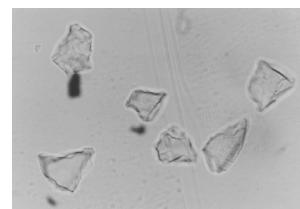
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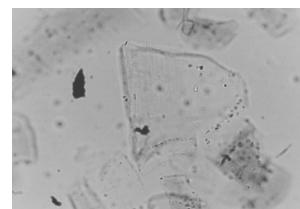
**PLATE 4.1** Fluorite showing strong relief in liquid with  $n=1.512$ .



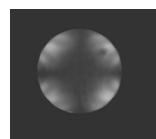
**PLATE 4.2** Fluorite showing weak relief in liquid with  $n=1.452$ .



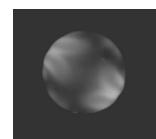
**PLATE 4.3** Fluorite in liquid with  $n=1.452$ ; the stage has been slightly lowered to show bright Becke line moving into the liquid.



**PLATE 4.4** Barite in liquid with  $n=1.636$ , nearly identical to that of barite.



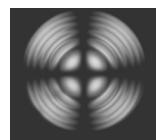
**PLATE 4.5** Olivine interference figure at extinction.



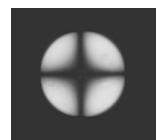
**PLATE 4.6** Olivine interference figure  $15^\circ$  from extinction.



**PLATE 4.7** Olivine interference figure  $45^\circ$  from extinction.



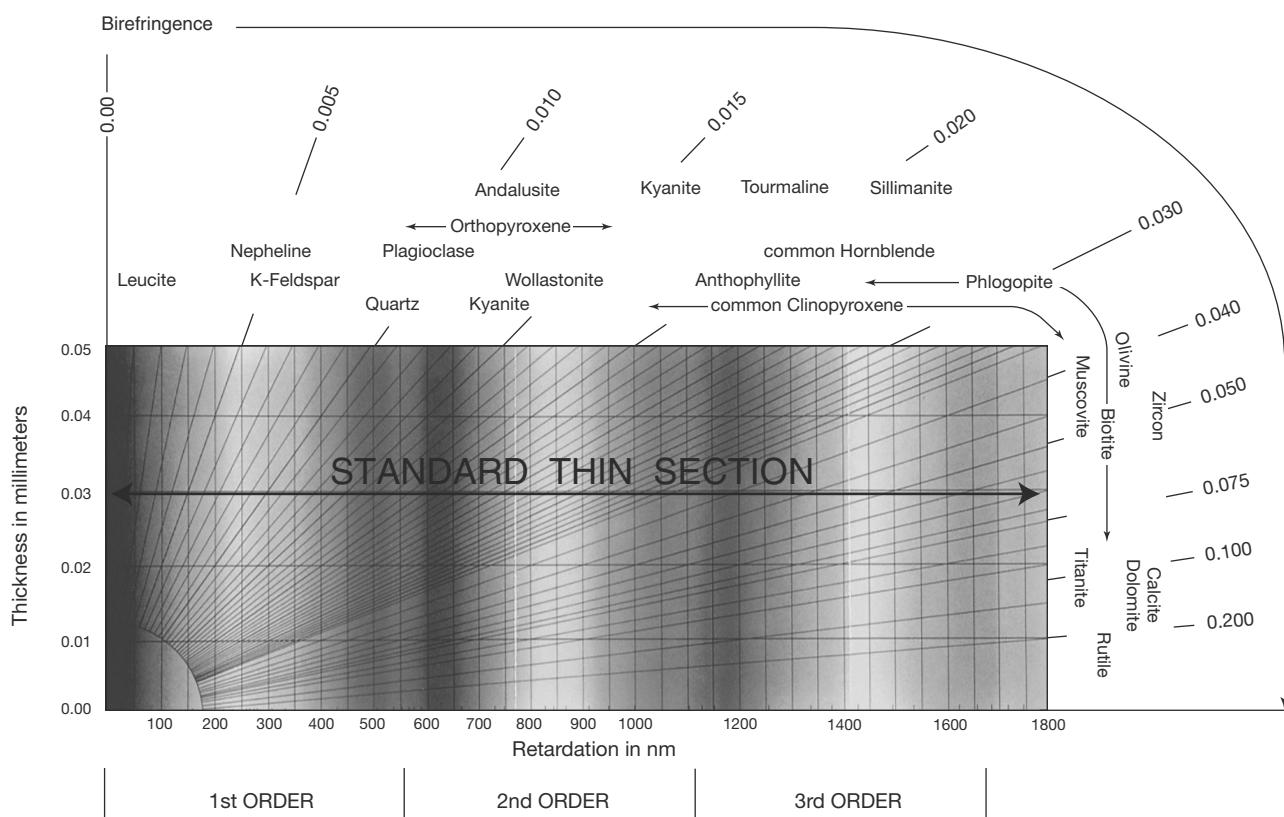
**PLATE 4.8** A nearly centered uniaxial interference figure exhibited by calcite.



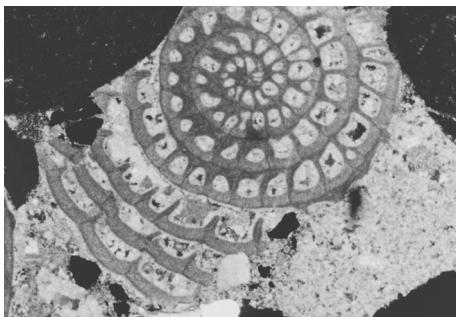
**PLATE 4.9** A nearly centered uniaxial interference figure exhibited by quartz.



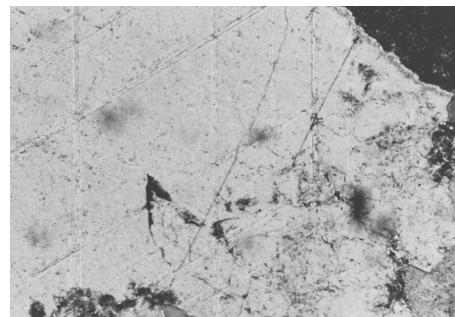
**PLATE 4.10** A nearly centered biaxial interference figure exhibited by biotite.



**PLATE 4.11** Michel Lévy Color Chart.



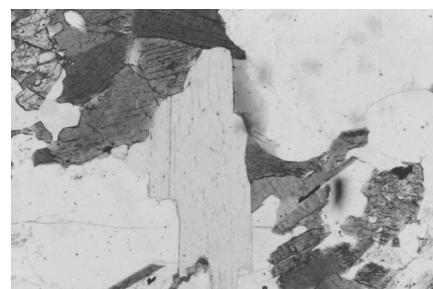
**PLATE 5.1** Thin section view of calcite replacing a foraminifera fossil.



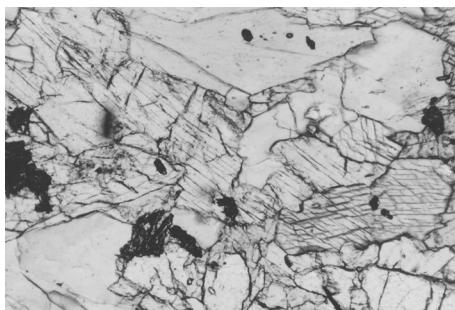
**PLATE 5.2** Calcite in thin section.



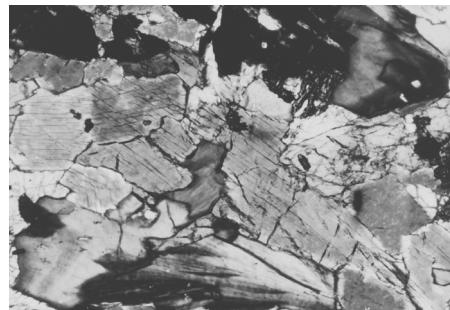
**PLATE 5.3** Thin section with brown biotite, green hornblende (with indistinct 60° cleavage), and clear quartz (PP light).



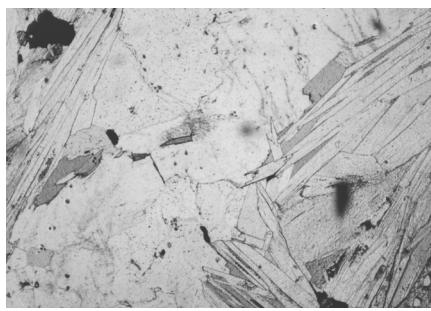
**PLATE 5.4** The same thin section as in Plate 5.3 after stage rotation; note pleochroism.



**PLATE 5.5** Sodic hornblende (blue to green with 60° cleavage), quartz (large, clear grains), chlorite (large, light green flake in top center of photo), and garnet (high-relief clear mineral in bottom center and right of photo) in thin section (PP light).



**PLATE 5.6** The same thin section as in Plate 5.5; yellow to pink interference colors in hornblende, undulatory extinction in quartz, anomalous gray interference colors in chlorite, opaque garnets (XP light).

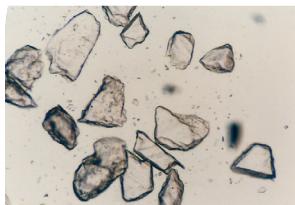


**PLATE 5.7** Quartz, muscovite, biotite, and polysynthetically twinned plagioclase in thin section (PP light).



**PLATE 5.8** The same thin section as Plate 5.7 (XP light).

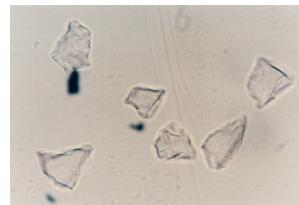
# Optical Mineralogy Color Plates



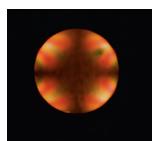
**PLATE 4.1** Fluorite showing strong relief in liquid with  $n=1.512$ .



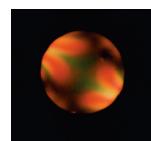
**PLATE 4.2** Fluorite showing weak relief in liquid with  $n=1.452$ .



**PLATE 4.3** Fluorite in liquid with  $n=1.452$ ; the stage has been slightly lowered to show bright Becke line moving into the liquid.



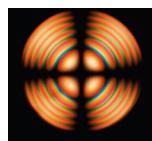
**PLATE 4.5** Olivine interference figure at extinction.



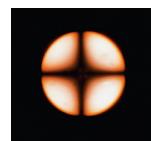
**PLATE 4.6** Olivine interference figure 15° from extinction.



**PLATE 4.7** Olivine interference figure 45° from extinction.



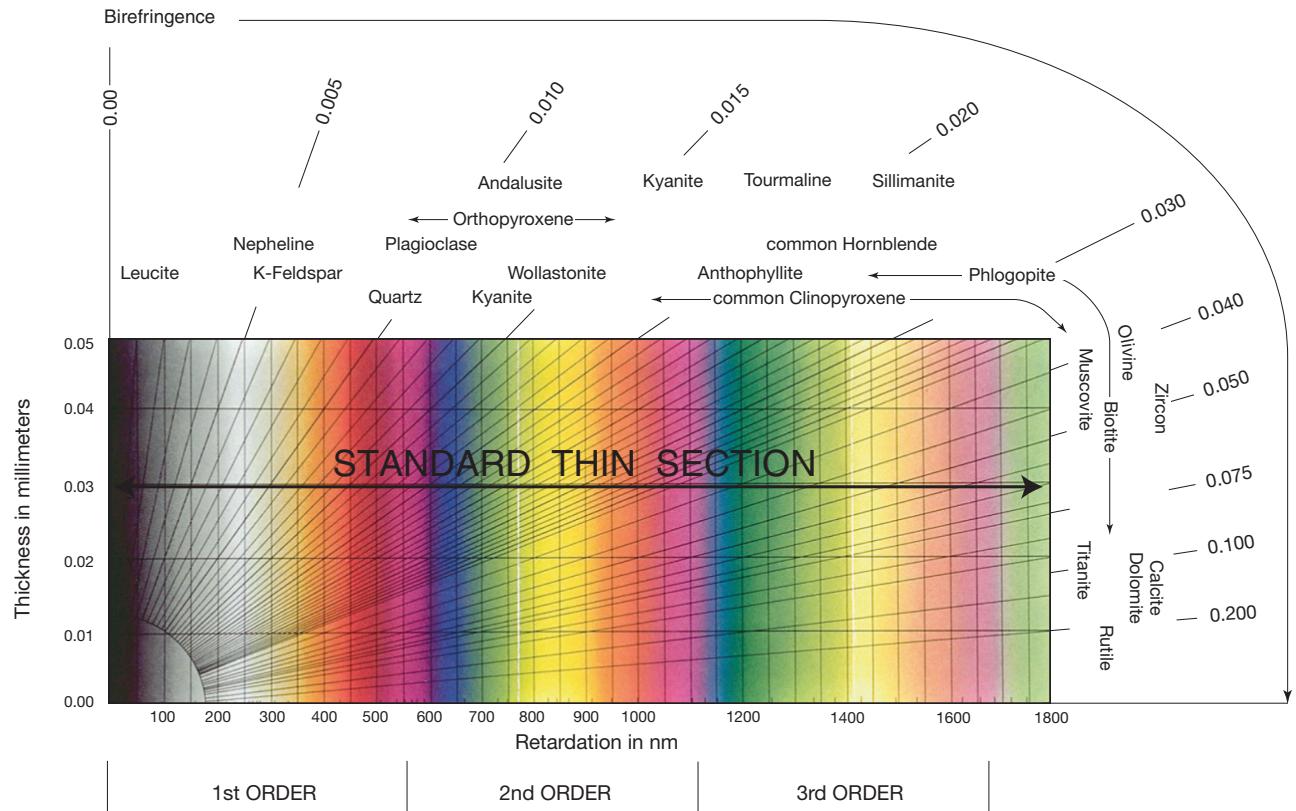
**PLATE 4.8** A nearly centered uniaxial interference figure exhibited by calcite.



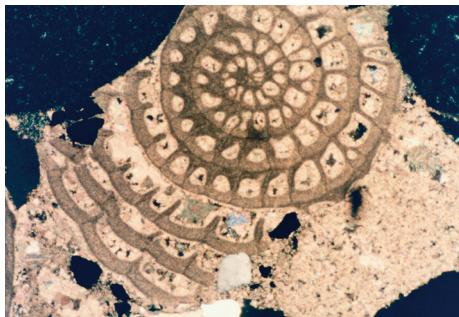
**PLATE 4.9** A nearly centered uniaxial interference figure exhibited by quartz.



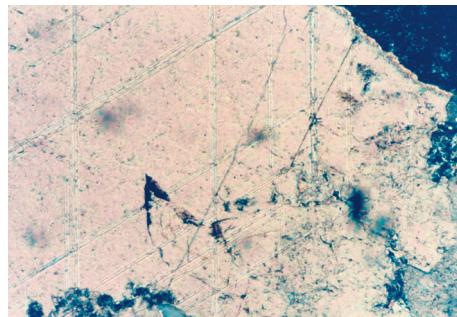
**PLATE 4.10** A nearly centered biaxial interference figure exhibited by biotite.



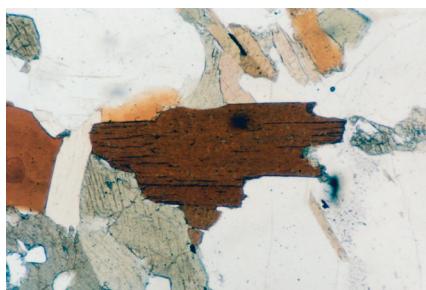
**PLATE 4.11** Michel Lévy Color Chart.



**PLATE 5.1** Thin section view of calcite replacing a foraminifera fossil.



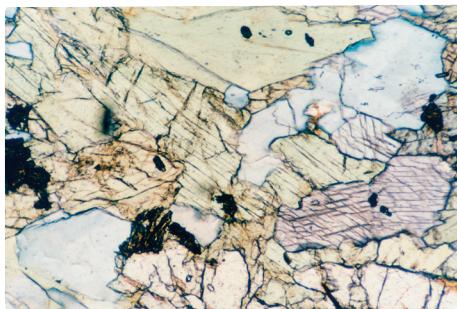
**PLATE 5.2** Calcite in thin section.



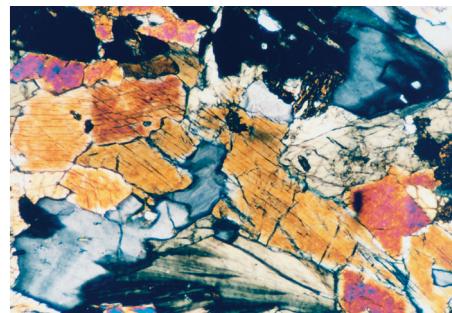
**PLATE 5.3** Thin section with brown biotite, green hornblende (with indistinct 60° cleavage), and clear quartz (PP light).



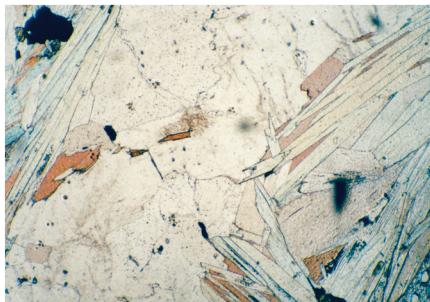
**PLATE 5.4** The same thin section as in Plate 5.3 after stage rotation; note pleochroism.



**PLATE 5.5** Sodic hornblende (blue to green with 60° cleavage), quartz (large, clear grains), chlorite (large, light green flake in top center of photo), and garnet (high-relief clear mineral in bottom center and right of photo) in thin section (PP light).



**PLATE 5.6** The same thin section as in Plate 5.5; yellow to pink interference colors in hornblende, undulatory extinction in quartz, anomalous gray interference colors in chlorite, opaque garnets (XP light).



**PLATE 5.7** Quartz, muscovite, biotite, and polysynthetically twinned plagioclase in thin section (PP light).



**PLATE 5.8** The same thin section as Plate 5.7 (XP light).

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# Igneous Rocks and Silicate Minerals

Igneous minerals crystallize from a magma to form igneous rocks. In this chapter we discuss crystallization processes and the resulting minerals. We point out the chemical differences between igneous rocks of various types and how their mineralogies vary. We place particular emphasis on silicate minerals because of their dominance in Earth's crust, and in igneous rocks in general. A simple scheme for naming igneous rocks is introduced, and some common types of igneous rocks are discussed.

## MAGMAS AND IGNEOUS ROCKS

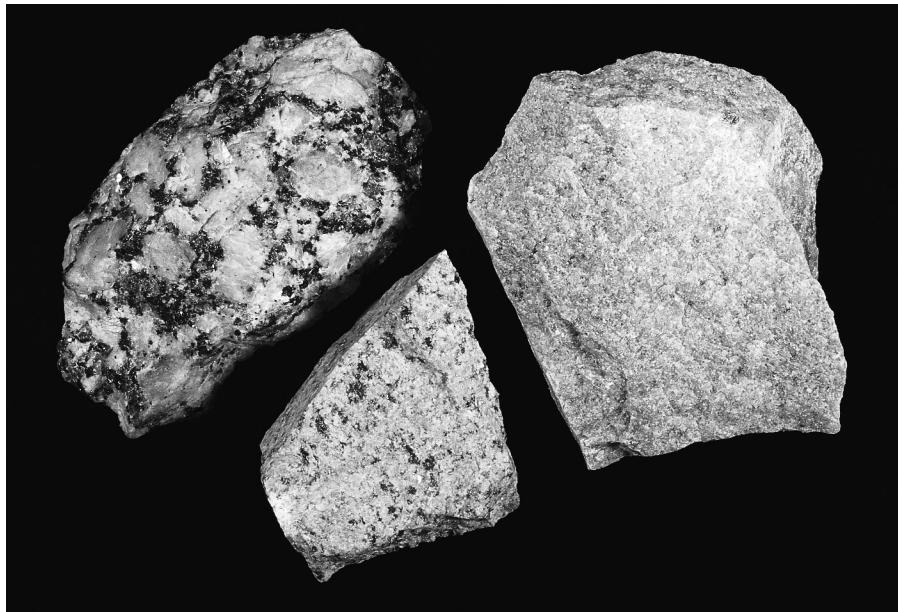
Igneous rocks and minerals form from **magmas**, molten rock that originates beneath Earth's surface. Magma often collects in large magma chambers, but magmas are also mobile; they can flow through fissures and sometimes reach the surface. Mid-ocean ridges and subduction zones account for most magmas at or near Earth's surface. Continental rifts and hot spots, places where anomalous heat rises from depth, account for the rest.

Magmas are complex liquids that vary greatly in composition and properties. They have temperatures as great as 1,400 °C (2,500 °F) and often originate in regions 50 to 200 km (30 to 125 mi.) deep in the Earth. They may be partially crystalline, containing crystals of high-temperature minerals such as leucite, olivine, or clinopyroxene. Because magma has a lower density than the solid upper mantle and crust of the Earth, buoyancy moves it upward. The race between upward movement and cooling ultimately determines whether magma becomes an **intrusive** or **extrusive** igneous rock (Figure 1). Magma solidifies as an intrusive rock if it crystallizes before it reaches the surface. Intrusive rocks often form **plutons** (a general term given to any intrusive igneous rock body), so geologists sometimes use the

terms *intrusive* and *plutonic* interchangeably. If magma reaches the surface while molten, or partially molten, we term it **lava**. The cooling lava forms an **extrusive rock**, also called a **volcanic rock** (although it does not necessarily form a volcano).

Magmas that reach Earth's surface cool quite quickly. In contrast, those that cool at some depth in the Earth do so more slowly, and cooling rate directly affects grain size of an igneous rock. The common plutonic rock granite contains crystals of quartz and potassium feldspar that are easily seen with the naked eye. A common volcanic rock, rhyolite, may contain the same minerals, but we need a microscope to see the crystals (Figure 1). The difference is due to cooling rate. Intrusive rocks cool and crystallize slowly; other very hot rocks surround and insulate them as crystallization occurs. Crystals in granites have a long time to form and grow. In contrast, volcanic rocks, such as rhyolite, crystallize rapidly because extrusion exposes the lava to water or to the cool atmosphere at the surface of the Earth. Sometimes extrusive igneous rocks cool so quickly that no crystals form. This is especially likely to occur if lava meets water. The result is a rock composed of glass called **obsidian**. In other cases,

**FIGURE 1** Three igneous rocks: coarse-grained granite (left), medium-grained granite (center), and rhyolite (right). Granite and other intrusive rocks are generally coarser grained than extrusive rocks such as rhyolite because they had a longer time to crystallize.



different minerals may grow to distinctly different sizes. The result is a **porphyry** in which coarse crystals called **phenocrysts** are floating in a sea of fine-grained crystals called **ground mass**.

Quickly cooled plutonic rocks may be very fine grained and difficult to tell from volcanic rocks. Some petrologists, therefore, prefer to classify and name igneous rocks based on their grain size rather than their genesis (origin). They divide rocks into those containing very fine grains (**aphanitic**), rocks containing very coarse grains (**phaneritic**), and rocks containing combinations of large and small crystals (**porphyritic**).

## COMPOSITIONS OF IGNEOUS ROCKS

### Mafic and Silicic Magmas

Although compositions cover a wide spectrum, most magmas contain 40 to 75 wt % SiO<sub>2</sub> (Box 1). Magmas richest in SiO<sub>2</sub> also tend to be rich in Al<sub>2</sub>O<sub>3</sub>. They may contain appreciable amounts of FeO and Fe<sub>2</sub>O<sub>3</sub>, but are usually deficient in MgO. We term such magmas **silicic** (Si rich), **sialic** (Si and Al rich), or **felsic**. Light-colored minerals dominate felsic rocks, so many geologists use the term *felsic* to refer to any light-colored igneous rock, even if the chemical composition is unknown. At the other end of the spectrum, magmas with <50 wt % SiO<sub>2</sub> are usually rich in MgO and contain more FeO and Fe<sub>2</sub>O<sub>3</sub> than silicic magmas. Thus, we call them **mafic** (Mg and Fe rich) and in some extreme cases, **ultramafic**. They are usually dark in color. The term **intermediate** describes rocks with compositions between mafic and silicic.

Melting of rocks occurs at many places in the Earth, and magma compositions reflect their sources. Mid-ocean ridge and ocean hot-spot magmas are mostly mafic; subduction zone magmas are generally silicic to intermediate. Continental rifts produce a variety of magma types. Besides distinctions between mafic, intermediate, and silicic rocks, petrologists often classify igneous rocks based on the alkali (K<sub>2</sub>O + Na<sub>2</sub>O) and alkaline earth (CaO) contents; alkalic rocks are those with high (K<sub>2</sub>O + Na<sub>2</sub>O): CaO ratios. Some rare and unusual magma types produce igneous rocks rich in nonsilicate minerals such as carbonates or phosphates, but we will not consider them here.

Rocks of different compositions have different melting temperatures because some elements combine to promote melting. Silicon and oxygen, in particular, promote melting because they form very stable molten **polymers** (long chains of Si and O). Silicic minerals, and SiO<sub>2</sub>-rich rocks, therefore, melt at lower temperatures than mafic minerals and SiO<sub>2</sub>-poor rocks. Conversely, magmas of different compositions crystallize at different temperatures. Temperatures measured in flowing lavas generally range from 900 to 1,100 °C (1,650 to 2,010 °F) with higher temperatures corresponding to basaltic (mafic) lavas and lower temperatures to andesitic or rhyolitic (intermediate to silicic) lavas. Eventually, as a magma cools, it crystallizes; the first crystals form at the **liquidus** temperature. With further cooling of up to 200 °C (390 °F), the magma completely solidifies. The last drop of melt crystallizes at the **solidus** temperature. Some magmas crystallize at temperatures well above

**BOX 1****Compositions of Magmas Producing Igneous Rocks (oxide wt %)**

The following table gives compositions of some common magma types, identified by the name of the plutonic rock they produce. The two most important compositional variations in magma— $\text{SiO}_2$  content and ratio  $(\text{K}_2\text{O} + \text{Na}_2\text{O}):\text{CaO}$ —are reflected in the chart.

Rock and mineral compositions are normally given in terms of oxides rather than individual element because (1) oxygen is the only significant anion in most minerals and igneous rocks; (2) oxygen is not normally directly analyzed, so its content must be inferred; and (3) rocks must be charge-balanced (cation charge balanced by anion charge), so it is convenient to list components that are charge-balanced. It should be emphasized that the chemical oxides listed in this table do not refer to specific oxide minerals; oxides are listed to describe the chemical composition only.

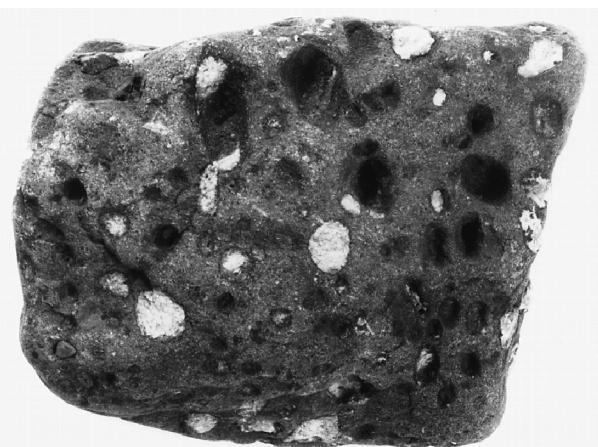
wt % Oxide	SiO <sub>2</sub> -Rich Magmas			SiO <sub>2</sub> -Poor Magmas				
	Higher (Na <sub>2</sub> O + K <sub>2</sub> O)/CaO		Lower (Na <sub>2</sub> O + K <sub>2</sub> O)/CaO	Higher (Na <sub>2</sub> O + K <sub>2</sub> O)/CaO		Lower (Na <sub>2</sub> O + K <sub>2</sub> O)/CaO		
	Alkali Granite	Granite	Tonalite	Alkali Syenite	Syenite	Diorite	Gabbro	Peridotite
SiO <sub>2</sub>	73.86	72.08	66.15	55.48	59.41	51.86	50.78	43.54
TiO <sub>2</sub>	0.20	0.37	0.62	0.66	0.83	1.50	1.13	0.81
Al <sub>2</sub> O <sub>3</sub>	13.75	13.86	15.56	21.34	17.12	16.40	15.68	3.99
Fe <sub>2</sub> O <sub>3</sub>	0.78	0.86	1.36	2.42	2.19	2.73	2.26	2.51
FeO	1.13	1.67	3.42	2.00	2.83	6.97	7.41	9.84
MnO	0.05	0.06	0.08	0.19	0.08	0.18	0.18	0.21
MgO	0.26	0.52	1.94	0.57	2.02	6.12	8.35	34.02
CaO	0.72	1.33	4.65	1.98	4.06	8.40	10.85	3.46
Na <sub>2</sub> O	3.51	3.08	3.90	8.86	3.92	3.36	2.14	0.56
K <sub>2</sub> O	5.13	5.46	1.42	5.35	6.53	1.33	0.56	0.25
H <sub>2</sub> O	0.47	0.53	0.69	0.96	0.63	0.80	0.48	0.76
P <sub>2</sub> O <sub>5</sub>	0.14	0.18	0.21	0.19	0.38	0.35	0.18	0.05

Analyses from Nockolds (1954).

1,000 °C (1,830 °F), but granites and other silicic magmas may crystallize at temperatures as low as 700 °C (1,290 °F).

### Volatiles

Magmas also contain **volatiles** (gas, liquid, or vapor). H<sub>2</sub>O and CO<sub>2</sub> are the most common, but compounds of sulfur, chlorine, and several other elements may also be present. Consequently, although igneous minerals crystallize at high temperatures, they may contain H<sub>2</sub>O, CO<sub>2</sub>, or other gaseous components. Volatiles may separate from a melt to form bubbles, most commonly in cooling lava, creating **vesicles** as the magma solidifies (Figure 2). Water is especially important in the crystallization process. A small amount will appreciably lower melting and crystallization temperatures, change magma viscosity, and produce large amounts of vapor or steam. Steam is often responsible for



**FIGURE 2** Vesicles (bubbles 0.5 to 1.0 cm across) in basalt that formed as the basalt solidified. Percolating pore waters have subsequently filled many of the vesicles with white calcite.



**FIGURE 3** Euhedral tourmaline from a pegmatite at Paraibo, Brazil (5 cm across). Compositional zoning has given different parts of the crystal different colors. Note especially the dark-colored rim. (See Plate 1.1 for a color version of this photo.)

explosions such as those that took place at Mount Saint Helens on May 18, 1980. The vesicle shown in Plate 1.7 may have been filled with liquid or steam after the surrounding basalt initially crystallized.

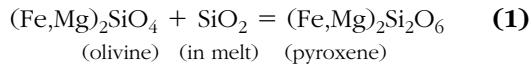
Slowly cooling magmas do not crystallize all at once. After partial crystallization, the remnant melt may contain water and dissolved **incompatible elements** that did not enter any of the minerals already formed. When the remnant melt finally crystallizes, **pegmatites** containing minerals rich in incompatible elements such as potassium (K), rubidium (Rb), lithium (Li), beryllium (Be), boron (B), or rare earth elements (REEs) may result. Pegmatites often contain large euhedral crystals because the water acts as a flux and promotes crystal growth (Figure 3 and Plate 1.4). Many spectacular and valuable mineral specimens come from pegmatites.

## CRYSTALLIZATION OF MAGMAS

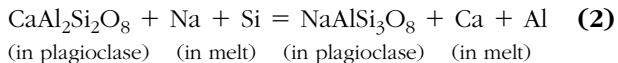
### Equilibrium Between Crystals and Melt

Every mineral has a characteristic melting temperature. This leads to an orderly and predictable process as magma solidifies. For many mafic magmas, olivine and Ca-rich plagioclase, which have high melting temperatures, will be the first minerals to crystallize. As temperature falls, olivine and

Ca-plagioclase may become unstable. Some or all of the olivine may disappear as it reacts with the remaining melt to produce pyroxene by reactions such as:



At the same time, the plagioclase, which has the general formula  $(Ca,Na)(Al,Si)_4O_8$ , may exchange some of its Ca and Al for Na and Si in the remaining melt:



Thus, plagioclase crystals often become richer in albite ( $NaAlSi_3O_8$ ) and poorer in anorthite ( $CaAl_2Si_2O_8$ ) as temperature falls. With continued falling temperature, the pyroxene may become unstable and react with the melt to produce amphibole and then mica, while the plagioclase continues to become more Na-rich. Thus we see that the minerals present during crystallization may change as crystallization continues. However, when crystallization is complete, the minerals present will reflect the overall magma composition.

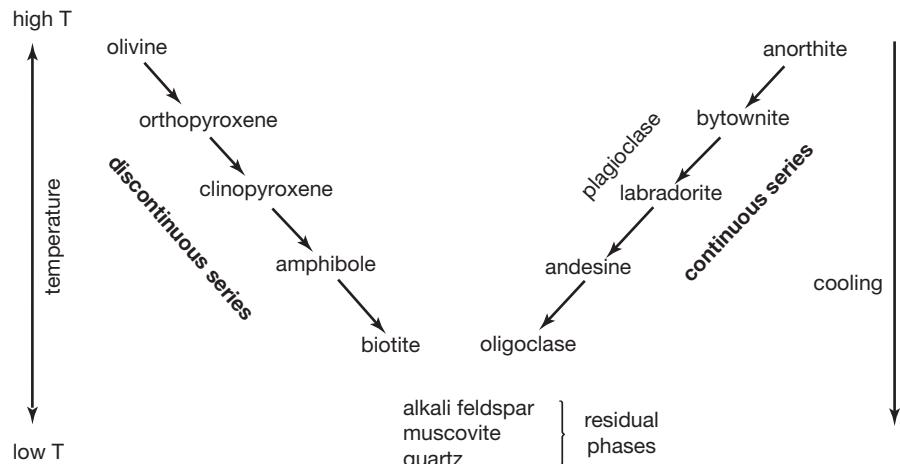
The first minerals to crystallize from silicic magmas are not normally olivine or pyroxene, but instead are more likely to be amphibole, mica, or feldspar. Reactions between minerals and melt take place as cooling continues. In the final stages of crystallization, many silicic magmas crystallize K-feldspar (K-rich alkali feldspar), muscovite, and quartz. When the rock is completely solidified, the relative abundances of the various minerals depend on the overall magma composition.

### Bowen's Reaction Series

N. L. Bowen pioneered in the study of magma crystallization, for which he received the Roebling Medal from the Mineralogical Society of America in 1950. Through study of naturally occurring igneous rocks and laboratory experimentation, he derived an idealized model for equilibrium crystallization in a magmatic system. We call the model **Bowen's reaction series** (Figure 4). Although we cannot discuss some magma types using Bowen's series, it is an excellent model to describe the process of magmatic crystallization. We could develop similar series for magmas of any composition.

Bowen's reaction series shows the order in which minerals crystallize from cooling magma. We call the left-hand side of the series the **discontinuous side** because abrupt changes occur when one mineral

**FIGURE 4** Bowen's reaction series. The names in the continuous series refer to specific compositions of plagioclase. The minerals of the discontinuous series are all solid solutions and so, too, may change composition as crystallization occurs. The residual phases are those often crystallizing from water-rich remnant melts. We frequently find them in pegmatites.



reacts with the melt to produce another (such as olivine reacting to form pyroxene). We call the right-hand side the **continuous side** because plagioclase is continually present during crystallization; as cooling progresses, plagioclase reacts with the melt to maintain an equilibrium composition. The minerals at the bottom of Bowen's series are sometimes called **residual phases** because they crystallize at the end of the process from whatever is left in the melt. Just like plagioclase, minerals on the discontinuous side of the series change composition as cooling proceeds. At higher temperatures, for example, olivine usually has a greater magnesium to iron ratio (Mg:Fe) than at lower temperatures.

Mineral crystallization temperatures depend on mineral composition. Although Bowen created his reaction series by observing the temperatures at which minerals crystallize, it reflects general changes in mineral chemistry during solidification of a magma. Minerals at the top of the series, such as olivine, pyroxene, and calcium-rich plagioclase, are silica poor. Those at the bottom are silica rich. Silica content is the most significant factor controlling melting and crystallization temperatures. The mafic minerals at the top of the discontinuous series also are deficient in aluminum and alkalis and rich in iron and magnesium, compared with minerals at the bottom.

It is important to remember that Bowen's reaction series is an idealized model. If the process always went to completion, all igneous rocks would be combinations of K-feldspar, quartz, and possibly muscovite. Such might be the case for a magma of felsic composition but is not true for most igneous rocks. Consider, for example, a hypothetical melt that is 100% SiO<sub>2</sub>. It cannot crystallize any minerals in Bowen's reaction series except quartz because it does not contain the necessary elements. It will skip all the other minerals.

On the other hand, if a melt were 100% Mg<sub>2</sub>SiO<sub>4</sub>, it would crystallize forsterite (olivine of composition Mg<sub>2</sub>SiO<sub>4</sub>) and be completely solidified. These two extreme examples do not exist in nature, but compositions of natural magmas do control the extent to which crystallization follows Bowen's reaction series. Although all magmas crystallize different minerals at different temperatures, few, if any, follow the complete series.

Mafic magmas, which crystallize at high temperature, may completely solidify after olivine, pyroxene, and some plagioclase have formed. Some rare ultramafic rocks crystallize to nearly 100% olivine. If no melt is left to react with the existing crystals, reactions will stop and the rock will continue to cool with no change in mineralogy. Silicic magmas, which crystallize at lower temperatures, yield rocks rich in K-feldspar and quartz. The melt completely resorbs any mafic minerals that may have crystallized initially.

## Disequilibrium

Minerals do not always remain in equilibrium with magmas as they crystallize. Several things may cause disequilibrium. The crystals may become separated from most of the magma as a whole if they settle or float to form a layer at the bottom or top of the magma chamber. The layer of crystals, termed a **cumulate** if it is sufficiently well developed, may not take part in additional reactions with the melt. Many minerals, including feldspars, pyroxenes, and oxides, can be found in thick, nearly **monomineralic** cumulates. Even if a cumulate layer does not develop, the composition of the upper part of the magma chamber may not be the same as the lower part. When a melt gets separated from early formed crystals, we call the process **partial crystallization** or **fractional crystallization** (Box 2).

**BOX 2****Layered Mafic Intrusions**

Mafic and ultramafic layered intrusions (complexes) are rare but are found worldwide, generally in old continental interiors. The largest, the Bushveld Complex of South Africa, is more than 66,000 km<sup>2</sup> (25,480 sq. mi.). Smaller layered intrusions, such as the Skaergaard Complex (Greenland), may be only 100 km<sup>2</sup> (40 sq. mi.) or less. These complexes show compositional layering due to fractional crystallization. They consist of cumulate layers piled on top of each other. Early formed crystals settle to the bottom of the magma chamber because they are denser than the melt. As the magma cools and other minerals crystallize, they too settle. Consequently a layered sequence develops with ultramafic (high-temperature) minerals at the bottom and successively more silicic (lower-temperature) on top. Besides silicates, chromite and other oxide minerals may settle to form layers. Rarely, plagioclase forms a cumulate layer at the top of a magma chamber when it floats on denser magma.

Because of their high metal content and natural separation into layers, layered complexes are often rich ore deposits, especially known for producing platinum group metals (ruthenium, rhodium, palladium, osmium, iridium, platinum). The Bushveld complex is, perhaps, the most valuable ore deposit in the world, producing significant amounts of platinum group metals, as well as chromium, iron, tin, titanium, and vanadium. In the United States, Montana's Stillwater Complex (Figure 5) is one of the world's leading producers of platinum group minerals and accounts for most of the platinum and palladium mined in the western hemisphere.

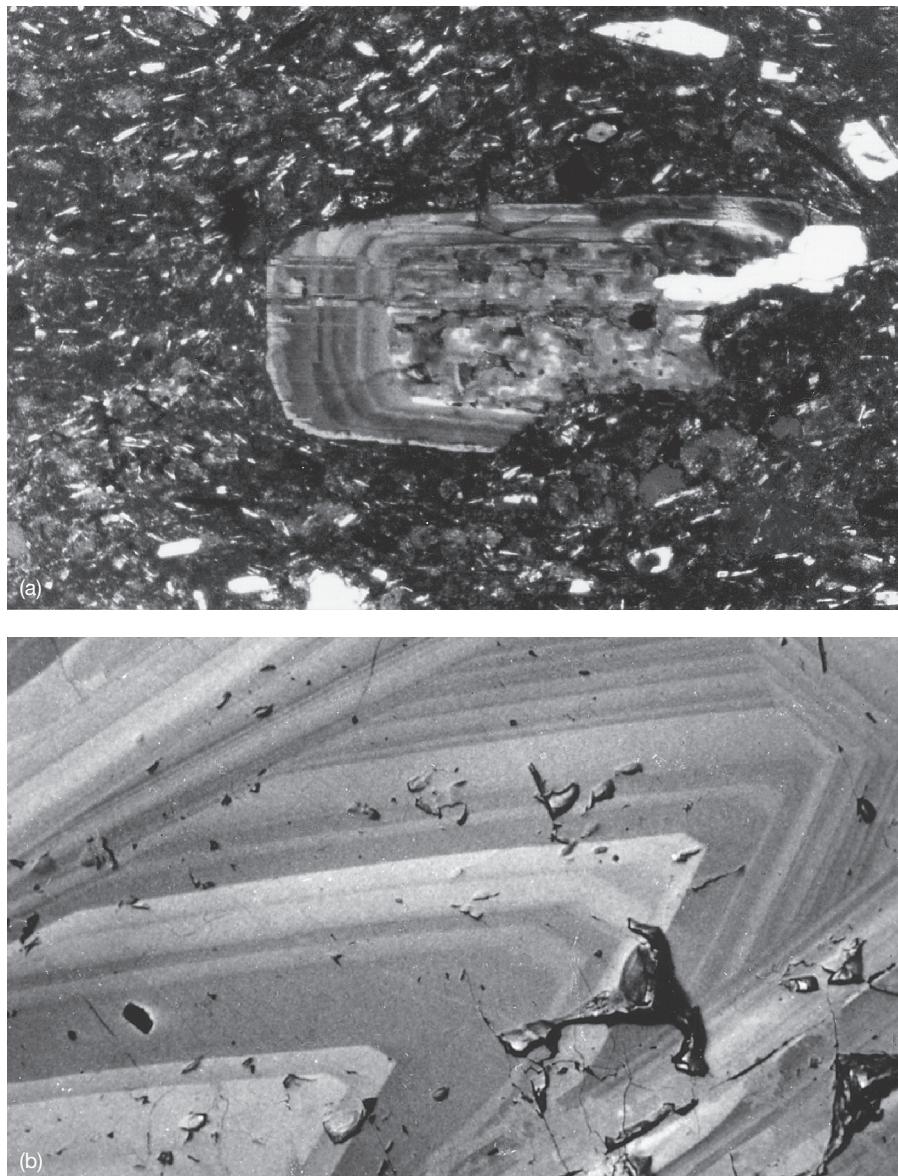


**FIGURE 5** The Stillwater Complex in Montana. The top view shows students examining an outcrop containing several different kinds of ultramafic rock. The bottom close-up shows the darker colored rock in the center of the top photograph. This rock is an orthopyroxene cumulate. Most of the dark grains are orthopyroxene that settled to the bottom of a magma chamber as it crystallized. Subsequently lighter-colored plagioclase filled the spaces between the pyroxene grains. Photographs taken by Kurt Hollocher.

Fractional crystallization is a significant process in the Earth; it caused the chemical differentiation making the Earth's crust more silicic than the mantle. Goldschmidt and others hypothesized that the process of differentiation due to melting and crystallization explained all compositional layering in the Earth. Today, most geologists believe that differentiation has been important throughout Earth's history but that the Earth may not have been completely homogeneous at its start.

Besides separation of crystals and melt, disequilibrium occurs for other reasons. Sometimes large mineral grains do not remain in equilibrium with a surrounding magma. Because diffusion of elements through solid crystals is slow, the central

parts of large crystals may not have time to maintain equilibrium compositions. In compositionally **zoned** crystals, only the outermost zones remain in equilibrium with the melt as crystallization takes place. Marked chemical zonation often occurs if a magma begins to cool at one depth and then rapidly moves upward to cooler terrane. The result will be a porphyritic rock with large zoned phenocrysts. The zones may be visible with the naked eye if color or textural variations mirror the compositional variations (Figure 3; Plates 1.1 and 1.2). If the zoning is not visible to the naked eye, it may be visible with a petrographic microscope or with a scanning electron microscope (Figure 6a and b). Sometimes, however, we can only discern zoning with sophisticated analytical instruments.



**FIGURE 6** A Zoned crystals:  
(a) plagioclase crystals sometimes show zoning as light and dark bands when viewed in thin section (photo is about 1 mm across); (b) zoning in a columbite crystal (photo is about 0.35 mm across) viewed with a scanning electron microscope.

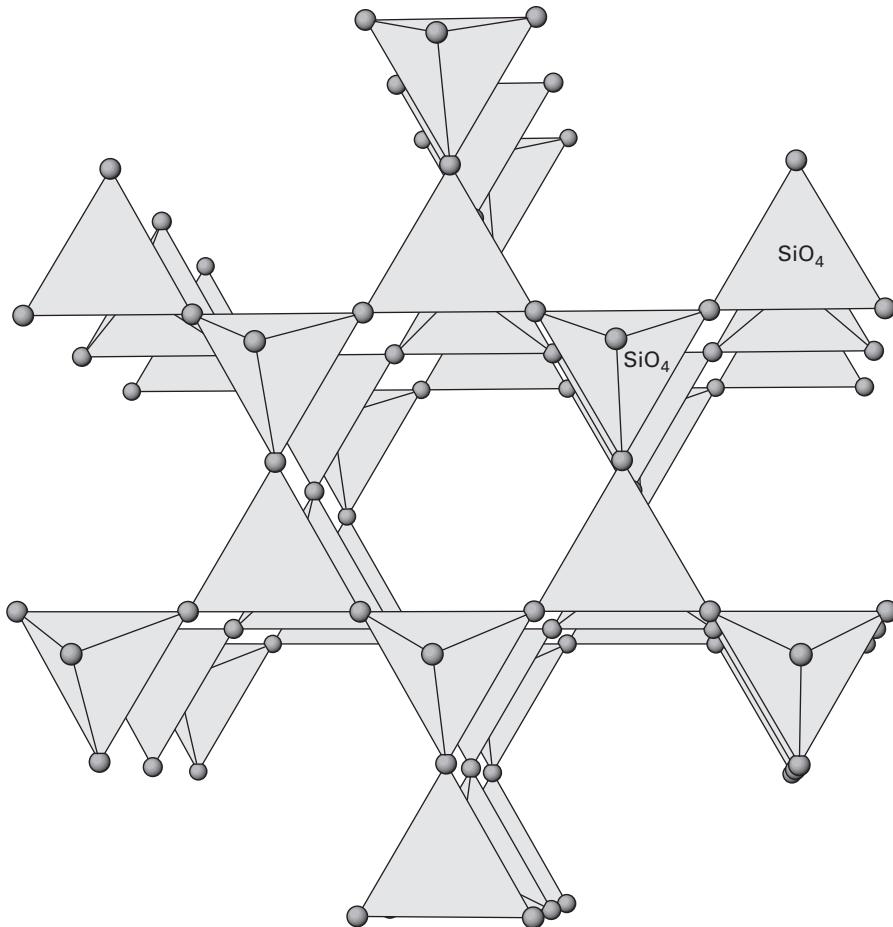
## SILICATE MINERALS

Silicate minerals dominate igneous rocks because silicon (Si) and oxygen (O) are the most common elements in the source regions for magmas. The following discussions systematically consider the important silicate minerals and groups. We begin by considering the  $\text{SiO}_2$  polymorphs, the feldspars, and the **feldspathoids**, mineral groups within the **framework silicate** subclass. Silicates have structures containing polymerized or combinations of  $\text{SiO}_4$  and  $\text{AlO}_4$  tetrahedra (Figure 7). In framework silicates, all oxygen atoms are shared between two tetrahedra, creating a three-dimensional network. In **feldspars** and

**feldspathoids**, alkalis and alkaline earths occupy large sites between tetrahedra. Figure 7 shows the structure of tridymite, one of the  $\text{SiO}_2$  minerals. Other framework silicates have tetrahedra arranged differently.

### **SiO<sub>2</sub>** Polymorphs

Quartz, like many other minerals, is polymorphic (meaning “having many forms”); mineralogists and chemists have identified more than 10 different  $\text{SiO}_2$  polymorphs, some of which do not occur as minerals. Common quartz, more properly called *low quartz* (because it has lower symmetry than high quartz), is the only common polymorph stable



**FIGURE 7** The structure of tridymite shows one way tetrahedra join to create a framework silicate. In tridymite, all tetrahedra contain  $\text{Si}^{4+}$  at their centers, but in feldspars, and some other framework silicates, some tetrahedra contain  $\text{Al}^{3+}$ .

under normal Earth surface conditions, but it has many different appearances (Plates 2.1 through 2.8). Other polymorphs, which exist metastably at the Earth's surface, often change into low quartz given enough time. Still others only exist at high temperatures or high pressures. If all rocks maintained and stayed at equilibrium, we would have no samples of any silica polymorphs other than low quartz to study.

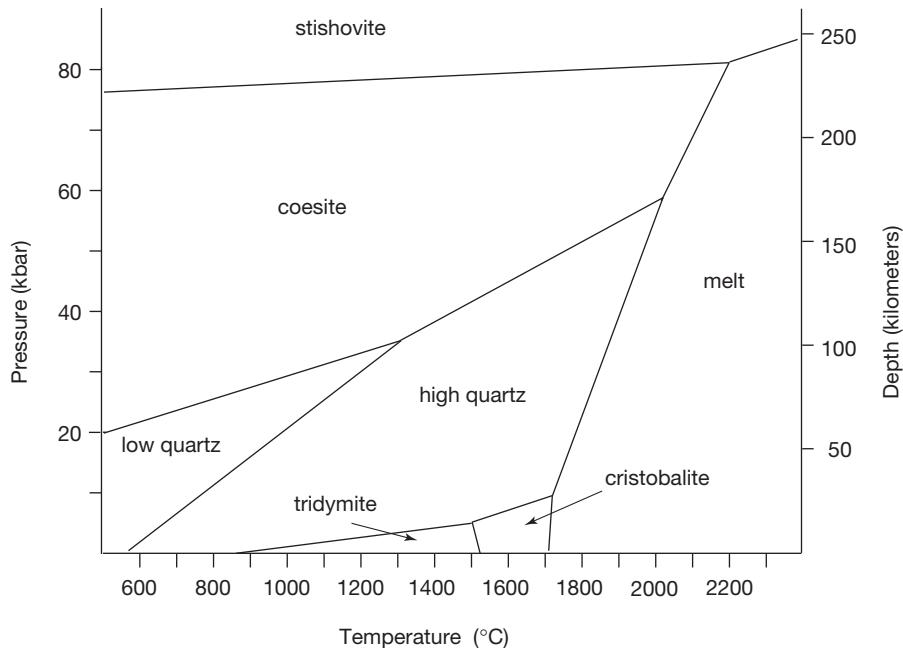
Quartz may crystallize from magmas, silica-saturated groundwaters, or hydrothermal solutions. It is an essential mineral in silicic and intermediate igneous rocks, many sediments, and many metamorphic rocks. In some sedimentary rocks, such as chert or sandstone, it may be the only mineral present. In silicic and intermediate igneous rocks, quartz is commonly found with K-feldspar. Both are Si-rich minerals that form at relatively low temperature. Quartz is not normally found in mafic igneous rocks;  $\text{SiO}_2$  is too scarce to remain after crystallization of mafic minerals such as olivine or pyroxene. Quartz cannot exist in rocks containing corundum,  $\text{Al}_2\text{O}_3$ , because the two would react to form an  $\text{Al}_2\text{SiO}_5$  mineral. It cannot exist in rocks containing feldspathoids (leucite, nepheline, or analcime)

because quartz and feldspathoids react to give feldspars. For similar reasons, quartz is absent or minor in many alkali-rich igneous rocks and in rocks containing the oxide mineral spinel,  $\text{MgAl}_2\text{O}_4$ .

For several decades, petrologists have understood that different silica polymorphs occur in different geological settings because they are stable under different pressure-temperature conditions. Figure 8, a phase diagram, shows the stability relationships of some  $\text{SiO}_2$  polymorphs. The vertical scale on the left gives pressures in kilobars (thousands of atmospheres), and the scale on the right shows the depths in the Earth corresponding to those pressures.

Pressure-temperature (P-T) phase diagrams such as Figure 8 show which mineral or mineral assemblage is stable for any combination of P-T (Box 3). Low quartz is the stable phase over a wide range of P-T, including normal Earth surface conditions; it is therefore the most common polymorph. Stishovite and coesite are dense minerals, only stable at very high pressures—pressures not normally encountered in the Earth's crust. They are usually associated with meteorite impact craters. Tridymite and cristobalite only exist in certain high-temperature silicic volcanic rocks. They require

**FIGURE 8** Phase diagram showing the stability fields of some of the  $\text{SiO}_2$  polymorphs, and the melting field at high temperature. Individual  $\text{SiO}_2$  polymorphs (e.g., stishovite, coesite, or high quartz) are stable in the regions labeled. Two polymorphs may coexist at pressure-temperature conditions that fall on a line. Three polymorphs may coexist if conditions fall on a point where lines intersect. Most of this diagram is space between lines. So, only one polymorph is stable under most pressure-temperature conditions.



temperatures greater than  $900\ ^{\circ}\text{C}$  ( $1,650\ ^{\circ}\text{F}$ ) to form. Although not shown in Figure 8, as with quartz, tridymite and cristobalite have both high- and low-symmetry polymorphs.

### Feldspar Group

**Feldspars** are the most abundant minerals in the Earth's crust, in part because they contain six of the seven most abundant elements in the crust. They are

### BOX 3

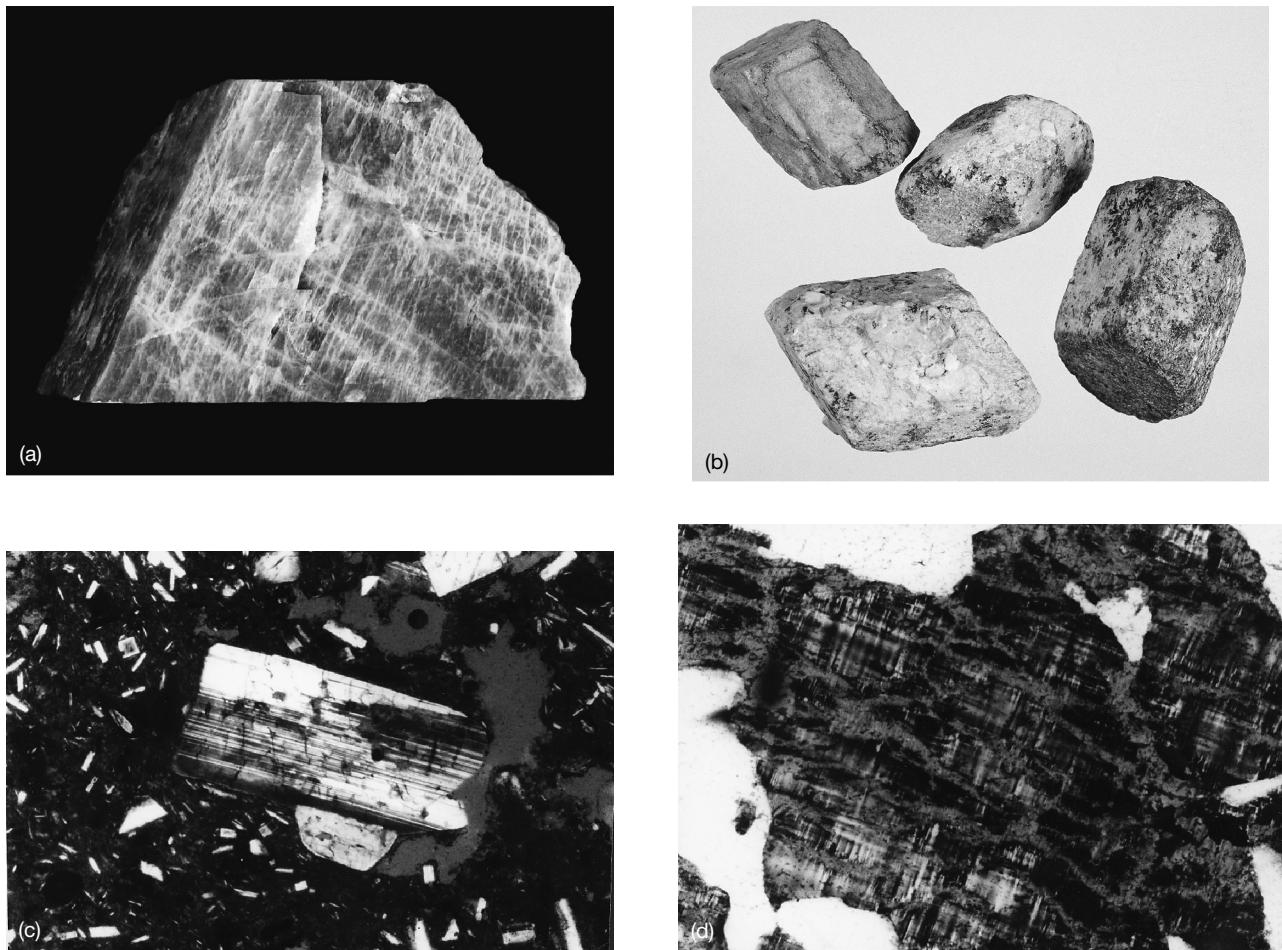
#### Experimental Petrology and Phase Diagrams

Mineralogists and petrologists use many types of phase diagrams. All are designed to show variation in mineral or mineral assemblage stability as physical or chemical conditions change. The most common kind of mineralogical phase diagram, referred to as a P-T diagram, has pressure and temperature as its two axes. Normally, pressure corresponds to the vertical axis, and temperature to the horizontal axis. P-T diagrams show the stability fields for specific minerals or mineral assemblages in pressure-temperature space. Figure 8 is a P-T diagram for the chemical system  $\text{SiO}_2$ , a system that includes quartz and its polymorphs. Pressure increases upward and temperature increases to the right. Some petrologists flip the vertical axis and draw P-T diagrams with pressure increasing downward, because the pressure within the Earth increases with depth.

Geologists generally derive phase diagrams by conducting experiments in the laboratory. They combine minerals or chemicals, allow them to react under different conditions, and then examine the results. We call this area of research *experimental petrology*. After many careful experiments, experimental petrologists can construct phase diagrams. Like most scientific results, phase diagrams are refined or modified when experimental petrologists gain more information or conduct further experiments. Experimental petrology is expensive and painstaking work. Consequently, only a few laboratories are producing most of the best results today.

Figure 8 shows which of the  $\text{SiO}_2$  polymorphs are stable under different pressure-temperature conditions. To determine the stable polymorph at any P-T, draw a horizontal line at the pressure of interest and a vertical line at the temperature of interest. They intersect within a specific *stability field*, labeled with the stable  $\text{SiO}_2$  mineral name. Although the temperature scale does not go below  $500\ ^{\circ}\text{C}$  ( $930\ ^{\circ}\text{F}$ ), at room temperature and pressure ( $25\ ^{\circ}\text{C}/77\ ^{\circ}\text{F}$  and 1 atm) low quartz is stable. At the highest pressures, stishovite is stable because, as we shall see, it is the densest of the  $\text{SiO}_2$  minerals. At the highest temperatures,  $\text{SiO}_2$  melts.

Although P-T diagrams such as in Figure 8 are often useful and informative, they only apply to specific chemical systems. Sometimes elemental substitutions in minerals cause significant changes in size and location of stability fields. Furthermore, phase diagrams only apply to mineral systems that stay in equilibrium, and many geological systems do not. For example, cristobalite, a mineral normally stable only at high temperature, sometimes crystallizes as chalcedony in low-temperature sedimentary rocks.



**FIGURE 9** Plagioclase and alkali feldspar in hand specimen (photos a and b are about 5 cm across) and thin section (0.7-mm field of view): (a) plagioclase feldspar; (b) orthoclase crystals, each about 1.5 cm in longest dimension; (c) large plagioclase crystal in thin section showing characteristic gray and white stripes indicative of twinning; (d) microcline (an alkali feldspar) in thin section showing characteristic Scotch-plaid twinning.

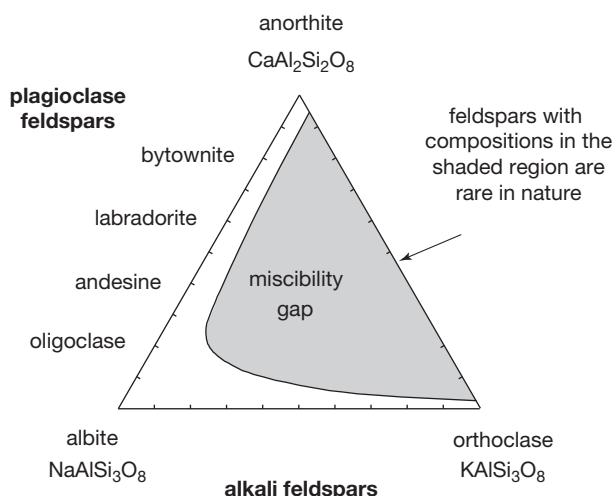
usually easy to distinguish in thin section but may be difficult to tell apart in hand specimen (Figure 9). Feldspars are essential minerals in many igneous, metamorphic, and sedimentary rocks and are stable over a wide range of pressure-temperature conditions, although they will eventually break down when subjected to weathering. They are solid-solution minerals and have the general formula  $(\text{Ca}, \text{Na}, \text{K})(\text{Al}, \text{Si})_4\text{O}_8$ . Rarely, they contain significant amounts of other elements such as  $\text{Ba}^{2+}$ ,  $\text{Sr}^{2+}$ ,  $\text{B}^{3+}$ , or  $\text{Fe}^{3+}$ . For most purposes, we consider them as ternary solutions, which means we can describe their composition in terms of three end members (Figure 10). Box 4 discusses in more detail how we use triangular diagrams to plot mineral compositions.

The important feldspar end members have compositions  $\text{NaAlSi}_3\text{O}_8$  (albite),  $\text{CaAl}_2\text{Si}_2\text{O}_8$  (anorthite), and  $\text{KAlSi}_3\text{O}_8$  (orthoclase). We call any feldspar near  $\text{NaAlSi}_3\text{O}_8$  in composition *albite*, and one near to  $\text{CaAl}_2\text{Si}_2\text{O}_8$  *anorthite*. Plate 6.8 shows albite from a

classic locality at the town of Amelia Court House, Virginia. We term feldspars having compositions close to  $\text{KAlSi}_3\text{O}_8$  *K-feldspar* or *alkali feldspar*. If we know the crystal structure, we may be more specific and distinguish among the different K-feldspar polymorphs: *orthoclase*, *microcline*, and *sanidine*. Plate 1.5 shows twinned orthoclase crystals.

Feldspars form two distinct series, shown on the triangular composition diagram in Figure 10. Plagioclase, sometimes called *plagioclase feldspar*, is generally a solid solution of  $\text{CaAl}_2\text{Si}_2\text{O}_8$  and  $\text{NaAlSi}_3\text{O}_8$ , anorthite and albite, although it may contain up to 10 wt %  $\text{KAlSi}_3\text{O}_8$ . Alkali feldspars, mostly solutions of  $\text{KAlSi}_3\text{O}_8$  and  $\text{NaAlSi}_3\text{O}_8$ , sometimes contain up to 15 wt %  $\text{CaAl}_2\text{Si}_2\text{O}_8$ . All feldspars are framework silicates containing both  $\text{SiO}_4$  and  $\text{AlO}_4$  tetrahedra.

Usually, we describe the compositions of feldspars by using abbreviations with subscripts. Ignoring  $\text{Fe}^{3+}$ , the feldspar has composition about  $(\text{Ca}_{0.03}\text{Na}_{0.62}\text{K}_{0.35})(\text{Al}_{1.03}\text{Si}_{2.97})\text{O}_8$ , so it contains 3 mol %



**FIGURE 10** The feldspar ternary. Natural feldspars rarely have compositions that fall within the shaded region (the miscibility gap). The gap gets smaller at high temperature. We normally describe feldspar compositions using the three end members at the corners of the diagram: anorthite, albite, and orthoclase. Less commonly we use bytownite, labradorite, andesine, and oligoclase to refer to intermediate plagioclase compositions.

anorthite ( $\text{CaAl}_2\text{Si}_2\text{O}_8$ ), 62 mol % albite, ( $\text{NaAlSi}_3\text{O}_8$ ), and 35 mol % orthoclase ( $\text{KAlSi}_3\text{O}_8$ ). We abbreviate its composition  $\text{An}_3\text{Ab}_{62}\text{Or}_{35}$  or say  $X_{\text{An}} = 3$ ,  $X_{\text{Ab}} = 62$ , and  $X_{\text{Or}} = 35$ . The symbol  $X$  stands for mole fraction when we use it to describe a solid solution. Because feldspars vary greatly in composition, mineralogists have divided the composition triangle into small ranges, each with its own name (Figure 10). Labradorite, for example, is plagioclase with composition between  $\text{An}_{70}\text{Ab}_{30}$  and  $\text{An}_{50}\text{Ab}_{50}$ . Small amounts of  $\text{KAlSi}_3\text{O}_8$  may be present in labradorite as well. Confusion arises because the names of some composition ranges are the same as the feldspar end members (albite, anorthite, orthoclase). Albite, for example, is the name given to end member  $\text{NaAlSi}_3\text{O}_8$ . It is also the name we give to any feldspar that is  $>90\%$   $\text{NaAlSi}_3\text{O}_8$ .

As with the  $\text{SiO}_2$  minerals, some feldspar compositions have more than one polymorph. Figure 12 is a temperature-composition phase diagram showing how alkali feldspars vary with temperature. Sodic (Na-rich) feldspars have different atomic structures at high, medium, and low temperatures. At high temperatures, just below their

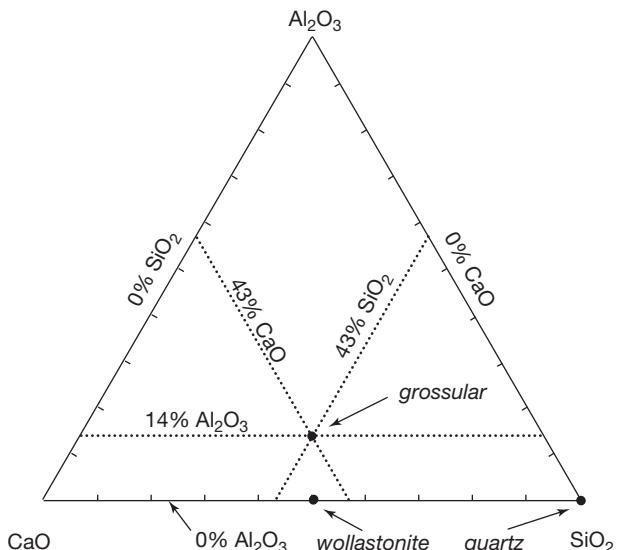
#### BOX 4

##### How to Use Triangular Diagrams

Triangular diagrams (**ternary diagrams**) may be used to plot the mineralogy or chemistry of rocks or magma. The diagrams provide a concise picture of composition. We may use them to differentiate different rocks and mineral assemblages, or to identify possible reactions that may take place between minerals or between minerals and magma.

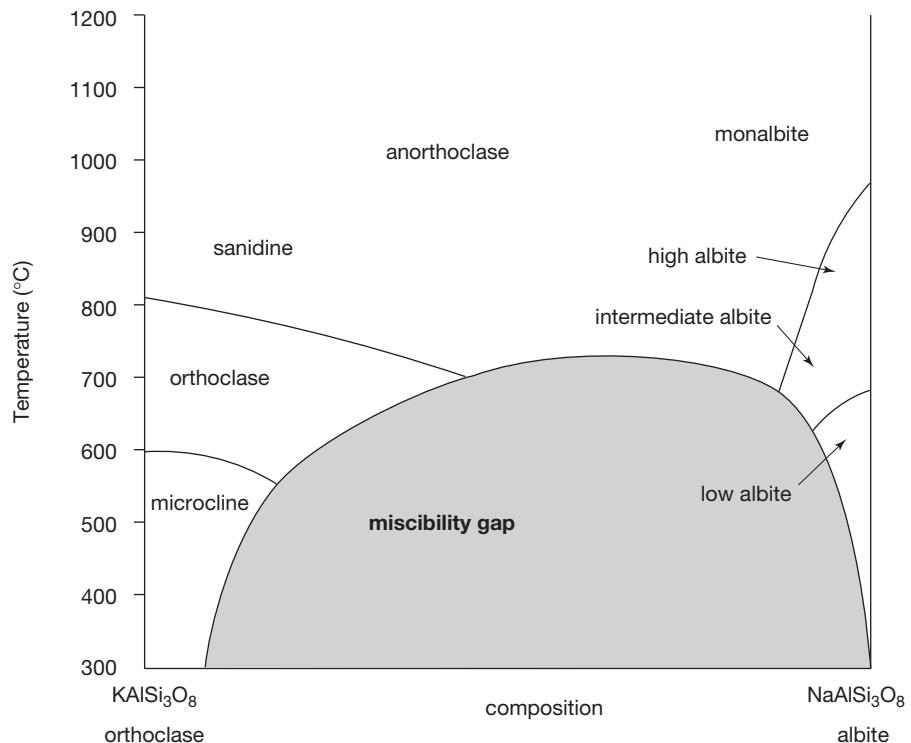
Figure 11 is a  $\text{CaO-Al}_2\text{O}_3-\text{SiO}_2$  ternary diagram; such diagrams are often used to plot the compositions of minerals in Ca-Al-rich metamorphic rocks. Each apex represents a chemical component. Mole percentages are generally used to plot mineral compositions. Quartz, 100 mol %  $\text{SiO}_2$ , plots at the  $\text{SiO}_2$  apex; compositions containing no  $\text{SiO}_2$  plot on the side opposite the  $\text{SiO}_2$  apex, on the line joining the  $\text{CaO}$  and  $\text{Al}_2\text{O}_3$  apices. Compositions containing some  $\text{SiO}_2$  plot between the  $\text{SiO}_2$  apex and the  $\text{CaO-Al}_2\text{O}_3$  join, depending on the amount of  $\text{SiO}_2$  they contain. Similarly, compositions containing all three components plot in the triangle's interior; the distance from the component apex is proportional to the amount of the component they contain.

Wollastonite,  $\text{CaSiO}_3$ , plots halfway between  $\text{CaO}$  and  $\text{SiO}_2$  because it contains an equal number of moles of  $\text{CaO}$  and  $\text{SiO}_2$  in its formula. Grossular,  $\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ , has  $\text{CaO}:\text{Al}_2\text{O}_3:\text{SiO}_2$  ratio 3:1:3, equivalent to 43%  $\text{CaO}$ , 14%  $\text{Al}_2\text{O}_3$ , and 43%  $\text{SiO}_2$ . Any two of the three percentages can be used to plot grossular on the diagram. Because it contains an equal number of moles of  $\text{CaO}$  and  $\text{SiO}_2$ , it plots at equal distances from the  $\text{CaO}$  and  $\text{SiO}_2$  apices.



**FIGURE 11**  $\text{CaO-Al}_2\text{O}_3-\text{SiO}_2$  ternary diagram. We use ternary (triangular) diagrams to plot the compositions of minerals or rocks containing three main chemical components. Such diagrams provide a visual picture of compositional relationships. This figure is useful for showing the compositions of minerals in some marbles and marls.

**FIGURE 12** Schematic diagram showing alkali feldspar polymorphs stable at different temperatures at 1 atm pressure. The vertical axis shows temperature and the horizontal axis shows feldspar composition. Mineralogists give names to feldspars of different compositions formed at different temperatures. Each feldspar species has its own stability field, and each has an atomic arrangement slightly different from the others. For compositions and temperatures that fall within the shaded area (the miscibility gap), no single feldspar is stable.



melting points, we call them *monalbite*. At lower temperature, three other polymorphs exist, all generally called albite. At the other end of the alkali feldspar series, the stable K-feldspars are sanidine, orthoclase, and microcline at high, medium, and low temperatures, respectively. Unlike the  $SiO_2$  polymorphs, the differences in atomic structure between the K-feldspar polymorphs are not great and the boundaries on phase diagrams are not well known. When high-temperature feldspars change into low-temperature ones because of cooling or reequilibration at the Earth's surface, twinning often results.

In principle, alkali feldspars can have any composition between albite and K-feldspar ( $Ab_{100}Or_0$  to  $Ab_0Or_{100}$ ), but intermediate compositions, called *anorthoclase*, are stable only at high temperatures, where the two end members are sanidine ( $KAlSi_3O_8$ ) and monalbite ( $NaAlSi_3O_8$ ). At low temperatures, two separate feldspars form instead because a **miscibility gap** exists between albite and orthoclase (Box 5). A miscibility gap is a composition range within which no single mineral is stable under a particular set of pressure-temperature conditions. Many mineral series show complete miscibility at high temperatures, meaning that all compositions are stable. At low temperatures, partial or complete **immiscibility** restricts possible compositions. We might make an analogy to a pot of homemade chicken soup that

separates into two compositions (fat and chicken stock) after cooling.

We call the process of a single feldspar separating into two compositions **exsolution**, equivalent to **unmixing**. If an intermediate-composition alkali feldspar cools rapidly, it may not have time to exsolve. Thus, we have examples of anorthoclase to study. On the other hand, if cooling is slow, the feldspar will unmix. This may result in separate grains of K-feldspar (orthoclase or microcline) and Na-rich feldspar. More often, it results in alternating layers or irregular zones of albite and orthoclase within the original grain. If the layers or zones are planar or nearly so (appearing long and thin in thin section), we call them **exsolution lamellae**. The layering or zones are sometimes visible with the naked eye, but frequently require a microscope to detect (see Figure 22a). If the original feldspar was K-rich, most of the layers will be K-feldspar. After it exsolves, we call it *perthite*. If the original feldspar was Na-rich, most of the layers will be albite. After exsolution, we call it *antiperthite*. Plate 6.7 shows salmon-colored perthite; the exsolution lamellae are thin, and it takes an active imagination to see them with the naked eye. If the lamellae in perthite or antiperthite are microscopic, they may give mineral grains a **schiller** effect that can help with mineral identification. Schiller is a play of colors caused by light interference due to very fine exsolution lamellae.

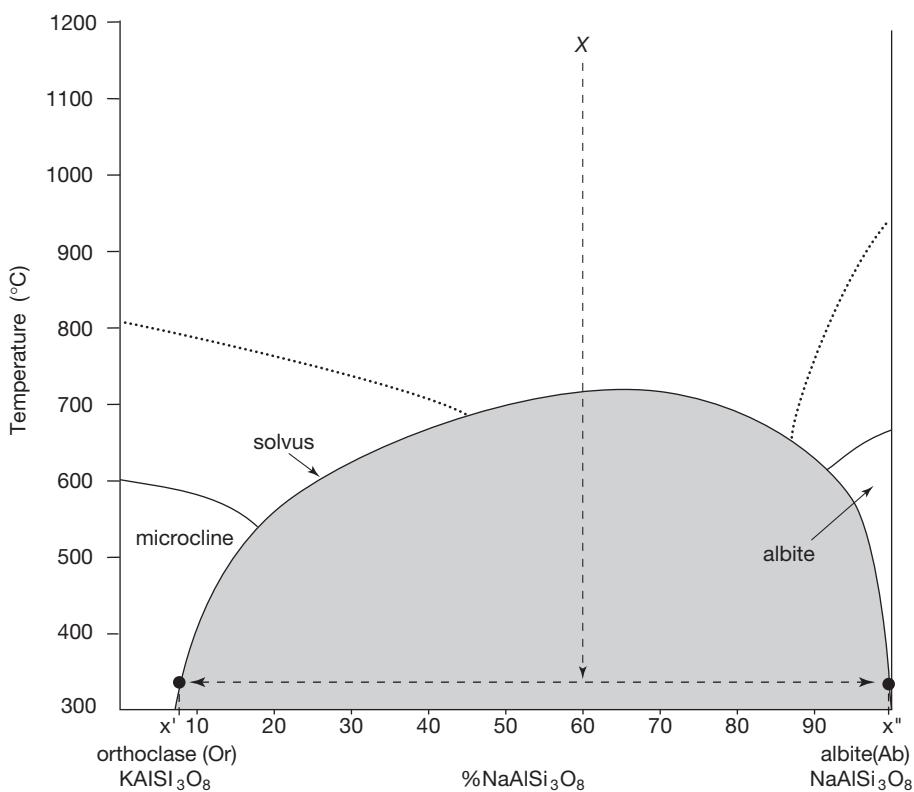
In contrast with alkali feldspars, plagioclase compositions spanning the entire albite-anorthite

## BOX 5

## Miscibility Gaps

Figure 13 shows the same temperature-composition ( $T$ - $X$ ) phase diagram as Figure 12. For a given composition and a given temperature, the diagram shows what mineral or minerals will be stable. The miscibility gap in the center of the diagram means that feldspars of intermediate composition are not stable except at very high temperatures ( $>700\text{ }^{\circ}\text{C}/1,292\text{ }^{\circ}\text{F}$ ). Instead, low-temperature rocks contain two separate feldspars (for example,  $X'$  and  $X''$ ), usually a K-feldspar and plagioclase. The curves outlining the miscibility gap and showing the compositions of the two separate feldspars are called the **solvus**.

Consider a feldspar of composition  $\text{Ab}_{60}\text{Or}_{40}$  (marked with an  $X$  on the diagram). At high temperature, it will exist as one alkali feldspar (anorthoclase). At low temperature it separates into two feldspars, as shown, one called *albite* (plagioclase, shown by  $X''$ ) and one called *microcline* (a K-feldspar shown by  $X'$ ). The phase diagram indicates that the composition of the albite will be very close to end member  $\text{NaAlSi}_3\text{O}_8$ , while that of the microcline will be about  $\text{Ab}_7\text{Or}_{93}$ .



**FIGURE 13** 1 atm pressure  $T$ - $X$  diagram for alkali feldspars. The compositions of stable feldspar species below about  $700\text{ }^{\circ}\text{C}$  can be found by drawing a horizontal line at the temperature of interest and noting the two points (and corresponding compositions) where it intersects the solvus.

series are common. At high temperatures all compositions are stable. At lower temperatures several small solvi exist which—if cooling is slow enough—may result in microscopic exsolution. The exsolution may give the feldspars an iridescence or a play of colors that helps to identify them. Labradorite, for example, often shows a bluish schiller in hand specimen. Because exsolution if present in plagioclase is on a very fine scale, mineral properties are relatively homogeneous. For most purposes, we can ignore the presence or absence of exsolution in plagioclase. In thin

section, we can usually identify plagioclase by its characteristic twinning (see Figure 9). Although generally only visible in thin section, less commonly the twinning appears as fine lines on crystal faces in hand specimens.

The melting temperatures of the two plagioclase end members are different, as depicted by Bowen's reaction series; albite melts at lower temperature than anorthite (Box 6). For intermediate compositions, melting relationships are complicated because when a feldspar melts, the first melt produced is more sodic than the feldspar itself. In

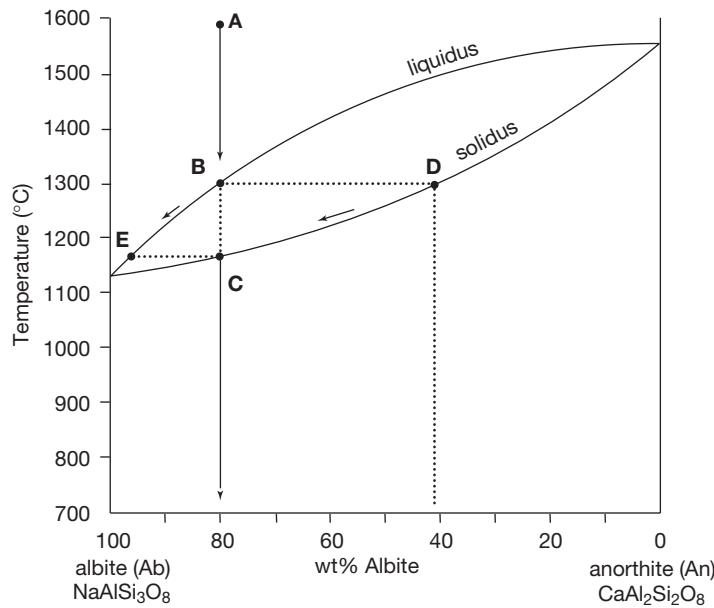
**BOX 6****The Plagioclase Phase Diagram and Fractional Crystallization**

Figure 14 is a T-X phase diagram describing plagioclase melting and crystallization at 1 atm pressure. Composition varies across the diagram because plagioclase is normally a mixture of two end members, albite and anorthite. Plagioclase that is 100% albite plots on the left-hand side, and albite content decreases across the diagram until 100% anorthite is reached on the right-hand side. Temperature increases from the bottom of the diagram to the top. At the highest temperatures, above the liquidus, plagioclase of any composition will melt. At the lowest, below the solidus, any plagioclase will be solidified. In between, some compositions will melt and some will be solid.

Point A represents an albite-rich feldspar melt at 1,600 °C (2,910 °F). The melt has the same composition as plagioclase that is 80% albite and 20% anorthite ( $\text{Ab}_{80}\text{An}_{20}$ ) but is completely molten. As the melt cools, at about 1,300 °C (2,370 °F), the first crystals begin to form. A horizontal line at 1,300 °C indicates the composition of the melt and the first crystals. It intersects the liquidus at the melt composition (Point B) and the solidus at the crystal composition (Point D). When this first crystallization occurs, the liquid still has its original composition, but the crystals that start to form are considerably more anorthite-rich ( $\text{Ab}_{42}\text{An}_{58}$ ).

As the melt continues cooling, crystals continue to form, but they change composition from D to C as they do so. Previously crystallized plagioclase reacts with the melt so all crystals have the same composition. A horizontal line can be drawn at any temperature. The intersection of the line with the solidus indicates plagioclase composition and the intersection of the line with the liquidus indicates melt composition, provided the melt and crystal stay in equilibrium. Because the crystals are more anorthite-rich than the melt, the melt becomes more albite-rich as crystallization continues. As crystallization goes to completion, plagioclase crystals change in composition from  $\text{Ab}_{42}\text{An}_{58}$  (Point D) to  $\text{Ab}_{80}\text{An}_{20}$  (the composition of the original melt). Melt composition changes from  $\text{Ab}_{80}\text{An}_{20}$  to an extremely albite-rich composition ( $\text{Ab}_{96}\text{An}_{04}$ ), indicated by Point E on the diagram. At about 1,165 °C (2,130 °F), the last drop of melt will crystallize. All plagioclase crystals have the same composition, which must equal that of the original melt.

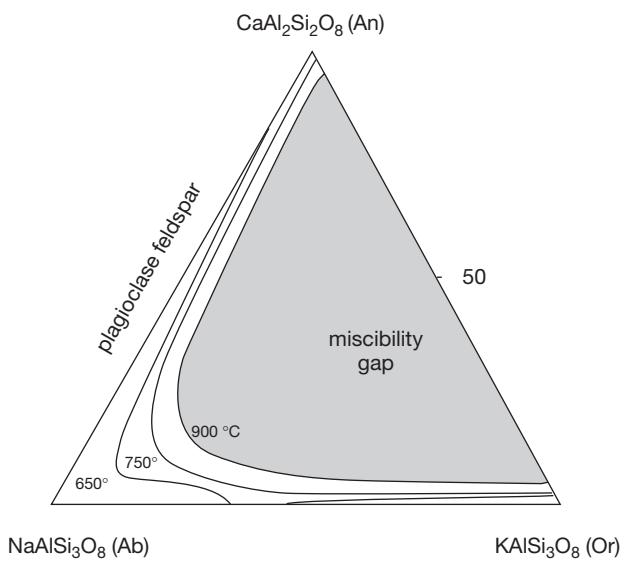
If the crystallization process always went to completion, plagioclase crystals would always end up the same composition as the original melt. However, several things can disrupt this equilibrium. Often crystallization occurs so fast that crystals do not have time to react with the melt as they form. In such cases, the first plagioclase to crystallize is preserved in the centers of large crystals. The crystals are compositionally zoned, the outer zones being more albite-rich. Another complication arises if crystals and melt get separated during the crystallization process. This may occur due to crystal settling, or because remaining melt "squirts off" after the melt is partially solidified. In such cases, crystal-melt equilibrium is not maintained.



**FIGURE 14** 1 atm pressure plagioclase T-X phase diagram. (See text for explanation.)

effect, the albite part of the feldspar melts faster than the anorthite. If an intermediate plagioclase is partially melted, the melt will be more albite-rich than the original feldspar. The remaining unmelted feldspar will therefore have to be more anorthite-rich

than the original feldspar. Similarly, if a magma begins to crystallize plagioclase, the first crystals to form will be more calcic than the melt. Box 6 discusses the melting and crystallization relationships of plagioclase in more detail.

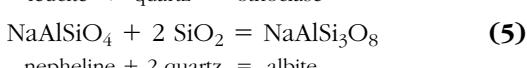
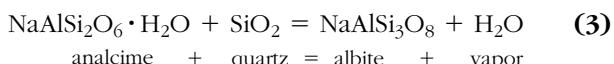


**FIGURE 15** Ternary feldspar miscibility gap. The gap varies with temperature as shown by the curves for 650 °C, 750 °C, and 900 °C. Feldspars that plot in the center of the diagram are unstable at all temperatures, but note that even some alkali feldspars (plotting on the bottom of the diagram) fall in the gap and are unstable at 650 °C.

Both K-feldspar and plagioclase exist in a wide range of igneous rocks. Feldspars with compositions in the middle of the feldspar ternary are almost never found because they unmix to form coexisting alkali feldspar and plagioclase (Figure 15). In most silicic rocks, such as granite, plagioclase is subordinate to K-feldspar. Similarly, in most mafic rocks, K-feldspar is not normally present. Intermediate rocks nearly always contain both feldspars. Plagioclase composition varies predictably with rock composition. Silicic rocks, which are usually relatively rich in sodium (Na), contain albitic plagioclase. Most mafic rocks, being relatively rich in calcium (Ca), contain anorthitic plagioclase.

### Feldspathoid Group

The feldspathoid minerals are similar to feldspars in many of their properties because they have similar atomic structures and chemistries. They are, however, much less common. The most important feldspathoids are analcime ( $\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$ ), leucite ( $\text{KAlSi}_2\text{O}_6$ ), and nepheline ( $\text{NaAlSi}_3\text{O}_4$ ). They are restricted to rocks in which quartz is not present because they will react with quartz to produce feldspars:



Leucite is a rare mineral found in K-rich volcanic rocks. It is unknown in plutonic, metamorphic, or sedimentary rocks. Nepheline is a common mineral in syenite and other silica-poor volcanic or plutonic igneous rocks. Leucite and nepheline are usually associated with K-feldspar. Analcime also crystallizes from a magma and it may form as a secondary mineral in vugs, cracks, or veins. Occasionally it is found as a secondary mineral in sandstones or tuffs. When it crystallizes from a magma, it is commonly associated with olivine, leucite, and perhaps sodalite. When it is secondary, other low-temperature minerals such as zeolites or prehnite often accompany it.

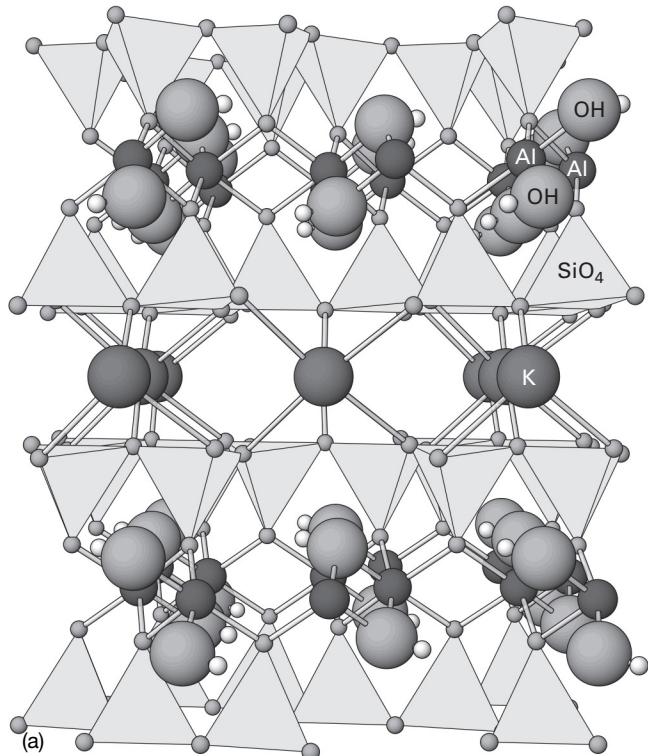
### Mica Group

The most important groups of minerals within the sheet silicate subclass are micas, chlorites, and clays. We will consider only the micas and, to a lesser extent, chlorites, in this chapter and defer discussion of clay minerals to the chapter on sedimentary rocks and minerals.

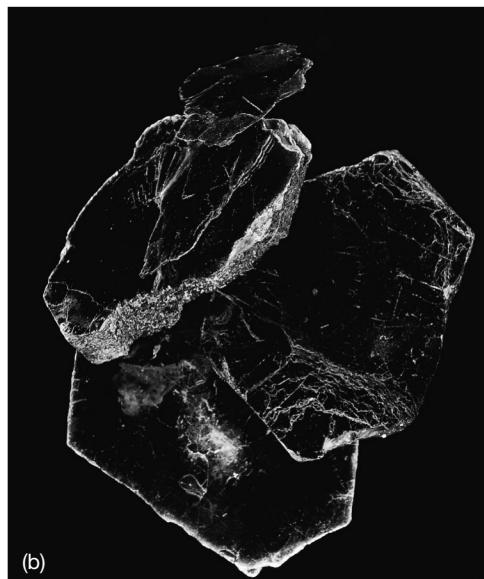
All sheet silicates have atomic structures composed of sheets (layers) of  $(\text{Si}, \text{Al})\text{O}_4$  tetrahedra with alkalies and other metals between (Figure 16a). Bonding within a sheet is much stronger than bonding between sheets. Consequently, as shown in Figure 16b and Plate 6.6, well-developed basal cleavage characterizes mica and most other sheet silicates. Common micas contain  $\text{K}^+$  as an interlayer cation between the tetrahedral layers.  $\text{Fe}^{2+}$ ,  $\text{Mg}^{2+}$ , and  $\text{Al}^{3+}$  occupy positions between the apices of the tetrahedra. Within the tetrahedral layers themselves,  $\text{Al}^{3+}$  commonly substitutes for some  $\text{Si}^{4+}$ . A general formula for micas is  $\text{K}(\text{Al}, \text{Mg}, \text{Fe})_{2-3}(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ . So, we can describe most mica compositions in terms of three end members:

muscovite	$\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$
annite	$\text{KFe}_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$
phlogopite	$\text{KMg}_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$

The two most important micas are biotite and muscovite (Figure 17). Other mica minerals exist, but are not common. Muscovite is usually close to the end-member composition given above. Biotite may have any composition between end members annite and phlogopite, and may incorporate a small amount of muscovite as well. The name *annite* refers only to the ideal end member, but the name *phlogopite* is often used in a more general sense to describe any magnesium-rich biotite. Phlogopite is often brown, compared to the more common black color of biotite, so many geologists use the names *muscovite*, *phlogopite*, and *biotite* to refer to silvery, brownish, and black micas, respectively. Besides



(a)



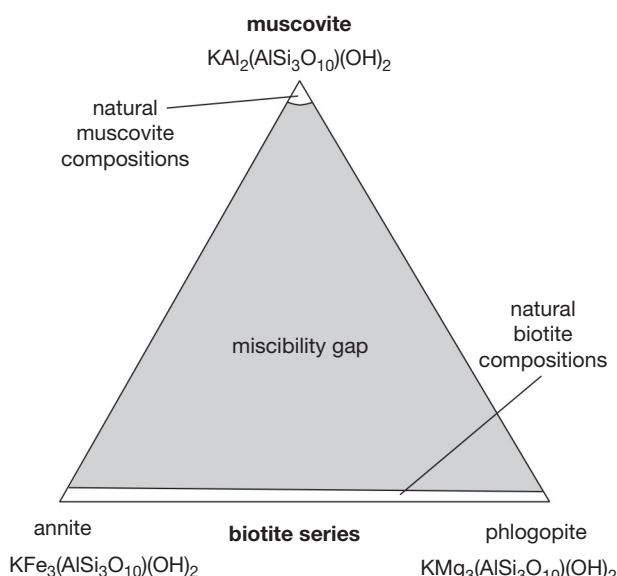
(b)

**FIGURE 16** Mica structure and cleavage: (a) the atoms in muscovite are arranged in layers;  $K^+$  ions link layers of  $SiO_4$  tetrahedra sandwiched around  $Al^{3+}$  ions; (b) due to its layered structure, biotite has one excellent cleavage and easily breaks into sheets and flakes.

Al-Fe-Mg substitutions, other substitutions (such as  $F^-$  substituting for  $OH^-$ ) occur in micas, but they are generally minor. Lepidolite, an especially lithium-rich mica similar to muscovite, is a common large and euhedral mineral in pegmatites. It is often associated with the lithium-aluminum pyroxene, spodumene.

Muscovite is more common than biotite, but both occur in a wide variety of igneous and metamorphic rocks. Micas react to form clays and other minerals when exposed to prolonged weathering, and are therefore absent from most sedimentary rocks. Biotite, and especially muscovite, are relatively Al- and Si-rich compared with many other igneous minerals. Muscovite, therefore, is found in silicic igneous rocks such as granite, but rarely in rocks of intermediate or mafic composition. Biotite is found in rocks ranging from granitic to mafic composition. Phlogopite is occasionally found in ultramafic rocks.

The name *chlorite* is often used colloquially to describe any greenish mica, but strictly speaking, the chlorite group consists of a number of different mineral species that are difficult to distinguish from each other. Minerals of this group have complex chemistries that can be described by a simplified general formula  $(Mg,Fe)_3(Si,A)_4O_{10}(OH)_2 \cdot (Mg,Fe)_3(OH)_6$ . Clinochlore— $(Mg_5Al)(AlSi)_3O_{10}(OH)_8$ —is perhaps the most important chlorite end member. Chlorite's atomic structure is similar to the micas (Figure 16) but the interlayer site contains  $(Mg,Fe)(OH)_6$  instead of  $K$ . Chlorite group minerals are stable over a wide range of conditions, being especially common in low-to medium-grade metamorphic rocks. They are also



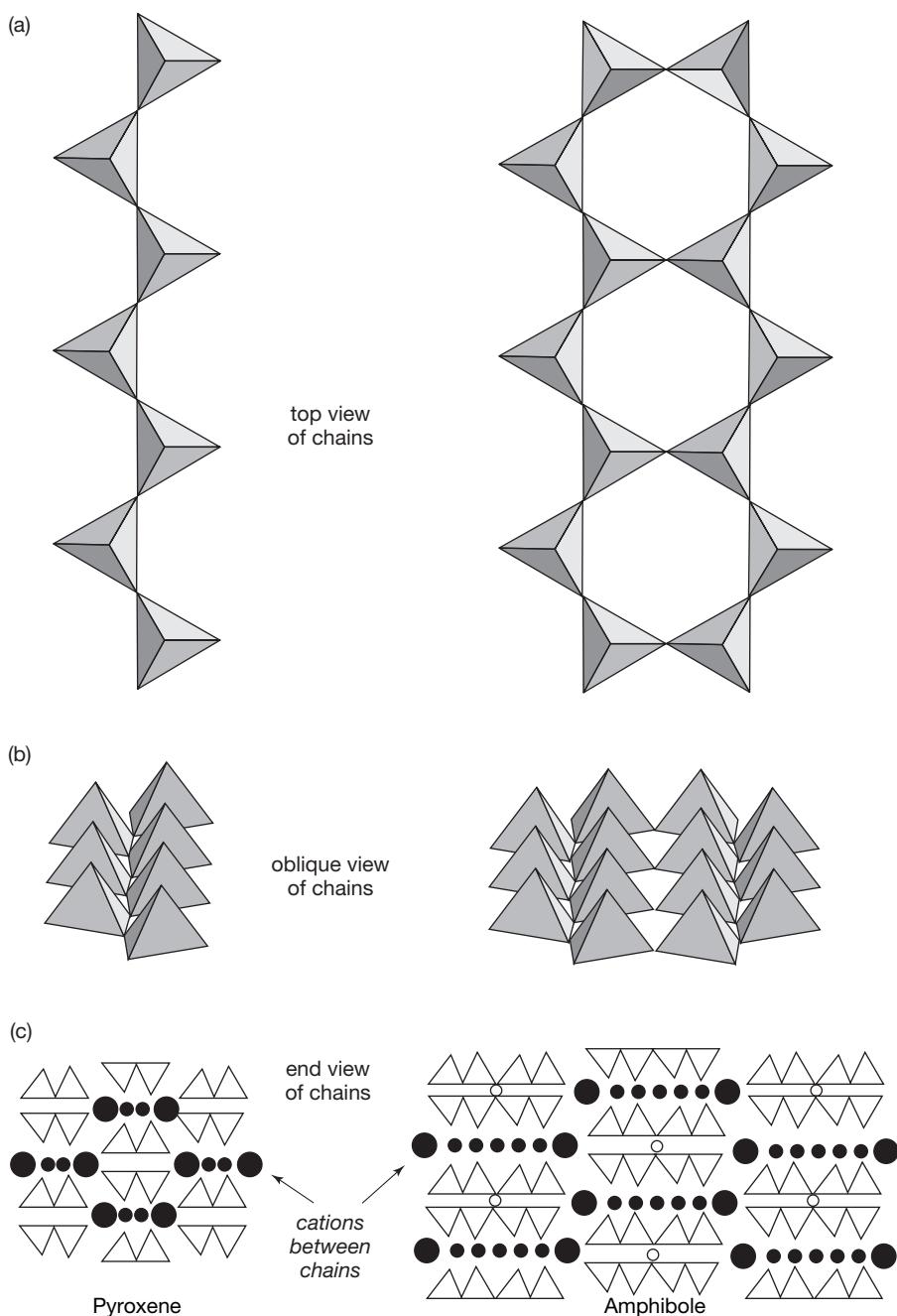
**FIGURE 17** Ternary diagram showing the principal mica end members: muscovite, phlogopite, and annite. Micas termed muscovite are generally close to end member  $KAl_2(AlSi_3O_{10})(OH)_2$  in composition. In contrast, biotite compositions range between annite and phlogopite. Compositions between muscovite and biotite do not exist due to the large miscibility gap.

common as alteration products in igneous rocks, where they form from biotite, pyroxene, amphibole, and other mafic minerals.

### Chain Silicates

**Pyroxenes** and **amphiboles** are the two most important groups of minerals within the chain silicate subclass. All chain silicates are characterized by single or double chains of  $\text{SiO}_4$  tetrahedra linked by monovalent or divalent cations. In most pyroxenes, the linking cations occupy two distinct kinds of sites between the chains; in amphiboles, they occupy

four or five kinds of sites between the chains. In both pyroxenes and amphiboles, one interchain site is significantly larger than the other(s). Figure 18 compares the structures of pyroxenes and amphiboles. Pyroxenes are anhydrous minerals having simple formulas compared with amphiboles, all of which are hydrous. The similarity between the structures of pyroxenes and amphiboles results in some similarity in physical properties. Unless cleavage is visible, it can be difficult to distinguish dark-colored pyroxenes from dark-colored amphiboles.



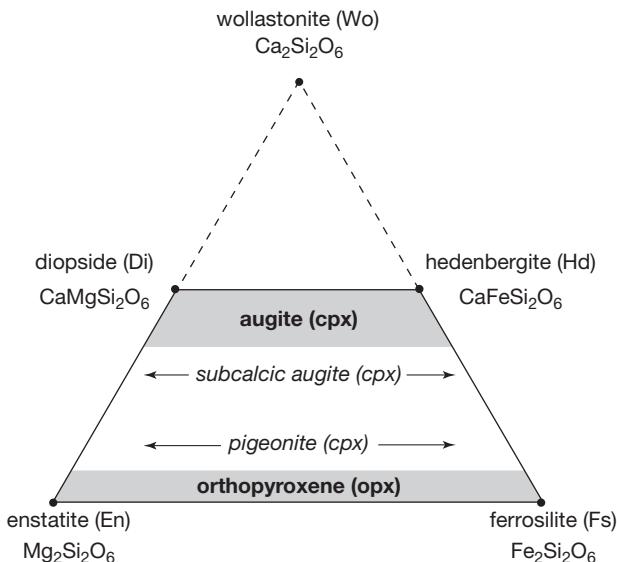
**FIGURE 18** Comparison of the structures of pyroxenes and amphiboles: (a) schematic drawing showing how silica tetrahedra are polymerized in both to form chains; (b) an oblique view of the chains; (c) schematic view looking down the chains to show the locations of interchain cations (solid black dots); the small open circles in the amphibole drawing show sites occupied by K or Na in hornblende and a few other amphiboles. Note that in these drawings, as in most drawings of silicates, the  $\text{Si}^{4+}$  cations at the centers of the tetrahedra are omitted for clarity.

## Pyroxene Group

Plates 6.1 to 6.4 show some pyroxenes. Pyroxenes may contain many different elements, but we describe the compositions of most pyroxenes in terms of five end members:

wollastonite	$\text{Ca}_2\text{Si}_2\text{O}_6 = \text{CaSiO}_3$
ferrosilite	$\text{Fe}_2\text{Si}_2\text{O}_6 = \text{FeSiO}_3$
enstatite	$\text{Mg}_2\text{Si}_2\text{O}_6 = \text{MgSiO}_3$
diopside	$\text{CaMgSi}_2\text{O}_6$
hedenbergite	$\text{CaFeSi}_2\text{O}_6$

A general formula, then, would be  $(\text{Ca}^{2+}, \text{Fe}^{2+}, \text{Mg}^{2+})_2\text{Si}_2\text{O}_6$ . Figure 19 shows a wollastonite-ferrosilite-enstatite ternary diagram, with end members indicated. The mineral wollastonite, although used as an end member to describe pyroxene compositions, is not a pyroxene. It has a slightly different structure and belongs to the pyroxenoid group. (In pyroxenoids, the silica tetrahedra do not zig-zag back and forth as shown in Figure 18a.) As with the feldspars, we use abbreviations to give composition. A pyroxene of



**FIGURE 19** Ternary diagram showing the principal pyroxene end members. Wollastonite, which is often used as an end member to describe pyroxene composition, is not a true pyroxene because pyroxenes cannot contain more calcium than augite. So, we term the bottom half of the diagram—cornered by diopside, hedenbergite, ferrosilite, and enstatite—the *pyroxene quadrilateral*. The most common clinopyroxenes have compositions that fall in the augite field, close to the diopside-hedenbergite join. Common orthopyroxenes have compositions close to the enstatite-ferrosilite join. The shapes and sizes of the shaded augite and orthopyroxene fields are only schematic; they vary with pressure and temperature. Subcalcic augite and pigeonite are clinopyroxenes with less Ca than the much more common augite, so their compositions plot within the quadrilateral.

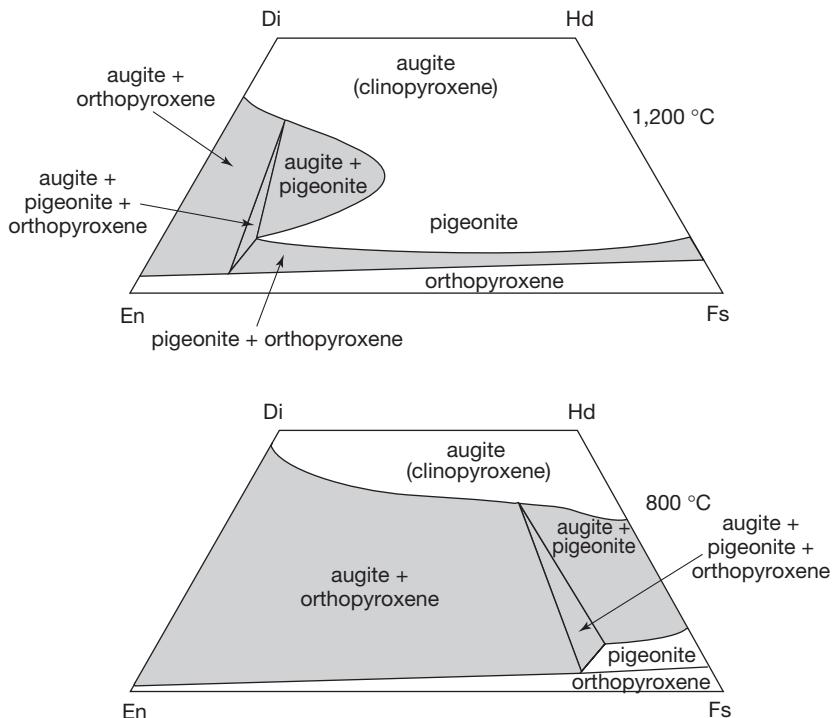
composition  $\text{Wo}_{10}\text{Fs}_{83}\text{En}_{07}$ , for example, has the formula  $(\text{Ca}_{0.10}\text{Fe}_{0.83}\text{Mg}_{0.07})\text{SiO}_3$ , equivalent to  $(\text{Ca}_{0.10}\text{Fe}_{0.83}\text{Mg}_{0.07})_2\text{Si}_2\text{O}_6$ .

Natural pyroxenes fall into two main series distinguished by different atomic arrangements and different crystal shapes (Figure 19). **Orthopyroxene**, predominantly solid solutions of end members ferrosilite and enstatite, has the general formula  $(\text{Mg}, \text{Fe})_2\text{Si}_2\text{O}_6$ . **Clinopyroxene**, predominantly solid solutions of diopside and hedenbergite, has the general formula  $\text{Ca}(\text{Mg}, \text{Fe})\text{Si}_2\text{O}_6$ . Figure 20 shows two examples of clinopyroxene; all the pyroxenes in Plates 6.1 to 6.4 are clinopyroxene. No pyroxenes have compositions more calcic than clinopyroxene because Ca is limited to only the larger two of the four sites between the chains (Figure 18c). We call lines between end members on diagrams such as Figure 19 **joins**. The four-sided polyhedron bounded above by the diopside-hedenbergite (clinopyroxene) join, and below by the enstatite-ferrosilite (orthopyroxene) join, is the **pyroxene**



**FIGURE 20** Two examples of clinopyroxenes: (a) augite, principally a Ca-Mg-Fe clinopyroxene, forms prismatic crystals and displays two prominent cleavages that intersect at 87° and 93°; the cleavage angles help distinguish clinopyroxene from hornblende; (b) several large euhedral crystals of hedenbergite (Ca-Fe clinopyroxene) in a pyroxene-feldspar matrix.

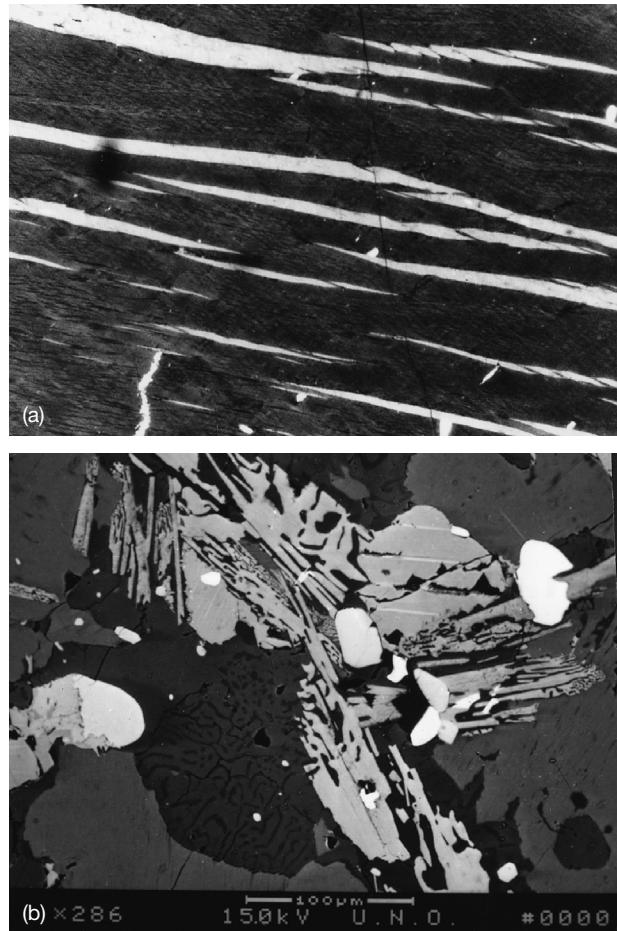
**FIGURE 21** The pyroxene quadrilateral showing the miscibility gap (gray areas) between augite, pigeonite, and orthopyroxene at about 800 and 1,200 °C. The size of the miscibility gap varies with temperature; at high temperatures (1,200 °C) it is quite small but it widens as temperature decreases. If an original pyroxene composition plots in one of the white areas, it will be stable and will exist as augite, pigeonite, or orthopyroxene, depending on temperature. However, if the original pyroxene has a composition that plots in a gray region, it will unmix to form two or three separate pyroxenes (labeled on figures), depending on temperature and original pyroxene composition. This process explains the texture shown in Figure 22b.



**quadrilateral.** It encompasses the compositions of all natural Ca-Mg-Fe pyroxenes.

Natural clinopyroxene can have any composition between diopside and hedenbergite, and often is somewhat deficient in  $\text{CaSiO}_3$ , giving it a composition that plots within the pyroxene quadrilateral (Figure 19). Similarly, orthopyroxene may have any composition between enstatite and ferrosilite, and often contains a small amount of  $\text{CaSiO}_3$ . However, orthopyroxene and clinopyroxene have different crystal structures and there is a complex solvus between them in the middle of the quadrilateral. Consequently, pyroxenes with compositions that plot in the middle of the quadrilateral are only found in some high-temperature rocks; augite, subcalcic augite, and pigeonite are names given to them when they occur (Figures 19 and 21). Augite and subcalcic augites are clinopyroxenes with  $\text{Ca}:(\text{Mg} + \text{Fe})$  values significantly less than 1.0. Pigeonites, first found at Pigeon Point, Minnesota, are very high-temperature pyroxenes that have an atomic structure dissimilar from both clinopyroxene and orthopyroxene.

Because subcalcic augite and pigeonite are only stable at high temperature, they tend to “unmix” at lower temperatures. Analogous to the feldspars, a homogeneous high-temperature pyroxene of intermediate composition may become unstable and form two pyroxenes at low temperature. This sometimes leads to exsolution similar to that of feldspars; Figure 22 compares the two. The compositions of exsolution lamellae depend on the temperature at which exsolution



**FIGURE 22** Two examples of exsolution: (a) photograph (1 mm wide) of a thin section showing exsolution in alkali feldspar; (b) scanning electron microscope image (0.4 mm wide) of pyroxene showing bleb and lamellar exsolution.

## BOX 7

## Diopside-Enstatite Solvus and Geothermometry

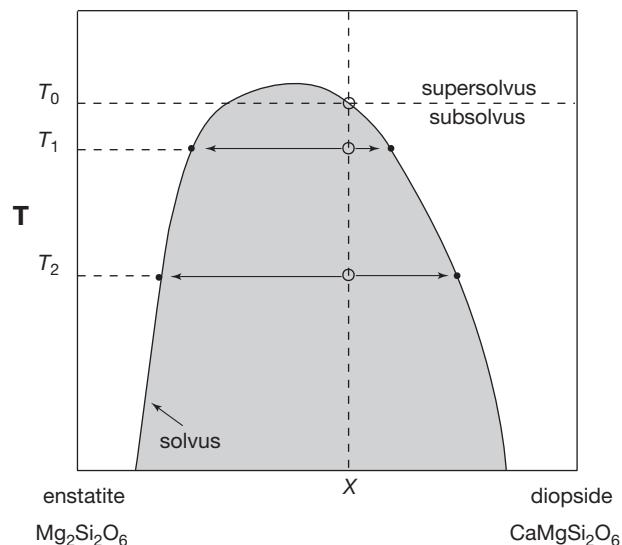
If a mineral system contains a miscibility gap, we can sometimes use mineral compositions to determine the temperature at which a rock equilibrated. Petrologists call such mineral systems **geothermometers**. Geothermometers are based on a fundamental consequence of thermodynamics: At high temperatures, solid-solution minerals may have intermediate compositions, but at low temperatures they tend to unmix so that compositions are relatively close to end members.

The miscibility gap between orthopyroxene (OPX) and clinopyroxene (CPX) is often used to calculate the temperature at which igneous or metamorphic rocks formed. Figure 23 is a schematic showing the OPX-CPX gap between enstatite and diopside. The solvus—the line that shows compositions of coexisting OPX and CPX at different temperatures—is narrower at high temperature than at low temperature. Consequently, low-temperature pyroxenes are closer to end member enstatite and diopside than high-temperature pyroxenes.

A pyroxene of composition  $X$  will be stable at high temperature (above  $T_0$ ), but if it crystallizes or equilibrates at lower temperature, it will unmixed to form two pyroxenes. Unmixing may produce separate grains of OPX and CPX in the same rock, or it may produce single grains of pyroxene containing blebs or exsolution lamellae of different compositions (Figure 22). By analyzing the compositions of coexisting OPX and CPX, petrologists can estimate the temperature of equilibration.

Pyroxenes are not the only minerals that can be used as geothermometers. Feldspars, carbonates, and others can serve the same purpose. Geothermometry is not, however, always as simple as Figure 23 might

imply. Many things besides temperature affect the compositions of coexisting minerals. Among others, petrologists must be concerned with the effects of pressure, of minor elements in minerals, and of disequilibrium.



**FIGURE 23** Schematic diagram showing the diopside-enstatite solvus: A pyroxene of composition  $X$  (indicated by the vertical dashed line) will be stable above  $T_0$  (at supersolvus temperatures). Below  $T_0$  (at subsolvus temperatures) it will unmixed to produce two pyroxenes (shown by solid dots). The degree to which it unmixed depends on the temperature: At  $T_2$  pyroxene compositions will be closer to end members than at  $T_1$ . Note that this diagram is equivalent to the left-hand side (Di-En join) of the pyroxene quadrilateral shown in Figure 21. The miscibility gap is narrower at high temperature than at low temperature.

occurred. So, both the pyroxene and feldspar solvi are sometimes used as **geothermometers** to learn the temperature at which a rock formed (Box 7).

Besides Ca, Mg, and Fe, pyroxenes, especially clinopyroxenes, often contain minor to appreciable amounts of Na<sup>+</sup> and Al<sup>3+</sup>. Na<sup>+</sup> may substitute for Ca, Mg, or Fe. Al<sup>3+</sup> can substitute for Ca, Mg, or Fe, and also for Si. An end-member pyroxene, jadeite, has the formula NaAlSi<sub>2</sub>O<sub>6</sub>. It exists in high-pressure metamorphic rocks. Other Na-bearing pyroxenes such as acmite (NaFeSi<sub>2</sub>O<sub>6</sub>) are found in some igneous rocks. So, a general formula for pyroxene can be written (Ca,Mg,Fe,Na)(Mg,Fe,Al)(Si,Al)<sub>2</sub>O<sub>6</sub>. Other elements including Li, Cr, and Ti also are found in pyroxene, but are normally minor elements. However, spodumene (LiAlSi<sub>2</sub>O<sub>6</sub>) is an important pyroxene in some pegmatites.

## Amphibole Group

The atomic structure of amphibole is more complex than pyroxene, although they are both chain silicates (Figure 18). Amphibole chemistry is highly variable and yields many different end-member formulas (Table 1). The amphibole ternary in Figure 24 shows some of the simpler end members. Along the base of the diagram, the figure is complicated because Ca-free amphiboles form two distinct series, having different atomic structures. We call the most Mg-rich amphiboles *anthophyllite* or, if they contain appreciable amounts of Fe, *ferroanthophyllite*. Plate 3.4 shows a fibrous variety of anthophyllite. We give aluminous anthophyllite (not shown on Figure 24) the name *gedrite*. The cummingtonite-grunerite series covers most intermediate and Fe-rich compositions. Calcic

**TABLE 1** Comparison of Amphibole and Pyroxene End Members and Series

Pyroxene End Member or Series	Amphibole End Member or Series
enstatite	$Mg_2Si_2O_6$
orthopyroxene	$(Mg,Fe)_2Si_2O_6$
ferrosilite	$Fe_2Si_2O_6$
diopside	$CaMgSi_2O_6$
Mg-Fe clinopyroxene	$Ca(Mg,Fe)Si_2O_6$
hedenbergite	$CaFeSi_2O_6$
jadeite	$NaAlSi_2O_6$
acmite	$NaFeSi_2O_6$
augite	$(Ca,Mg,Fe,Na)(Mg)(Si,Al)_2O_6$
	magnesio-anthophyllite
	anthophyllite
	ferroanthophyllite
	tremolite
	actinolite
	ferroactinolite
	glaucophane
	riebeckite
	hornblende
	$Mg_7Si_8O_{22}(OH)_2$
	$(Mg,Fe)_7Si_8O_{22}(OH)_2$
	$(Fe,Mg)_7Si_8O_{22}(OH)_2$
	$Ca_2Mg_5Si_8O_{22}(OH)_2$
	$Ca_2(Fe,Mg)_5Si_8O_{22}(OH)_2$
	$Ca_2Fe_5Si_8O_{22}(OH)_2$
	$Na_2Mg_3Al_2Si_8O_{22}(OH)_2$
	$Na_2Fe_5Si_8O_{22}(OH)_2$
	$(K,Na)_{0-1}(Ca,Na,Fe,Mg)_2-$
	$(Mg,Fe,Al)_5(Si,Al)_8O_{22}(OH)_2$

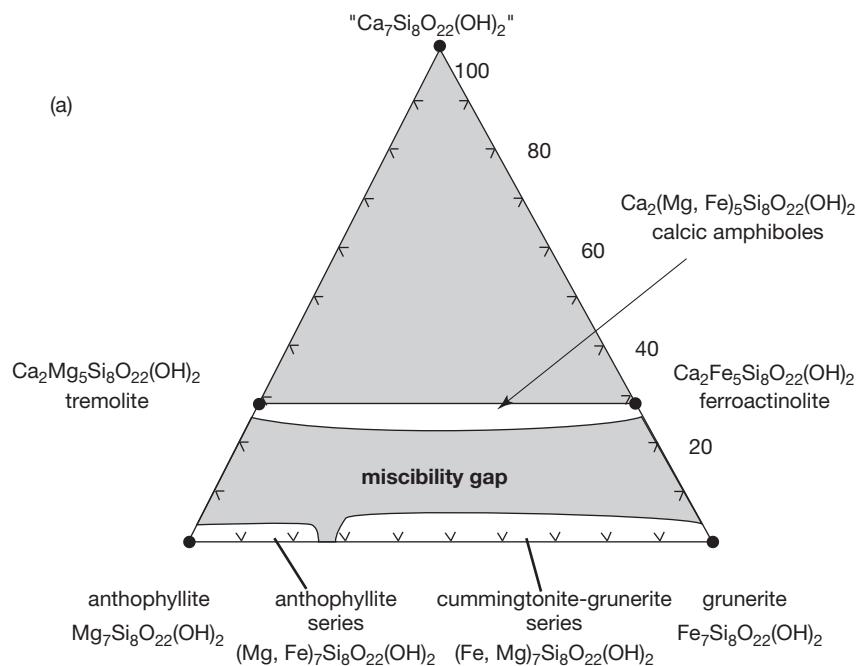
amphiboles (such as the actinolite in Plate 3.2) can have any composition between an Mg end member (tremolite) and an Fe end member (ferroactinolite). A miscibility gap exists between the calcic amphiboles and the Ca-poor amphiboles, analogous to the one between clinopyroxene and orthopyroxene.

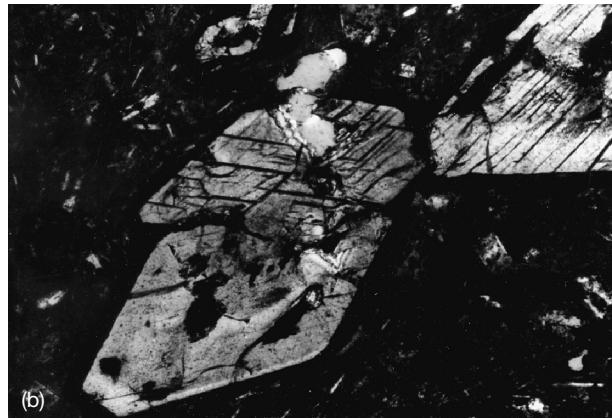
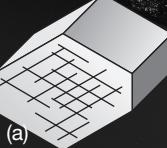
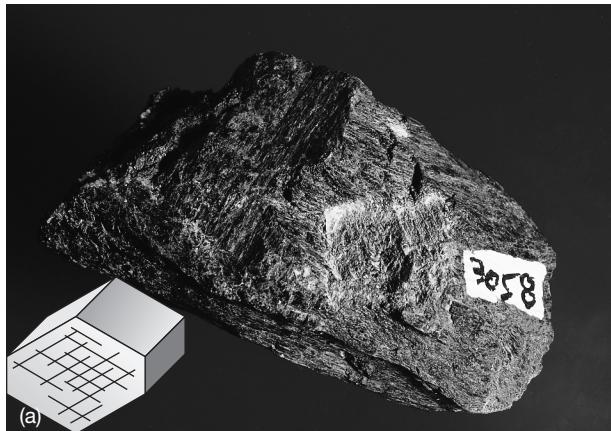
Amphibole chemistry also varies in ways not shown by Figure 24. The diagram depicts variations in Ca, Mg, and Fe content well, but many amphiboles contain K, Na, Al, Ti, and other elements in significant amounts. Additionally, some amphiboles do not contain the same number of atoms in their formulas as quadrilateral amphiboles. We generally call such amphiboles *hornblende*. Hornblende, the most common amphibole, has an idealized formula,  $(K,Na)_{0-1}(Ca,Na,Mg)_2(Mg,Fe,Al)_5(Si,Al)_8O_{22}(OH)_2$ . Even this complicated formula does not do justice to all the possible compositional variations. Without

chemical analyses, telling different amphiboles apart is difficult, and the name hornblende is often used to refer to any black amphibole (Figure 25). Many amphibole end members have analogs in the pyroxene group; we compare some of the more important end members in Table 1.

Amphiboles are important and essential minerals in many kinds of igneous rocks. Hornblende is absent from many granitic rocks but is common in rocks of intermediate to mafic composition where it coexists with plagioclase. Besides hornblende, other amphiboles are also found in igneous rocks. Amphiboles also exist in many metamorphic rocks, including marbles and metamorphosed mafic igneous rocks. They are especially common in high-temperature metamorphic rocks called *amphibolites*, which contain predominantly hornblende and plagioclase. *Glaucophane*, a blue sodic amphibole, has

**FIGURE 24** The principal amphibole end members. Calcic amphiboles generally have compositions falling near the tremolite-ferroactinolite join and noncalcic amphiboles have compositions near the anthophyllite-grunerite join. Natural amphiboles are never more calcic than tremolite-ferroactinolite.





**FIGURE 25** Hornblende: (a) can be confused with black pyroxene, but the  $60^\circ$  and  $120^\circ$  angles between cleavages (shown in the enlarged drawing) help distinguish it. Seeing cleavage in hand specimen may require a hand lens; (b) cleavage is more easily seen in thin section views such as this one.

the general formula  $\text{Na}_2\text{Al}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$ . Its presence is often associated with rocks formed in subduction zones under high pressures and moderate temperatures. Other Ca-free amphiboles (anthophyllite, gedrite, cummingtonite, and grunerite) are found in metamorphic rocks and occasionally in extrusive igneous rocks. Tremolite is common in high-temperature marbles. As with some other silicates that exist in marbles, identifying it may be difficult because of its inconspicuous white color. Amphiboles are absent in the highest temperature marbles and other metamorphic rocks.

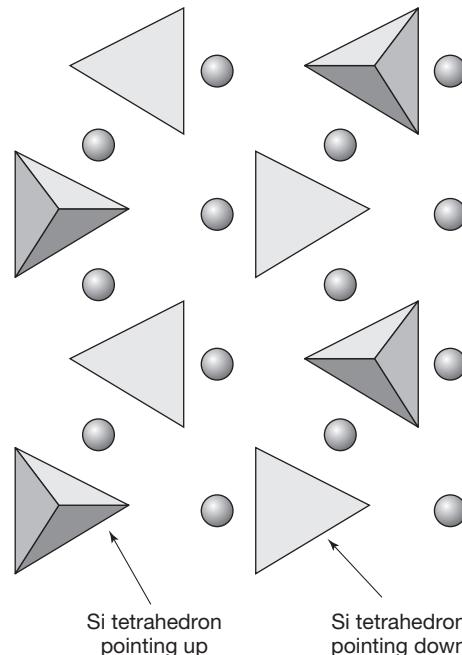
### Olivine Group

**Olivines**, belonging to the isolated tetrahedra silicate subclass, have structures comprising individual  $\text{SiO}_4$  tetrahedra linked by divalent cations (Figure 26). In contrast with some of the other silicates previously discussed, olivine chemistry is quite simple. Its general formula is  $(\text{Mg}, \text{Fe}, \text{Mn}, \text{Ca})_2\text{SiO}_4$  but often we omit Mn and Ca because they are generally minor components. End members are:

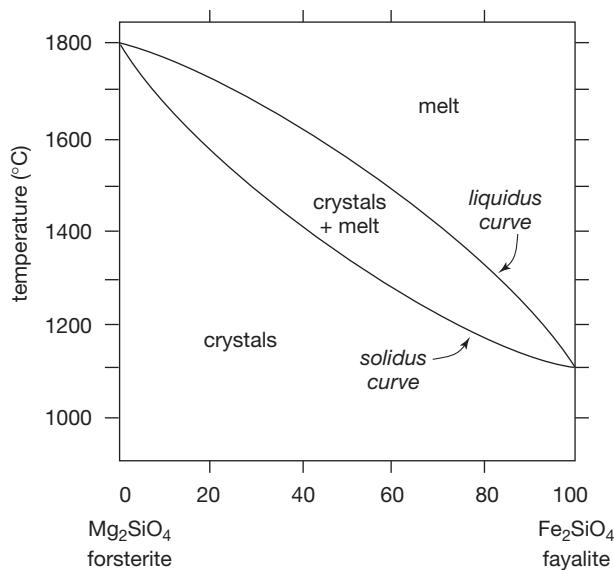
forsterite	$\text{Mg}_2\text{SiO}_4$
fayalite	$\text{Fe}_2\text{SiO}_4$
tephroite	$\text{Mn}_2\text{SiO}_4$
larnite	$\text{Ca}_2\text{SiO}_4$

Natural olivines are generally solid solutions of fayalite and forsterite with only minor tephroite and larnite. Other end members and elemental substitutions in olivine are very minor. We usually use abbreviations and subscripts to indicate olivine compositions.  $\text{Fo}_{88}\text{Fa}_{09}\text{Te}_{02}\text{La}_{01}$ , for example, refers to an olivine of composition  $(\text{Mg}_{0.88}\text{Fe}_{0.09}\text{Mn}_{0.02}\text{Ca}_{0.01})_2\text{SiO}_4$ . This might be the composition of the forsterite-rich olivine shown in Plate 6.5.

Olivine is primarily an igneous mineral, crystallizing from high-temperature magmas. Its two most important end members, forsterite and fayalite, melt at different temperatures, so olivine's melting behavior is similar to that of plagioclase (Figure 27). Olivine occurs predominantly in mafic and ultramafic igneous rocks. Its very mafic composition restricts its occurrence, and other mafic minerals containing the same elements with additional Si are more common. In some basalts Mg-rich olivine



**FIGURE 26** Schematic view of the atomic arrangement of olivine showing isolated silica tetrahedra, some pointing up and some pointing down, with metal cations (black dots) between. In most olivines,  $\text{Mg}^{2+}$  and  $\text{Fe}^{2+}$  are the principal cations linking silica tetrahedra.



**FIGURE 27** Phase diagram showing the melting and crystallization temperatures of forsterite-fayalite olivines at 1 atm pressure. Compare this diagram with Figure 13 and read Box 5 for more explanation.

forms large green phenocrysts in a fine-grained plagioclase-pyroxene groundmass (Plate 6.5). Mg-rich olivine is never found in silicic rocks, but Fe-rich olivine is occasionally found in some granites. Olivine occurs in some metamorphic rocks, including marble and metamorphosed igneous rocks.

### Other Minerals in Igneous Rocks

This chapter focuses on silicates, but igneous rocks often contain other minerals (Table 2). Most are only common as accessory minerals because they are composed of rare elements or of elements that easily fit into other minerals. Magnetite and ilmenite, for example, are generally minor because they comprise elements that also easily fit into other more abundant essential

**TABLE 2** Accessory Minerals in Igneous Rocks

Mineral	Chemical Formula
magnetite	$\text{Fe}_3\text{O}_4$
ilmenite	$\text{FeTiO}_3$
apatite	$\text{Ca}_5(\text{PO}_4)_3(\text{OH},\text{F},\text{Cl})$
zircon	$\text{ZrSiO}_4$
titanite	$\text{CaTiSiO}_5$
pyrite	$\text{FeS}_2$
pyrrhotite	$\text{Fe}_{1-x}\text{S}$
allanite	$(\text{Ca},\text{Ce})_2(\text{Al},\text{Fe})_3\text{Si}_3\text{O}_{12}(\text{OH})$
tourmaline	$(\text{Na},\text{Ca})(\text{Fe},\text{Mg},\text{Al},\text{Li})_3\text{Al}_6(\text{BO}_3)_3\text{Si}_6\text{O}_{18}(\text{OH})_4$
sodalite	$\text{Na}_3\text{Al}_3\text{Si}_3\text{O}_{12} \cdot \text{NaCl}$
fluorite	$\text{CaF}_2$

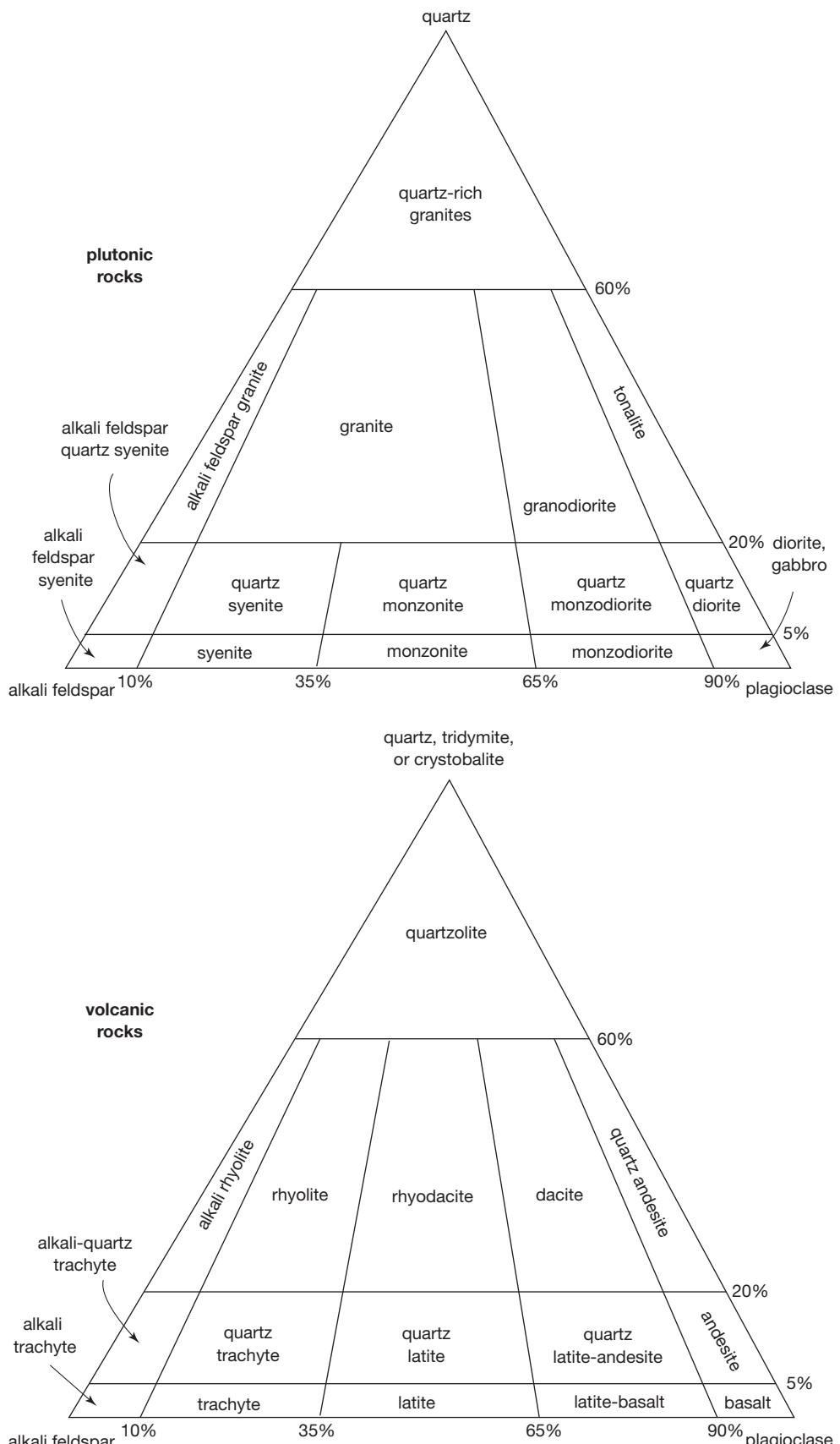
minerals. Rocks that contain fluorine (F), zirconium (Zr), or phosphorus (P) may contain fluorite, zircon, or apatite, but F, Zr, and P are very minor elements in all but the most unusual rocks. Although not abundant, zircon often contains uranium and lead, which we may analyze to learn radiometric ages of igneous rocks.

### THE NAMING OF IGNEOUS ROCKS

There are a number of different ways to divide igneous rocks into groups and to give them names. Assigning names can be complicated because igneous rocks vary greatly in mineralogy and texture, and rock types grade from one to another. If we invoke too many names, terminology becomes too complicated to be useful. If we invoke too few names, they are too broad to have much meaning. The task is somewhat simplified because, with rare exceptions, the major elements in all igneous rocks are the same (see Box 1). In addition, certain minerals have affinities for each other because of their chemical compositions. Mafic igneous rocks, for example, generally contain pyroxene and Ca-plagioclase. Silicic igneous rocks contain predominantly quartz, alkali feldspar, and micas. Mafic rocks, therefore, have a characteristic dark color, while silicic rocks are white or pink. Despite these generalizations, however, igneous petrology is complex and highly variable.

### SIMPLE CLASSIFICATION SCHEME

Most igneous rocks contain feldspar and quartz. Figure 28 depicts a widely used and relatively simple classification scheme for igneous rocks based on the relative amounts of quartz, plagioclase, and alkali feldspar that are present. Figure 28 works well for most igneous rocks, and we can often identify quartz, plagioclase, and alkali feldspar in the field. The diagrams do not work well for rocks that do not contain significant amounts of quartz or feldspar, and they ignore compositional variations in feldspars. Magmas poor in  $\text{SiO}_2$  but rich in alkalis will crystallize nepheline or leucite (both members of the feldspathoid group) instead of feldspars. Similarly, ultramafic rocks (those without any quartz or alkali feldspar) are not well represented on this diagram. Petrologists have developed diagrams similar to Figure 28 for feldspathoid-bearing rocks and for ultramafic rocks. Box 1 gives the chemical compositions of some of the rocks in Figure 28. We can verify that the relative proportions of quartz, alkali feldspar, and plagioclase reflect variations in



**FIGURE 28** The IUGS (International Union of the Geological Sciences) classification scheme for quartzofeldspathic igneous rocks. The numbers on the right side of the triangles are the percent quartz in the rock. The numbers across the bottom of the triangle are the percent of feldspar that is plagioclase. These figures are adapted from Hyndman, 1972, and Klein and Hurlbut, 1993.

silica ( $\text{SiO}_2$ ), alkali ( $\text{K}_2\text{O}$  and  $\text{Na}_2\text{O}$ ) and alkaline earth ( $\text{CaO}$ ) content.

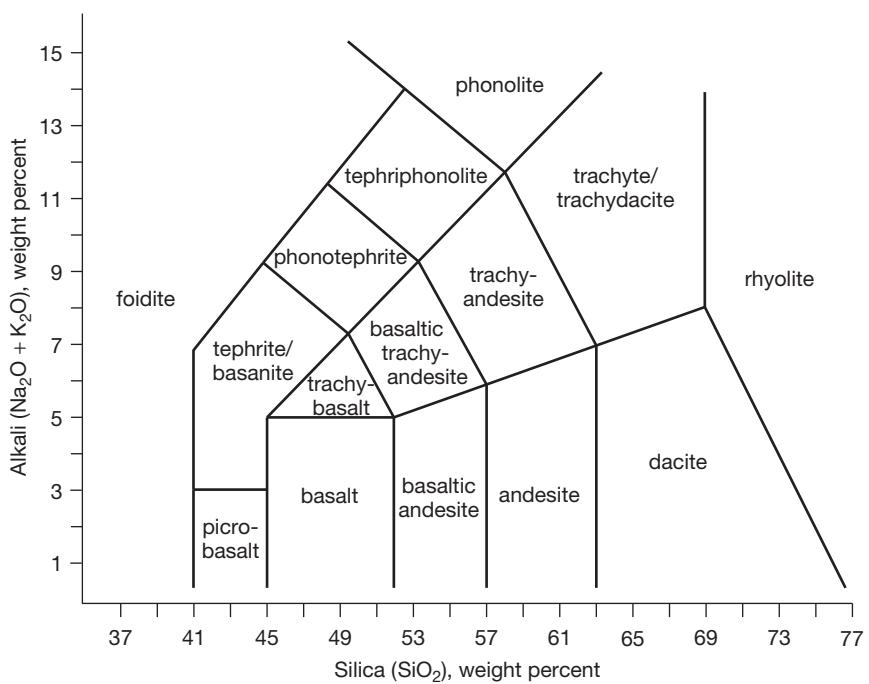
Volcanic rocks may be very fine grained, making mineral identification difficult or impossible, and they may contain significant amounts of volcanic glass. Petrologists often assign names to such rocks based on alkali and silica content (Figure 29). Comparison of Figure 29 with Figure 28 confirms that the amounts of quartz, plagioclase, and alkali feldspar in an igneous rock are reflections of the rock's composition.

### Occurrences

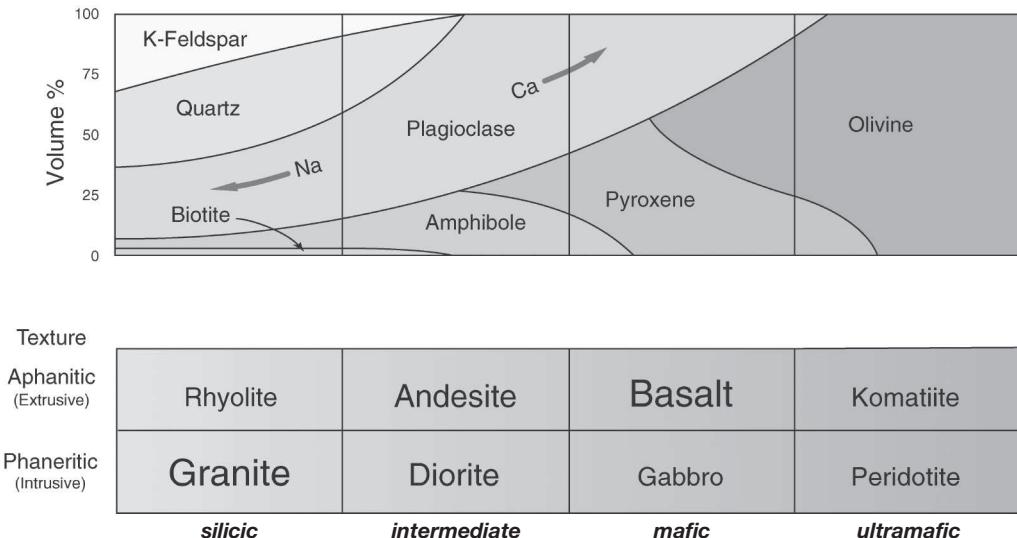
Extrusive igneous rocks are found worldwide, and individual varieties are not restricted to a single tectonic setting. The most abundant igneous rock in Earth's crust is basalt. The oceans cover two-thirds of Earth, and basalt forms at mid-ocean ridges to become the main component of the uppermost oceanic crust. Ocean basalt typically is found in 1/2-km-thick layers that may or may not be covered by sediments. The top layer of basalt is underlain by a 1- to 2-km-thick layer of basaltic dikes that, in turn, is underlain by gabbros and ultramafic rocks. Lesser amounts of basalt are found at subduction zones where, in association with andesites, rhyolites, and related rocks, basalts may be part of composite volcanoes. In continental interiors, hot spots and rifts have produced large volumes of basalt, in some places creating huge flood basalt provinces such as the Columbia River flood basalts of Idaho, Washington, and Oregon.

Large volumes of andesite, the most common volcanic rock after basalt, are found with dacite and rhyolite in island arcs and at continental margin subduction zones. Less commonly, andesite is associated with continental rifts or hot spots. Even more rarely, andesite is found at mid-ocean ridges. Rhyolite occurs in the same settings as basalt and andesite but is only common in continental areas. Rhyolites are especially abundant at hot spots such as the Yellowstone hotspot, associated with continental rifts such as the Rio Grande Rift, and at subduction zones.

Plutonic igneous rocks, too, are found in many diverse settings. Granites, granodiorites, and related rocks collectively called **granitoids** are found worldwide and are major components of the continental crust. They are especially common in Precambrian shields and younger mountain belts, where they form intrusions of all sizes, from small dikes and stocks to large batholiths. The Idaho Batholith, for example, is a granitic mass that covers more than 40,000 km<sup>2</sup> (15,444 sq. mi.) in central Idaho. Although typically found in shields, mountain belts, and subduction zones, granitoids are also associated with rifts, spreading centers, and hot spots. Intermediate and mafic plutonic rocks, including gabbro, also form plutons of all sizes. Large volumes of gabbro make up the lower part of oceanic crust. Lesser amounts are found in layered mafic intrusions or associated with continental hot spots and rifts. The Duluth Complex, north of Lake Superior, is one of the largest known gabbroic occurrences, and one of



**FIGURE 29** The TAS (total alkali-silica) classification scheme for volcanic rocks (LeMaitre et al 2002). Using this diagram, rocks are named on the basis of their chemistry. This is especially useful for fine-grained volcanic rocks due to the difficulty of identifying the minerals present.



**FIGURE 30** The major minerals and their proportions (modes) in silicic to ultramafic igneous rocks. Granite and basalt are the two most common igneous rocks, andesite and rhyolite slightly less common, and the others relatively rare.

the largest layered intrusions on Earth. The complex is a 16-km (10-mi.) -thick sill, composed mostly of gabbro with lesser amounts of anorthosite and granitic rocks.

## MINERAL MODES

Figure 30 is an idealized diagram showing the relative amounts by volume—also called the *modes*—of key minerals present in some common igneous rocks. This figure emphasizes the affinities that some minerals have for others. Mafic rocks often contain Mg-rich olivine or pyroxene along with Ca-rich plagioclase. They contain little quartz or K-feldspar. Silicic rocks are more likely to contain hydrous minerals such as muscovite or biotite and are often rich in quartz, K-feldspar, or Na-rich plagioclase. Olivine, nepheline, and other feldspathoid minerals can never coexist

with quartz. Thus, certain minerals can be associated with each other in nature, while others cannot. Different igneous rock types, formed in different environments, have characteristic mineral assemblages. Such relationships are primarily controlled by the composition of the magma, which in turn reflects the process and source that generated it.

## COMMON TYPES OF IGNEOUS ROCK

### Silicic Igneous Rocks (>20% Quartz)

Silicic igneous rocks include the plutonic rocks granite, tonalite, and granodiorite, and their volcanic equivalents (rhyolite, andesite, and dacite). Table 3 lists some varieties. All contain >20% quartz; we name them based on their feldspar content. Biotite, hornblende, and muscovite also may be present as minor minerals. Some

**TABLE 3** Examples of Silicic Igneous Rocks and Minerals

Feldspars Present	Plutonic Rock Name	Volcanic Rock Name	Major Minerals	Minor Minerals
more K-feldspar than plagioclase	granite	rhyolite	K-feldspar quartz plagioclase	biotite hornblende
more plagioclase than K-feldspar	granodiorite	dacite	plagioclase K-feldspar quartz hornblende	biotite
much more plagioclase than K-feldspar	tonalite	quartz andesite	plagioclase quartz	K-feldspar biotite hornblende

granitic rocks contain no plagioclase, and some tonalitic rocks contain no K-feldspar, but feldspars of some sort are always present. Plagioclase in granitic rocks may be nearly pure albite (the Na end member), but in other silicic igneous rocks plagioclase is more Ca-rich. In extrusive rocks, K-feldspar may be sanidine instead of orthoclase or microcline, and cristobalite or tridymite may replace quartz. Accessory minerals include magnetite, ilmenite, rutile, pyrite, pyrrhotite, zircon, sphene, and apatite. Because they contain large amounts of quartz and feldspars, granitic and granodioritic rocks are light in color (Figure 31) Granite and

rhyolite may have a pinkish color due to oxidized Fe in K-feldspar. Tonalite may be darker in color due to large amounts of biotite, hornblende, and, occasionally, pyroxene. Often, however, telling silicic rocks apart without using a microscope is difficult.

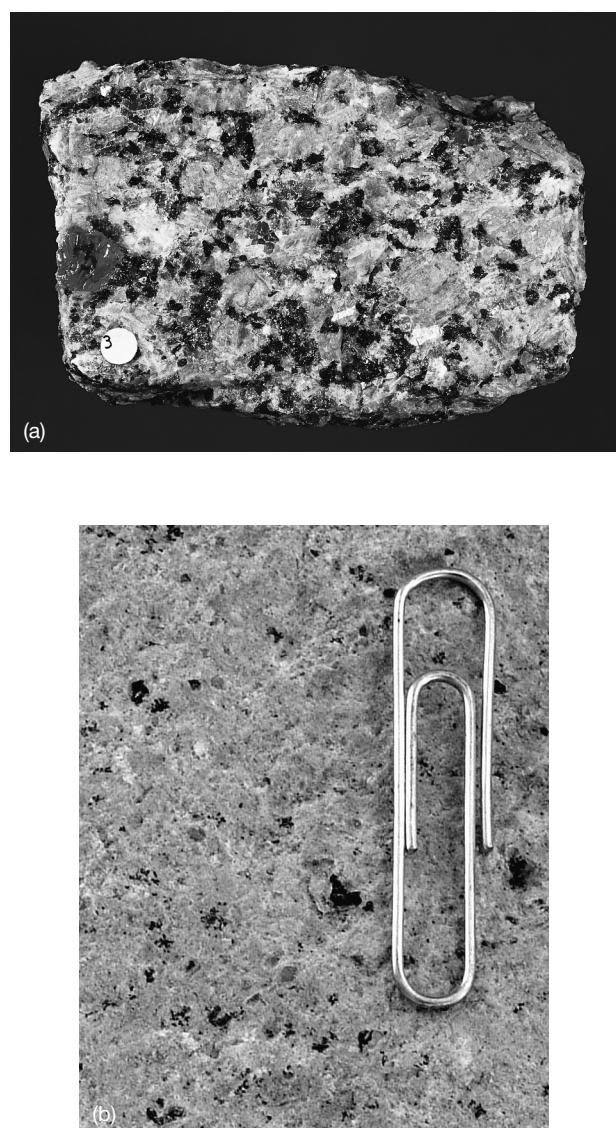
Granitic melts form at temperatures as low as 650 °C (1,200 °F). While some granitic magmas come from deep within the Earth, partial melting (**anatexis**) of shallow crustal rocks produces others. Silicic melts may intrude to form large plutons or dikes. If they reach the surface, violent volcanic activity may result. More commonly, they crystallize to form large plutons. Huge **batholiths**, plutons of extreme size, are common in many mountain belts around the world.

### Intermediate and Mafic Igneous Rocks (0% to 20% Quartz)

Intermediate igneous rocks are those in which quartz accounts for 5% to 20% of the rock. They include quartz syenite, quartz monzonite, and quartz diorite, and their volcanic equivalents quartz trachyte, quartz latite, and quartz andesite. K-feldspar dominates syenitic rocks (Table 4). Plagioclase is the only feldspar in most diorites. The plagioclase varies from an Na-rich composition in syenite to intermediate Na-Ca compositions in diorite. Hornblende, biotite, and pyroxene are common in these rocks, but usually in small amounts. As with silicic rocks, intermediate rocks with more plagioclase (diorite and some monzonite) tend to have more mafic minerals and thus a darker color. Magnetite, ilmenite, and apatite are common as accessory minerals.

A dark color, due to an abundance of hornblende, clinopyroxene, or olivine, characterizes mafic rocks (Figure 32). Examples in Table 4 include basalt (volcanic), and diorite and gabbro (plutonic). K-feldspar and quartz are minor or absent in all mafic rocks. Plagioclase varies from an intermediate Ca-Na composition (in diorite) to one that is very Ca-rich (in gabbro). While all intermediate and mafic igneous rocks may contain hornblende and clinopyroxene, hornblende is more common in diorite and andesite, and clinopyroxene is more common in gabbros and basalts. Gabbros and basalts may also contain olivine. Some spectacular basalts contain large green olivine crystals in a fine matrix of plagioclase and clinopyroxene (Plate 6.5). Magnetite, ilmenite, apatite, sphene, and zircon are common accessory minerals in all mafic rocks.

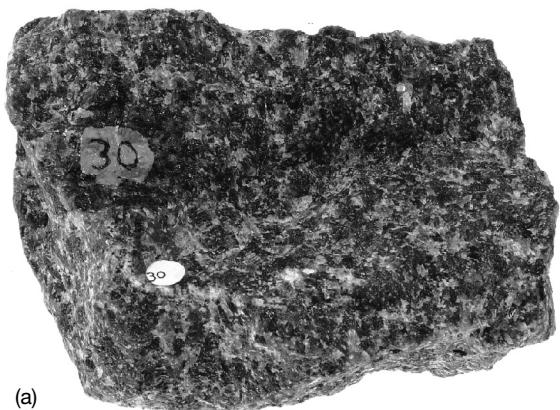
Mafic magmas (<52 wt% SiO<sub>2</sub>) form at very high temperatures 1,100 °C/2,010 °F. Melting of



**FIGURE 31** Silicic igneous rocks in hand specimen: 6-cm wide samples of (a) granite and (b) rhyolite. The granite contains black crystals of biotite, white K-feldspar, and gray quartz. The rhyolite contains the same minerals but they are too fine grained to be seen. Both photos are at the same scale.

**TABLE 4 Examples of Intermediate and Mafic Igneous Rocks**

Feldspars Present	Plutonic Rock Name	Volcanic Rock Name	Major Minerals	Minor Minerals
more K-feldspar than plagioclase	syenite	trachyte	K-feldspar plagioclase ±quartz	biotite hornblende
equal amounts of K-feldspar and plagioclase	monzonite	latite	plagioclase K-feldspar ±quartz	biotite hornblende clinopyroxene
mostly plagioclase	diorite	andesite	plagioclase hornblende	hornblende biotite K-feldspar
plagioclase only	gabbro	basalt	plagioclase clinopyroxene	orthopyroxene olivine



(a)



(b)

**FIGURE 32** Mafic rocks in hand specimen:  
 (a) gabbro and (b) vesicular basalt. The plutonic rock (gabbro) is coarser grained than the volcanic rock (basalt). Both rocks are dominated by plagioclase. They contain lesser amounts of clinopyroxene and very minor amounts of olivine. The vesicles (bubbles) in the basalt formed from gas that was present when the rock crystallized.

crustal rocks cannot produce them; most come from great depth. If they reach the surface, the result may be lava flows, called **flood basalts**, that cover large areas. Excellent examples are found on the Snake River Plain of eastern Idaho and eastern-central Washington. They also produce quiescent volcanoes, such as those found in Hawaii. Scientists studying the Hawaiian volcanics sometimes closely approach vents and lava fountains, something that is never done on Mount Saint Helens or other potentially violent mountains characterized by silicic volcanics.

### ULTRAMAFIC IGNEOUS ROCKS

Ultramafic rocks are especially poor in Si and have high Mg:Fe ratios; Table 5 gives some examples. Peridotite is a general term used for all of them. Pyroxene (either orthopyroxene or clinopyroxene), olivine, and plagioclase are the dominant minerals in peridotites. We call rocks composed nearly entirely of pyroxene *pyroxenite*, and those composed nearly entirely of olivine *dunite* (Figure 33). Many dunites look like light-green equivalents of sandstone. Because of their very high melting temperatures and mafic compositions, ultramafic magmas must come from deep within the Earth. They rarely reach the surface to produce volcanic rocks, but some Precambrian terranes contain spectacular examples of ultramafic lava flows called *komatiites*.

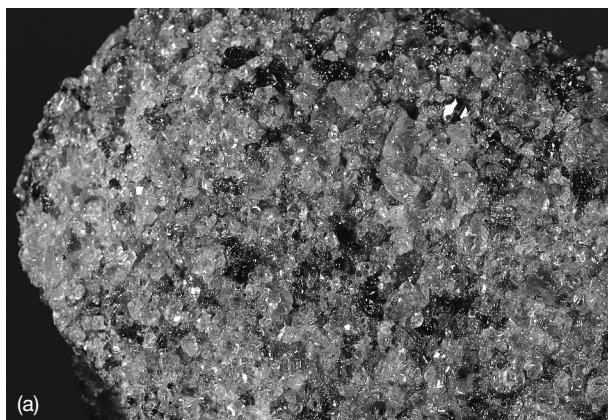
Ultramafic minerals are most stable at high temperature and tend to alter by reaction with water or carbon dioxide when exposed to normal Earth surface conditions. Consequently, finding fresh, unaltered ultramafic rock is difficult. Variable

**TABLE 5 Ultramafic Igneous Rocks**

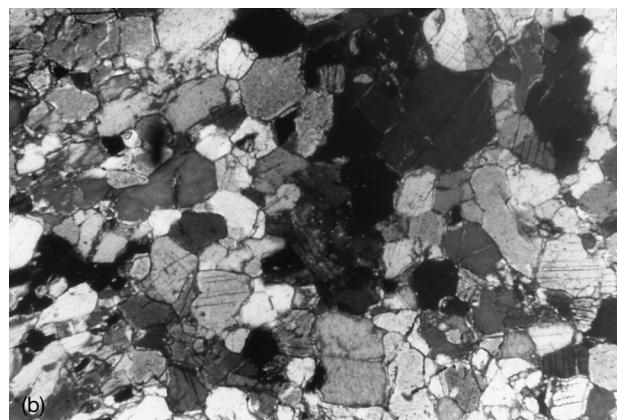
Plutonic Rock Name	Volcanic Rock Name	Major Minerals	Minor Minerals
peridotite	komatiite	olivine clinopyroxene orthopyroxene	hornblende
pyroxenite	does not exist	clinopyroxene orthopyroxene	olivine hornblende
dunite	does not exist	olivine	spinel

amounts of secondary serpentine, chlorite, talc, brucite, or calcite are nearly always present. Rocks called *serpentinites*, in which serpentine has replaced all mafic minerals, often result. Many

ultramafic rocks—including *kimberlites*, ultramafic rocks associated with diamonds—have been altered so much that we cannot determine the original mineralogy.



(a)



(b)

**FIGURE 33** Dunite in hand specimen and thin section: (a) 0.5-cm wide view of dunite in hand specimen, showing only olivine; (b) dunite in thin section showing high relief olivine grains (1-mm-wide view).

## BOX 8

### Minerals from the Moon

Moon rocks collected by the Apollo astronauts and unmanned Soviet missions include anorthosites, gabbros, and basalts. Most are basalts. Although these rocks indicate an active volcanic history, significant eruptions ceased on the moon about 3.2 billion years ago. Petrologists classify the ancient basalts exposed at the Moon's surface into several groups: olivine basalts, silica-rich basalts, aluminum-rich basalts, titanium-rich basalts, and so on. All have equivalents on the Earth, but lunar basalts are generally richer in  $TiO_2$ ,  $FeO$ ,  $MgO$ , and  $Cr_2O_3$ , and poorer in volatiles ( $H_2O$ ,  $CO_2$ ,  $O_2$ ) than terrestrial basalts.

Lunar basalts and other moon rocks contain the same minerals found in terrestrial rocks, including pyroxenes, plagioclase, olivine, ilmenite, and small amounts of K-feldspar. However, the chemical differences between Earth and Moon rocks result in slight differences in mineral chemistries. For example, lunar anorthosites typically consist of very calcium-rich plagioclase ( $An_{97-98}Ab_{2-3}$ ) with lesser amounts of orthopyroxene, olivine, clinopyroxene, pigeonite, and magnesium-rich spinel. In contrast, terrestrial anorthosites tend to have more sodium in plagioclase ( $An_{34-77}Ab_{23-66}$ ), and spinels are normally rich in iron. Study of lunar rocks also disclosed some previously undiscovered minerals resulting from excess titanium and other chemical differences. Two new silicates include pyroferroite,  $CaFe_6(SiO_3)_7$ , and tranquillityite,  $Fe_8(Zr,Y)_2Ti_3Si_3O_{24}$ , which is named after the Sea of Tranquility, the site of the first Moon landing. Armalcolite,  $(Fe,Mg)Ti_2O_5$ , is named after the three Apollo 11 astronauts, Neil Armstrong, Ed Aldrin, Jr., and Michael Collins.

## Questions for Thought

(Some of these questions have no specific correct answers; they are intended to promote thought and discussion.)

1. Why are igneous rocks dominated by silicate minerals?
2. Most igneous rocks contain either oxide or sulfide minerals (or both) as accessory minerals. Why?
3. Why do some elements become concentrated in pegmatites?
4. All granites contain quartz and K-feldspar. Why?
5. Suppose some olivine or pyroxene crystallize from a mafic magma. The remaining magma then moves upward, leaving the crystals behind. If this process repeats, how will the magma's composition change?
6. The Earth's upper mantle is roughly gabbroic (mafic) in composition and acts as a source region for magmas that move up into the crust. Partial crystallization, alluded to in question 5, commonly occurs. If crystals are left behind in the mantle and the magma then crystallizes in the crust, what effect does this have on the relative compositions of the crust and mantle?
7. Quartz has conchoidal fracture. Biotite has perfect planar cleavage. Why?
8. Suppose olivine begins to crystallize from a magma at high temperature. As cooling progresses, the olivine crystal grows larger as its composition changes. If the olivine stays in equilibrium, it will always be homogeneous. What compositional changes would you expect to occur as cooling takes place? Suppose the cooling is too rapid for the olivine crystal to stay in equilibrium. It will then develop compositional growth rings. How will the composition of the center of the grain compare to the composition of the margins?
9. Plagioclase is the most abundant mineral in the Earth's crust. However, if you wander outside in most places, even if you could see the bedrock you probably wouldn't see a lot of rocks containing plagioclase. What kind of rocks contains lots of plagioclase? Where is all the crustal plagioclase?

## Resources

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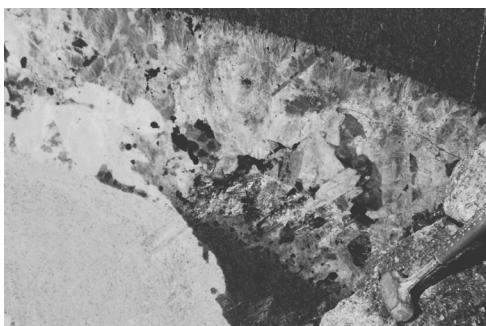
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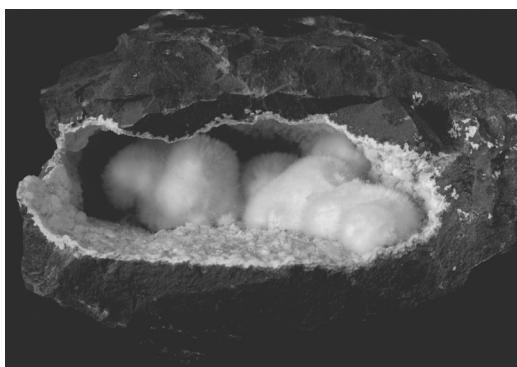
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**PLATE 1.1** Tourmaline from Paraiba, Brazil, with colors showing compositional zonation.



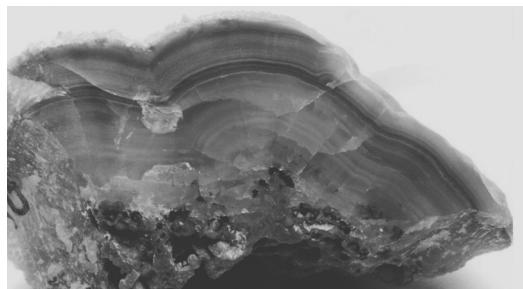
**PLATE 1.4** Small pegmatite exposed in Larvikite quarry near Larvik, Norway.



**PLATE 1.7** Acicular okenite in a geode from Bombay, India.



**PLATE 2.2** Rose quartz from Custer, South Dakota.



**PLATE 1.2** Smithsonite from Rush Creek, Arkansas, with colors showing compositional zonation.



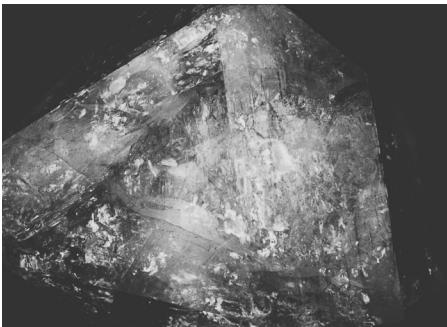
**PLATE 1.5** Orthoclase from Petschau, Bohemia, showing penetration twins.



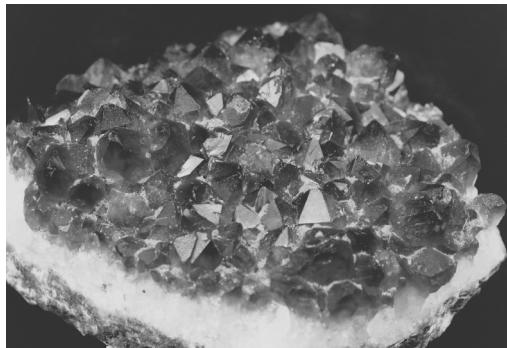
**PLATE 2.1** Rutile needles in quartz from Brazil showing conchoidal fractures.



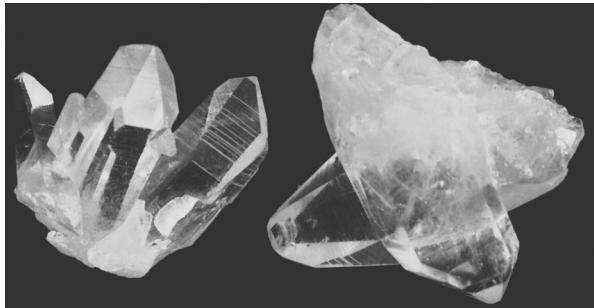
**PLATE 2.3** Amethyst, a purple variety of quartz.



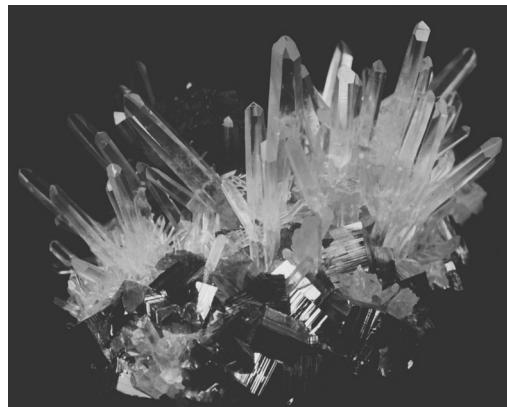
**PLATE 2.4** Quartz showing play of colors and internal reflection due to internal fractures.



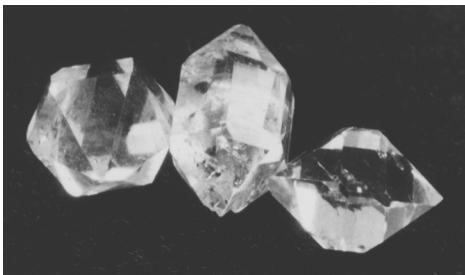
**PLATE 2.5** Brown quartz from California.



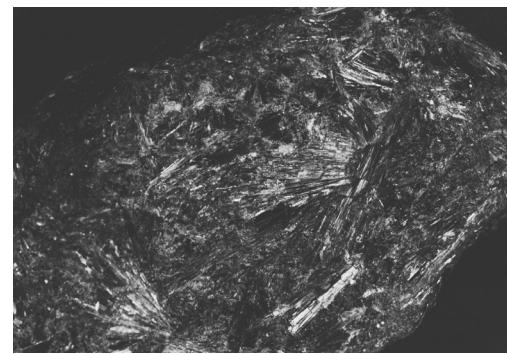
**PLATE 2.6** Clear quartz crystals from Hot Springs, Arkansas, showing growth striations.



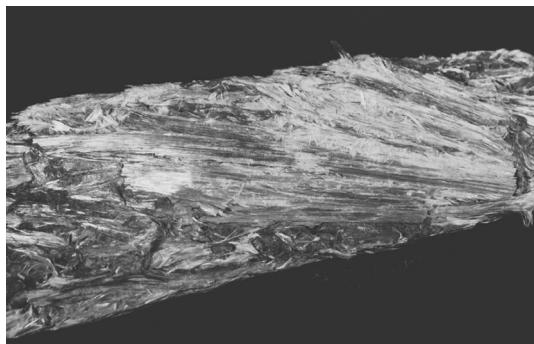
**PLATE 2.7** Prismatic quartz crystals on pyrite; sphalerite is the dark mineral behind the quartz crystals (sample from Huaron, Peru).



**PLATE 2.8** Herkimer diamonds (in reality, quartz crystals) from Herkimer, New York.



**PLATE 3.2** Actinolite from the Adirondack Mountains, New York, showing bladed habit.



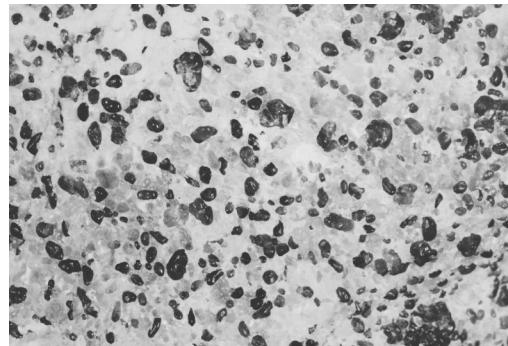
**PLATE 3.4** Fibrous anthophyllite from Gainesville, Georgia.



**PLATE 6.1** Massive green-black augite from Monzoni, Italy.



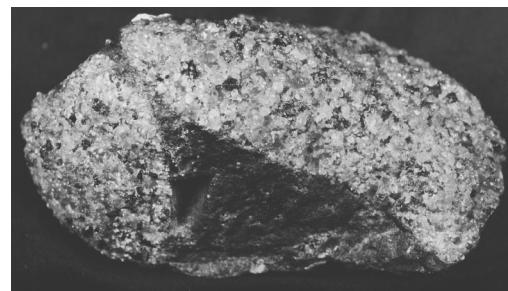
**PLATE 6.2** Chrome diopside (green) and quartz from Minas Gerais, Brazil.



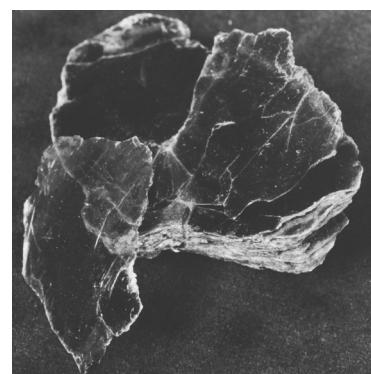
**PLATE 6.3** Marble from Lake Placid, New York, containing green diopside and white calcite.



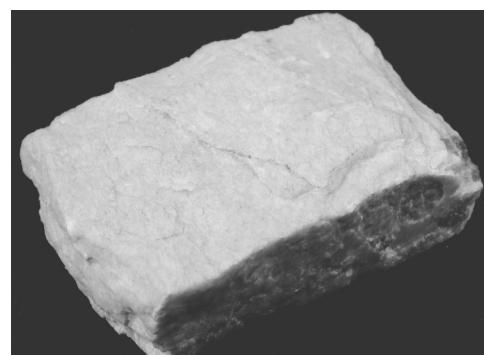
**PLATE 6.4** Aggregate of hedenbergite crystals from Nordmarken, Sweden.



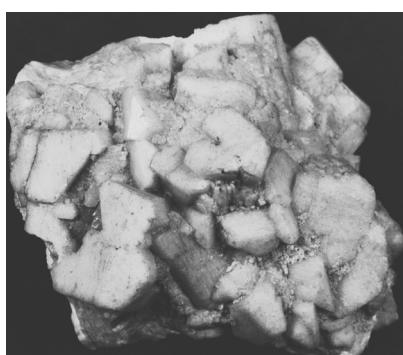
**PLATE 6.5** Green olivine crystals in a basalt from San Carlos, Arizona.



**PLATE 6.6** A book of biotite from Sioux Lookout, Ontario, Canada.



**PLATE 6.7** Perthite, a variety of K-feldspar, from Keystone, South Dakota.



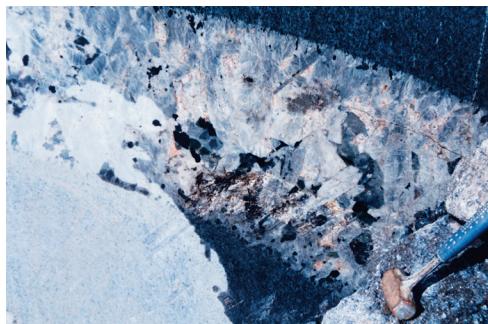
**PLATE 6.8** Albite from Amelia Courthouse, Virginia.

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# Igneous Rocks and Silicate Minerals Color Plates



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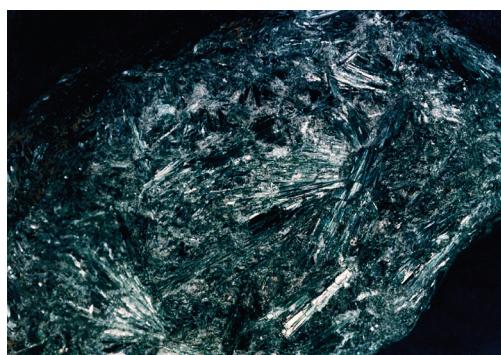
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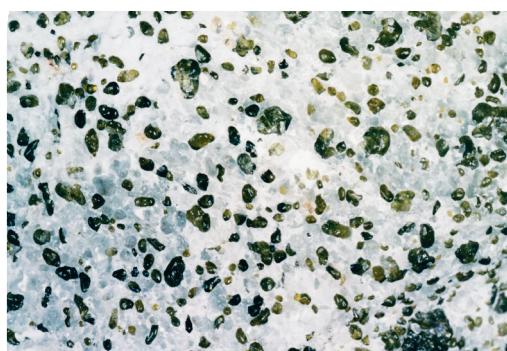
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# Sedimentary Minerals and Sedimentary Rocks

Sedimentary rocks and minerals cover most of the dry surface of the Earth. The processes that produce them are more variable than those that produce igneous rocks and minerals, but the number of common sedimentary minerals is small. In this chapter we talk about sedimentary processes and common sedimentary minerals and introduce a classification scheme for sedimentary rocks.

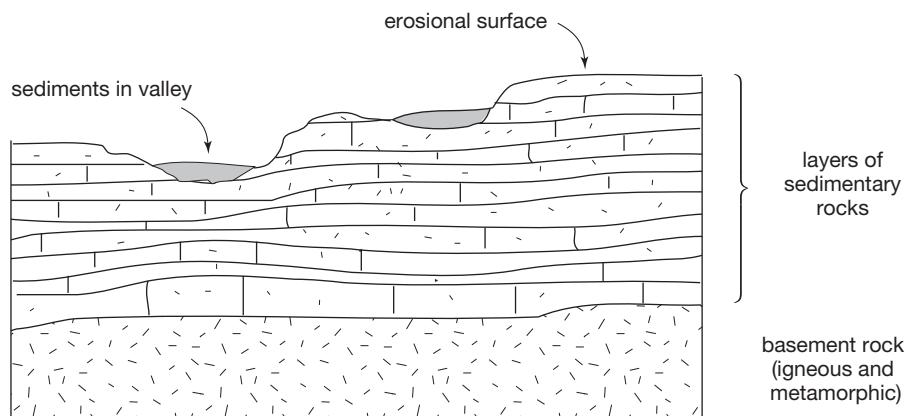
**Sediments** and **sedimentary rocks** cover about 80% of all continental areas but are less than 1% of the volume of the Earth's crust. They are, in effect, a thin blanket on top of igneous and metamorphic **basement rocks** (Figure 1). Sediments, and thus sedimentary rocks, are mostly recycled materials derived from preexisting igneous, metamorphic, or sedimentary rocks.

Petrologists usually divide sedimentary rocks into two main groups: **detrital rocks** and **chemical rocks**. Detrital sedimentary rocks are formed by **compaction** and **cementation** of **clastic** sediments composed of individual mineral grains or **lithic fragments** (pieces of rock). The mineral grains and lithic fragments vary greatly; we call them collectively **clasts** (from *klastos*, the Greek word meaning “broken”), so we often call detrital sedimentary rocks **clastic rocks**. Because their mineralogy varies so much, we generally classify detrital sedimentary rocks based on grain size rather than composition. **Conglomerate** contains large rounded clasts (>2 mm in longest dimension) separated by a fine-grained material called **matrix**. **Sandstone** contains sand-sized (0.062 to 2 mm in longest dimension) quartz or feldspar grains, and sometimes lithic fragments. **Mudstone** and **shale** primarily contain microscopic

(<0.062 mm in longest dimension) clay and quartz grains. Sedimentary petrologists use the term **clay** to refer to clastic grains smaller than 0.004 mm in longest dimension; in this text, however, we use it to refer to minerals of the clay mineral group, regardless of grain size. In the coarser-grained sedimentary rocks, the compositions of lithic fragments give clues to the origin of the sediment. In the finer-grained rocks, mineralogical composition is often difficult to determine and interpret.

Chemical sedimentary rocks are formed by precipitation of minerals from water, or by alteration of already precipitated material. Many **limestones**, **dolostones**, **evaporites**, and **cherts** form this way. In contrast with most detrital sedimentary rocks, petrologists name chemical sedimentary rocks based on chemical composition. Chemical sedimentary rocks usually include only one or a few minerals because the chemical processes that form them tend to isolate certain elements. The most common precipitated minerals consist of elements of high solubility (for example, sodium or potassium) or elements of great abundance (for example, silicon).

Some sedimentary rocks are formed largely from **biogenic** (organic) debris. Examples are limestones formed from shell or skeletal remains,



**FIGURE 1** Sedimentary rocks over basement rock. In some parts of North America, the layers of sedimentary rocks are thousands of feet thick. In other places, notably Precambrian shields and mountain ranges, the layers of sedimentary rocks are completely missing.

**coquina** (a sedimentary rock made of shell fragments), **diatomite** (a sedimentary rock made of the remains of diatoms), and **coal**. Petrologists often classify such rocks separately from chemical and detrital sedimentary rocks. We will not, however, consider them separately here. Much overlap exists between chemical, detrital, and organic sedimentary rocks. Many chemical sedimentary rocks contain clastic material, and many detrital sedimentary rocks are held together by chemical cements precipitated from water. Both chemical and detrital rocks may contain biogenic components.

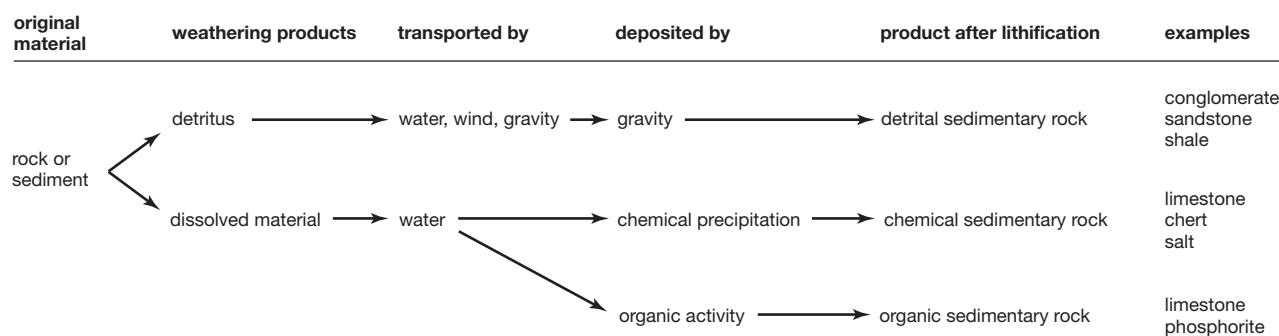
## WEATHERING

Figure 2 shows the two parallel processes that result in sedimentary rocks. An original source rock (igneous, metamorphic, or sedimentary) is exposed to weathering. The weathering forces may be **mechanical** (water, wind, gravity, glaciers, waves, and frost) or **chemical** (dissolution by water, perhaps containing acids). Mechanical weathering, which produces clastic material called **detritus**, is of much less significance than chemical weathering. Even apparently dry climates have

enough water to promote chemical weathering on exposed surfaces, although the weathering rate may be slow.

Chemical weathering produces dissolved material, called the **hydrolysate**, and leftover rock and mineral detritus that did not dissolve. We sometimes call the undissolved material the **resistate** because it resists dissolution. More easily dissolved elements, especially the alkalis and alkaline earths, go into solution, while resistate remains to become sediment (Table 1). Typical resistates include quartz, clay, K-feldspar, garnet, zircon, rutile, or magnetite.

Chemical weathering often produces clay minerals, the most important being montmorillonite, illite, and kaolinite. Reactions that produce clays are complex, involving the reaction of water with previously existing minerals, such as feldspars, to produce clays and dissolved elements. We call such reactions **hydrolysis reactions**. Figure 3 depicts a K-feldspar grain undergoing hydrolysis. Mechanical and chemical decomposition produces kaolinite and dissolved ions, including  $K^+$  and  $Si^{4+}$ . The dissolved material is carried away and will eventually precipitate elsewhere. The **residual** kaolinite may remain where it forms, but



**FIGURE 2** Processes that form sedimentary rocks. The weathering products—rock debris and dissolved material—are transported and then deposited by gravity, chemical precipitation, or organic activity to produce sediments and eventually sedimentary rocks.

**TABLE 1** Products of Weathering of Some Common Igneous Minerals

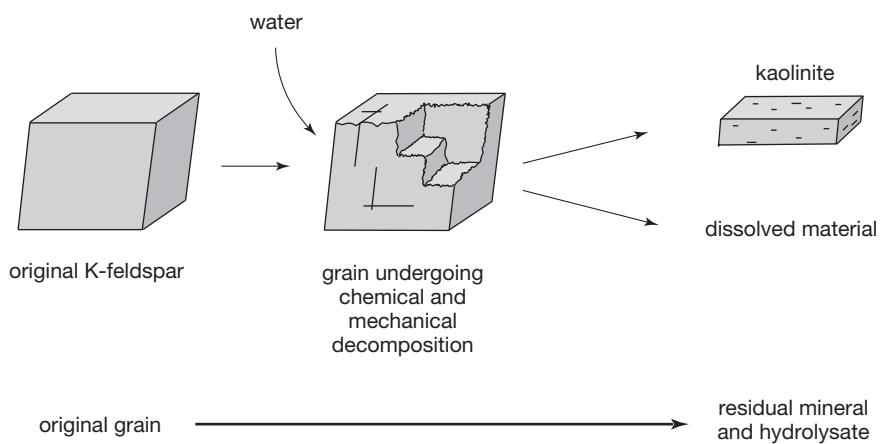
Mineral	Formula	Resistate Minerals	Formula	Hydrolysate Cations
quartz	$\text{SiO}_2$	quartz	$\text{SiO}_2$	
feldspar	$(\text{Ca}, \text{Na}, \text{K})(\text{Al}, \text{Si})_4\text{O}_8$	quartz muscovite clays	$\text{SiO}_2$ $\text{KAl}_2(\text{AlSi}_3)\text{O}_{10}(\text{OH})_2$ complex chemistry	$\text{K}^+, \text{Na}^+, \text{Ca}^{2+}$
olivine	$(\text{Mg}, \text{Fe})_2\text{SiO}_4$	hematite goethite magnetite quartz muscovite clays	$\text{Fe}_2\text{O}_3$ $\text{FeO(OH)}$ $\text{Fe}_3\text{O}_4$ $\text{SiO}_2$ $\text{KAl}_2(\text{AlSi}_3)\text{O}_{10}(\text{OH})_2$ complex composition	$\text{Mg}^{2+}$
pyroxene	$(\text{Ca}, \text{Mg}, \text{Fe})_2\text{Si}_2\text{O}_6$	Same as for olivine		$\text{Ca}^{2+}, \text{Mg}^{2+}$
amphibole	$(\text{K}, \text{Na})_{0-1} (\text{Ca}, \text{Na}, \text{Fe}, \text{Mg})_2 (\text{Mg}, \text{Fe}, \text{Al})_5 (\text{Si}, \text{Al})_8 \text{O}_{22} (\text{OH})_2$	Same as for olivine		$\text{K}^+, \text{Na}^+, \text{Ca}^{2+}, \text{Mg}^{2+}$

water, gravity, or wind can transport clays produced by hydrolysis, just like any other detrital material.

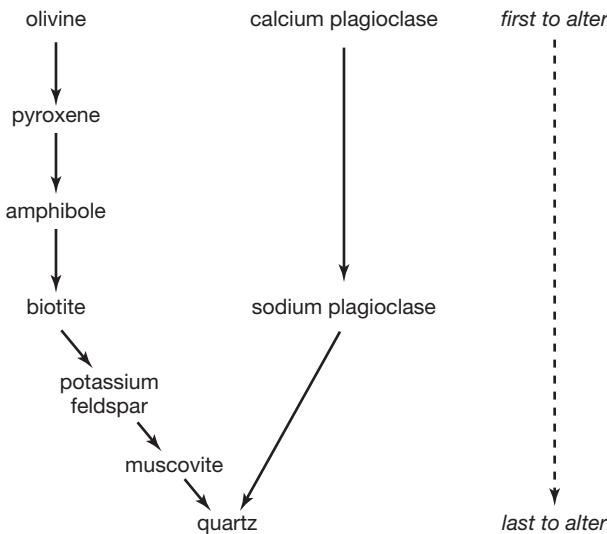
If we examine fresh outcrop (unweathered) in a road cut, rock often appears hard and shiny. Examination with a hand lens reveals that minerals have well-defined boundaries and jagged outlines and may show good cleavage or crystal faces. Minerals have their normal diagnostic colors: quartz is clear, feldspars are white or pink, muscovite is silvery and sparkly, magnetite appears metallic, and biotite and other mafic minerals appear black. The picture is not the same in outcrops exposed to weathering for a long time. After weathering, rock and most minerals have a dull or drab appearance. Grain boundaries and cleavages are obscured. Red, brown, and gray material coats all surfaces, obscuring diagnostic minerals.

Goldich (1938) made such observations, publishing a well-known weathering series showing the ease with which some common igneous minerals

break down (Figure 4). He derived his series from studying the formation of clays on outcrops of granite, diabase, and amphibolite in the Minnesota River Valley. The keen reader will notice that Goldich's series is nearly identical to Bowen's reaction series. Minerals that crystallize from a magma at high temperature—minerals relatively poor in silicon (Si) and oxygen (O)—are generally less resistant to weathering than those that crystallize at low temperature. Iron-magnesium (Fe-Mg) silicates, such as olivine or pyroxene, calcic feldspars, and many minerals with high solubilities in water, break down relatively easily. Quartz, some feldspars, and some nonsilicate minerals are relatively resistant to weathering because they contain more Si - O bonds, which do not break easily. It should not be surprising that minerals stable in high-temperature igneous rocks, or those most often precipitated from water, are the first to decompose under Earth surface conditions.



**FIGURE 3** Hydrolysis reaction. Feldspar reacts with water as it undergoes both mechanical and chemical weathering to produce kaolinite and dissolved material.



**FIGURE 4** A modified version of Goldich's weathering series describing the relative order in which minerals decompose due to weathering. Olivine and Ca-plagioclase weather most rapidly, while quartz is the most resistant.

## TRANSPORTATION, DEPOSITION, AND LITHIFICATION

Flowing water transports detrital sediments to a place where they collect, perhaps a river or lake bottom. Wind, gravity, and other agents can move sediments as well. Eventually when the forces of gravity overcome

those trying to move them, sediments will be deposited. After deposition, the loose sedimentary material will, over time, change into a detrital sedimentary rock by **lithification** (from *lithos*, the Greek word meaning stone), a process that involves compaction and cementation. Common cementing agents include the minerals quartz, calcite, and hematite.

Water transports dissolved material produced by chemical weathering until precipitation of chemical sediment occurs. Several things may cause precipitation; most common are changes in temperature, acidity (pH), and biological activity. Hot springs deposit a form of calcite called **travertine**, for example, when cooling water becomes oversaturated with  $\text{CaCO}_3$ . In freshwater streams or lakes, a pH change due to biological activity may cause dissolution or precipitation of another form of calcite called **marl**. Many reef-building organisms have shells or skeletons made of organic calcite. Calcite and other chemical sedimentary minerals, then, precipitate in many ways. In contrast with detrital sediments, chemical sediments are usually lithified as they are deposited.

Before, during, and after lithification, sedimentary rocks undergo textural or chemical changes due to heating, compaction, or reaction with groundwaters. We call these changes **diagenesis**. Diagenesis is a low-temperature/pressure form of metamorphism. New minerals formed by this process are termed **authigenic minerals**. Zeolites (Box 1), clays, feldspar, pyrite, and quartz can all be authigenic

### BOX 1

#### Zeolites

The zeolite group includes more than 40 minerals. All are framework silicates containing open cavities capable of holding loosely bonded large cations and water. Different zeolites have different-sized openings, and in some zeolites the openings connect to form channels. Because of the cavities, zeolites can be used as molecular sieves or as ion-exchange media. Manufacturing industries also use zeolites as drying agents, catalysts, and washing materials. Synthetic zeolites have, for some purposes, replaced natural ones. The most common zeolites include:

natrolite	$\text{Na}_2\text{Al}_2\text{Si}_3\text{O}_{10} \cdot 2\text{H}_2\text{O}$
laumontite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 4\text{H}_2\text{O}$
chabazite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 6\text{H}_2\text{O}$
clinoptilolite	$(\text{Na}, \text{K})\text{Al}_2\text{Si}_7\text{O}_{18} \cdot 6\text{H}_2\text{O}$
heulandite	$\text{CaAl}_2\text{Si}_7\text{O}_{18} \cdot 6\text{H}_2\text{O}$
stilbite	$\text{CaAl}_2\text{Si}_7\text{O}_{18} \cdot 7\text{H}_2\text{O}$
sodalite	$\text{Na}_3\text{Al}_3\text{Si}_3\text{O}_{12} \cdot \text{NaCl}$

The compositions of zeolites seem highly variable, but the ratio  $(\text{Ca}, \text{Sr}, \text{Ba}, \text{Na}_2, \text{K}_2)\text{O} : \text{Al}_2\text{O}_3$  is always 1:1, and the ratio  $(\text{Al} + \text{Si})\text{:O}$  is always 1:2. Zeolites and feldspathoids are closely related, but zeolites have more open structures and contain loosely bonded  $\text{H}_2\text{O}$ . Sodalite is sometimes grouped with the feldspathoids rather than the zeolites, but it has a zeolite-type structure and contains loosely bonded NaCl. Analcime,  $\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$ , is also sometimes considered a zeolite, but is closer to leucite and other feldspathoids in structure.

Zeolites are best known for their occurrences in vugs and other open cavities in volcanic rocks. Large volumes are found, however, in volcanic ashes and saline lake deposits. Zeolites also may be present as products of diagenesis or low-grade metamorphism in sediments and rocks.

**BOX 2****Laterites and Bauxites**

Consider a tropical area with warm weather and abundant rainfall. Weathering and leaching will be extreme, and even clay minerals may decompose. Normally soluble elements, and even relatively insoluble silica, will be dissolved and carried away. The remaining material, called a *residual deposit*, is often composed primarily of aluminum oxides and hydroxides, the least soluble of all common minerals. We term such deposits **laterites** (if not lithified) or **bauxites**. They are our most important source of aluminum. The mineralogy of a laterite depends on the composition of rocks weathered to produce it; laterites can also be important sources of iron, manganese, cobalt, and nickel, all of which have low solubilities in water.

Most laterites are aluminous. The most important aluminum ore in laterites is bauxite, a mixture of several minerals, including the polymorphs boehmite and diaspore,  $\text{AlO(OH)}$ , and gibbsite,  $\text{Al(OH)}_3$ . Bauxite is mined in large amounts in Australia and Indonesia, and in smaller quantities in the Americas and in Europe. In some places, relatively young laterites produce ore, but in Australia economical laterite deposits are more than 65 million years old.

minerals. The Herkimer diamonds (quartz) in Plate 2.8 are authigenic minerals. Diagenesis creates many minerals, but most are so fine grained that they cannot be identified without X-ray analysis.

The most important agents causing diagenesis are pressure, heat, and water. Biological agents, such as small animals or bacteria, also can be important, as can chemical agents brought in by flowing water. Dissolution of minerals (**leaching**) and the formation of clay minerals are both common during diagenesis (Box 2). Textural changes, including **compaction** and loss of pore space, are common and are part of diagenesis. **Recrystallization**, the changing of fine-grained rocks into coarser ones, is another form of diagenetic textural change.

The processes of sedimentation, lithification, diagenesis, and low-grade metamorphism form a continuum. Lithification changes unconsolidated sediment into a rock. Cementation by quartz, calcite, or hematite may be part of the lithification process. It also may be considered a diagenetic process. Similarly, the formation of many low-temperature minerals such as zeolites (Box 1), a normal part of diagenesis, overlaps with the beginnings of metamorphism. Metamorphic petrologists often define the onset of metamorphism by the first occurrence of metamorphic minerals. This definition can be hard to apply because many diagenetic minerals are also metamorphic minerals. Furthermore, laumontite, often considered to be formed at the lowest temperature of all metamorphic minerals, is a zeolite hard to distinguish from those that form diagenetically.

## **SEDIMENTARY MINERALS**

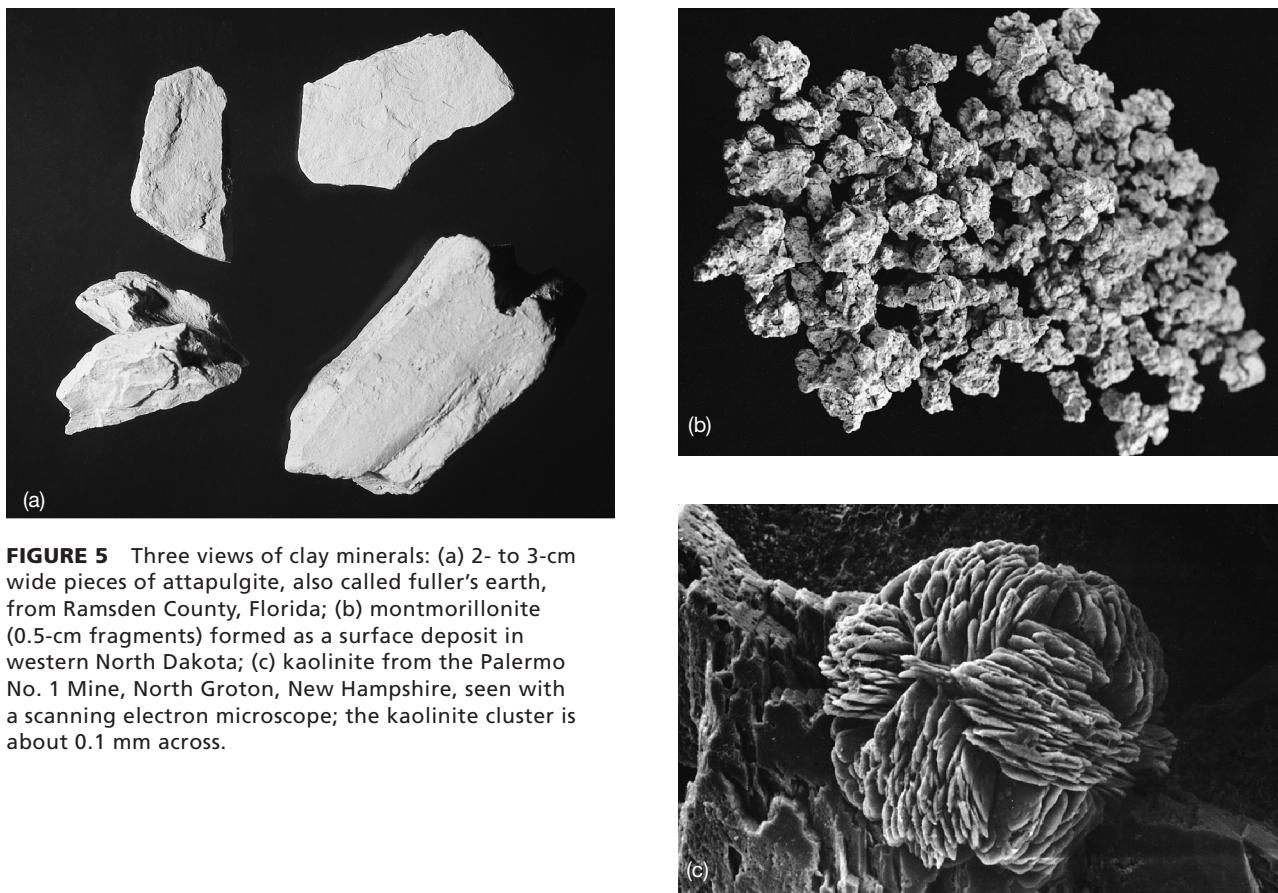
### **Silicates**

In principle, silicate minerals could all exist in sediments and sedimentary rocks. In

practice, most break down so quickly that they cannot be weathered or transported very much before completely decomposing. Quartz is the most resistant to weathering. It is also a common component of many igneous and metamorphic rocks found at the Earth's surface. It is no surprise, therefore, that quartz is the main component of many clastic sediments. Feldspars are also found in clastic sediment rocks. They are usually subordinate to quartz, and are rare in sediments transported long distances or weathered for long times. Mafic silicate minerals occasionally exist in detrital rocks but are never major components. Besides quartz, the other common silicates in sedimentary rocks are clays and zeolites (Box 1). Important nonsilicate minerals found in sedimentary rocks include carbonates, sulfates, and halide minerals.

### **Clay Minerals**

Clays account for nearly half the volume of sedimentary rocks. They are usually very fine grained, often less than  $1 \mu\text{m}$  ( $10^{-6} \text{ m}$ ) in size, have complex chemistries, and are structurally variable, which makes identification of individual clay species difficult (Figure 5). X-ray analysis is often necessary to tell them apart. In contrast with quartz and feldspar, clays do not form in igneous and metamorphic environments. Clays crystallize in sedimentary environments and their compositions depend on the sources of the sediment. The clay mineral group includes many different minerals, all sheet silicates. They have layered atomic structures, similar in many respects to micas. Clays are hydrous, some containing as much as 15 to 20 wt %  $\text{H}_2\text{O}$ . Their layered structure and the weak bonding between layers give them a characteristic slippery feel when wet. Clays are common in shales and other sedimentary rocks. Although usually fine grained, they form thick beds or layers. They also form as coatings on other minerals undergoing



**FIGURE 5** Three views of clay minerals: (a) 2- to 3-cm wide pieces of attapulgite, also called fuller's earth, from Ramsden County, Florida; (b) montmorillonite (0.5-cm fragments) formed as a surface deposit in western North Dakota; (c) kaolinite from the Palermo No. 1 Mine, North Groton, New Hampshire, seen with a scanning electron microscope; the kaolinite cluster is about 0.1 mm across.

weathering. These generalizations are true of all clay minerals, but many different kinds of clay exist. In part, the many varieties are due to the low temperatures at which clay minerals form. At high temperatures, minerals and mineral structures tend to be simple, and a relatively small number of stable minerals exist. At low temperatures, structures are often more complex or disordered, and many different minerals may exist. Montmorillonite dominates modern clay-rich sediments and sedimentary rocks; illite dominates most sedimentary rocks that are older than about 100 million years. Geologists ascribe this development to variations in tectonic activity resulting in changes in sediment sources, changes in biological activity, and diagenesis.

Talc, a secondary mineral that forms when Mg-silicates such as olivine or pyroxene are altered, and pyrophyllite, an uncommon metamorphic mineral, are often grouped with the clays. They are, however, less variable in their structure and composition and contain less H<sub>2</sub>O. They are transitional between clays and micas in structure and, when seen in hand specimen or thin section, are typically easier to identify than clays. The three most important kinds of clays are illite, montmorillonite, and the clays of the kaolinite group (Table 2). Kaolinites, also called *kandites*, vary less in composition and structure than other clays, although several kaolinite polymorphs are known. Kaolinite is the principal clay used to make ceramic ware

**TABLE 2** Important Clay Minerals

Clay	Chemical Formula
kaolinite	Al <sub>2</sub> Si <sub>2</sub> O <sub>5</sub> (OH) <sub>4</sub>
illite	K <sub>1-1.5</sub> Al <sub>4</sub> (Si, Al) <sub>8</sub> O <sub>20</sub> (OH) <sub>4</sub>
smectite group:	
montmorillonite	(Ca, Na) <sub>0.2-0.4</sub> (Al, Mg, Fe) <sub>2</sub> (Si, Al) <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub> • n H <sub>2</sub> O
vermiculite	(Mg, Ca) <sub>0.3-0.4</sub> (Mg, Fe, Al) <sub>3</sub> (Al, Si) <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub> • n H <sub>2</sub> O

**BOX 3****Clays Used in Industry, Arts, and Ceramics**

Clays are widely used to make bricks, tile, paper, rubber, water pipes, and china. They are even used today by some restaurants to thicken milkshakes. Early peoples made bowls and other artifacts by shaping clay and allowing it to dry in the sun. Many different clays have industrial uses. Porcelain and china makers commonly use kaolinite. If baked to temperatures above 500 °C (930 °F), kaolinite will dehydrate to metakaolinite ( $\text{Al}_2\text{Si}_2\text{O}_7$ ), a nonmineral that is relatively hard. Such temperatures can be obtained over open fires, and much of the early pottery consists of metakaolinite. Although metakaolinite is porous, it will not soften when wetted, in contrast to sun-baked clays.

**Porcelain** refers to a special type of high-grade white ceramic. The white color is only obtained by using extremely pure kaolinite. Porcelain is baked, or fired, at very high temperatures. At temperatures of 925 °C (1,700 °F) and above, metakaolinite converts to a mixture of cristobalite, mullite, and other phases, but it does not melt unless the temperature exceeds 1,600 °C (2,910°F). Prior to firing, feldspar or talc is mixed with the kaolinite in small amounts. When fired at 1,200 to 1,450 °C (2,190 to 2,640 °F), the feldspar or talc melts to form a glass, which gives porcelain its glassy luster without melting the kaolinite and destroying the object being made.

(Box 3). Illite is similar to muscovite in some ways, but contains more Si and less K. Montmorillonites, which belong to the smectite group, can take up extra water or other fluids between the layers of their atomic structure. In the process they expand; thus, we sometimes call them *expandable* or *swelling clays*. Because they absorb liquids so well, gas station operators use them to clean up spilled oil, and homeowners use them as kitty litter. They are the major components of earthy material called *bentonite*, sometimes prized for its water-absorbing and cation-exchange properties. Another clay of the smectite group, vermiculite, is often used to lighten up potting soil.

**Carbonate Minerals**

Mineralogists have identified more than 50 different carbonate species; all contain  $(\text{CO}_3)^{2-}$  but some contain other anions or anionic groups. Plate 1.2

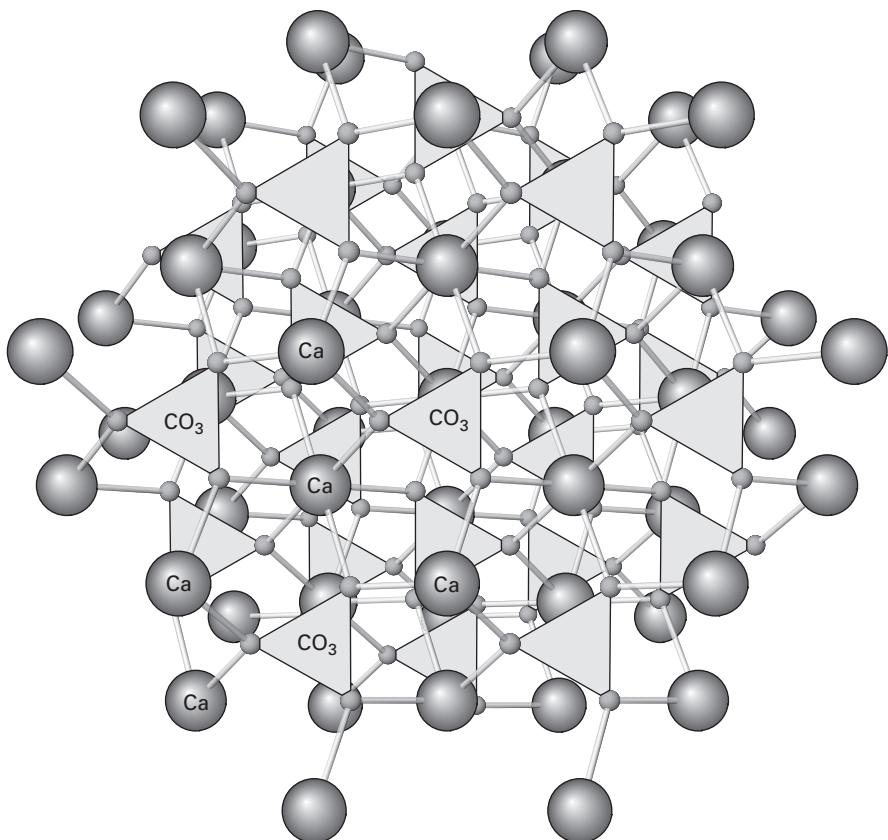
shows smithsonite,  $\text{ZnCO}_3$ , one of the rarer carbonates. Few carbonate minerals are common, and many have complex compositions and structures. The atomic structures of calcite and dolomite, the most common carbonates by far, contain  $(\text{CO}_3)^{2-}$  groups alternating with divalent cations (Figure 6). Both calcite and dolomite may exist as spectacular individual crystals, as essential minerals in limestones, or as clastic fragments in other sedimentary rocks (Figure 7). Calcite also exists in metamorphic rocks such as marbles, in some hydrothermal deposits, and in rare igneous rocks called carbonatites. Dolomite is common in limestones and dolostones (limestones containing dolomite instead of calcite), and occurs in metamorphic and hydrothermal deposits. Most dolomite is secondary and forms by reaction of calcite with Mg-rich solutions during diagenesis. Magnesite,  $(\text{MgCO}_3)$ , a related carbonate, forms as an alteration product of mafic and ultramafic rocks.

**BOX 4****Lime Kilns, Mortar, and Cement**

Calcite is an important component in the production of cement and mortar. Both have been used since at least 2700 to 2100 B.C., when ancient Egyptians built one of the Seven Wonders of the World: the Great Pyramids. Subsequently, Greeks and Romans used cement produced from volcanic ash and lime in much of their building construction.

To make cement or mortar, calcite is **calcined** at temperatures above 900 °C (1,650°F) in a **lime kiln** to get quicklime ( $\text{CaO}$ ) and carbon dioxide. Mortar is then produced by mixing the lime with sand and water. When lime reacts with water, portlandite,  $\text{Ca}(\text{OH})_2$ , forms, consuming much of the water. The formation of portlandite (also called *slaked lime*) releases heat, which aids in hardening or “setting” as the remaining water evaporates.

**Portland cement**, the most widely used cement, consists of a mixture of lime, silica, alumina, and iron oxides. Silica, alumina, and iron oxides may be obtained from clays, blast furnace slag, or even coal fly ash. Gypsum is typically added to Portland cement to control setting time. The mixture is combined with water and, depending on its composition, hardens rapidly. After setting, Portland cement consists of a number of  $\text{Ca-Al-Fe-Si-O}$  phases, some of which resemble minerals. The strength of cement derives from the presence of the nonmineral phases  $\text{Ca}_3\text{Al}_2\text{O}_6$  and  $\text{Ca}_2\text{SiO}_4$ .



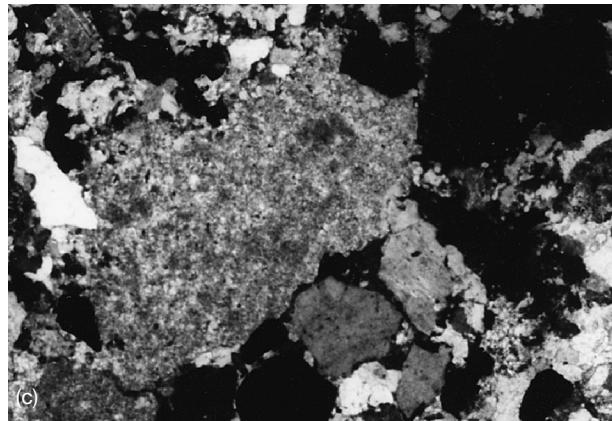
**FIGURE 6** Atomic arrangement in calcite. The large spheres represent  $\text{Ca}^{2+}$  ions and the triangles represent  $\text{CO}_3$  groups. Many other carbonates have similar structures.



(a)

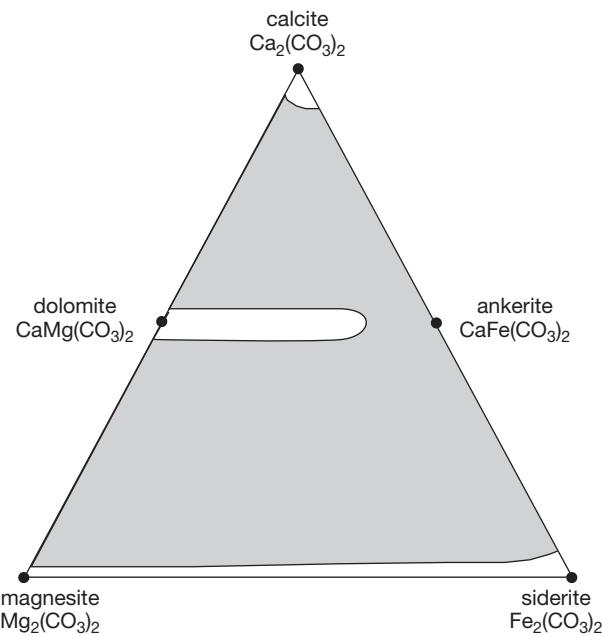


(b)



(c)

**FIGURE 7** Dolomite and calcite: (a) 0.5-cm dolomite crystals on a carbonate rock; (b) 3-mm-wide thin-section view (XP) of calcite in a limestone (note concentric growth lines); (c) 2.5-mm-wide thin-section view (XP) of a large grain of calcite (in center of photograph) in a sandstone. Note the twinned plagioclase, quartz, and other detrital grains.



**FIGURE 8** The principal end members of carbonate minerals. Natural compositions falling in the shaded region are rare due to immiscibility. Here and in Figure 9, the formulas of calcite, magnesite, and siderite have been doubled to be consistent with the formulas of dolomite and ankerite.

We can plot the compositions of Ca-Mg-Fe carbonates on a triangular diagram similar to that used for pyroxenes (Figure 8). Miscibility gaps exist between the Ca-bearing carbonates and the Ca-free ones, similar to the gaps between wollastonite, clinopyroxene, and orthopyroxene. This can best be seen by looking at a temperature composition diagram (Figure 9). Compositions intermediate between calcite and dolomite are not stable, except at high temperature where calcite may contain

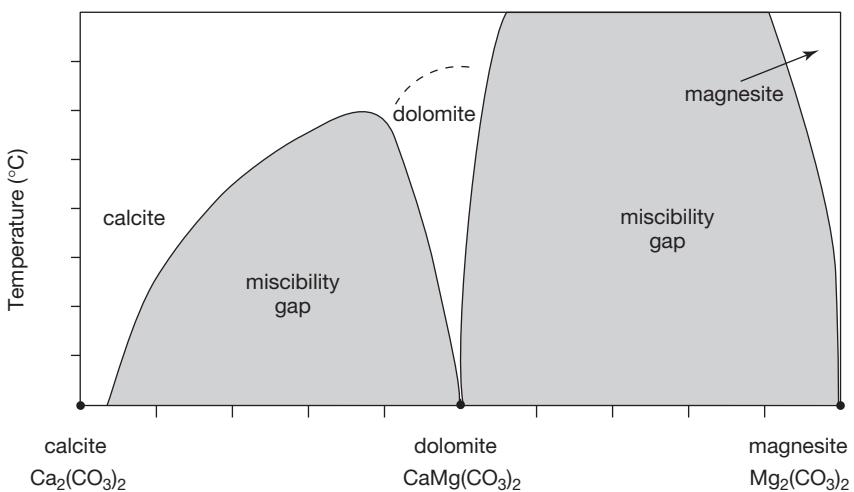
extra Mg. Compositions intermediate between dolomite and magnesite are never stable. At temperatures above about 900 °C (1,650 °F) calcite breaks down to produce quicklime (CaO) and CO<sub>2</sub> gas. The other carbonates also break down at high temperature.

### Sulfate Minerals

More than 100 sulfate minerals are known. They fall into two main groups: those that contain no water (anhydrous sulfates) and those that do (hydrated sulfates). Examples in the first group include anhydrite (CaSO<sub>4</sub>), barite (BaSO<sub>4</sub>), celestite (SrSO<sub>4</sub>), and anglesite (PbSO<sub>4</sub>) (Figures 10a and b). Plate 1.6 shows a spectacular example of celestite from Ohio. In the second group are gypsum (CaSO<sub>4</sub> · 2H<sub>2</sub>O), shown in Figure 10c, and some rare species. Rare green gypsum from Australia is shown in Plate 3.5. Gypsum and anhydrite can both be major rock-forming minerals. Thick deposits of gypsum or anhydrite, or both, are associated with limestone, dolostone, or halite beds. They may also associate with native sulfur (S) deposits. All the sulfate minerals can be found in vugs or fractures in a variety of rock types, and many occur in soils. Some sulfates are common as minor, and sometimes major, minerals in ore deposits—typically as replacements for primary sulfides. Anglesite (PbSO<sub>4</sub>), for example, forms during weathering or alteration as a replacement for galena (PbS).

### Halides

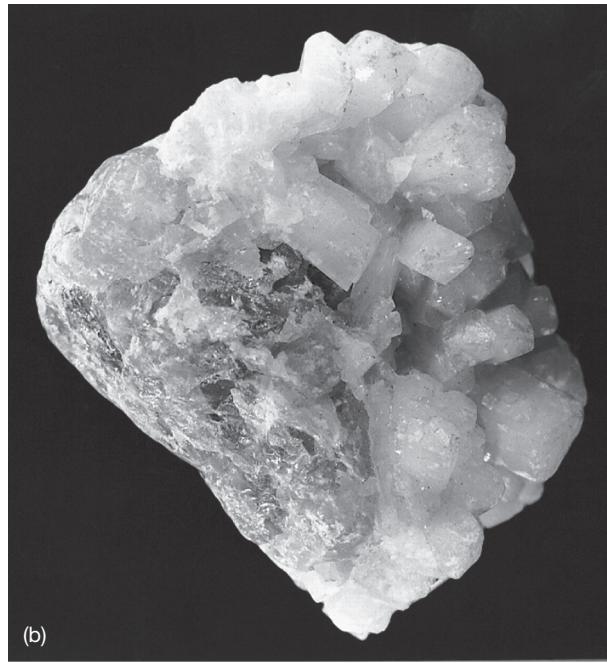
The halide group consists of minerals containing a halogen element, most commonly chlorine or fluorine, as an essential anion (Table 3; Figure 11).



**FIGURE 9** Temperature composition diagram for calcite-dolomite-magnesite carbonates. Two large miscibility gaps restrict carbonate compositions. The boundary limiting the dolomite field at high temperature is poorly known. At high temperature, calcite may contain excess magnesium and approach dolomite in composition, but carbonates intermediate between dolomite and magnesite are never stable.



(a)



(b)

**FIGURE 10** Sulfate minerals. The field of view is about 10 cm across for each: (a) barite,  $\text{BaSO}_4$ ; (b) celestite,  $\text{SrSO}_4$ .

Halide atomic structures are highly ionic. In halite,  $\text{Na}^+$  and  $\text{Cl}^-$  alternate in a cubic three-dimensional arrangement. In fluorite, the arrangement of atoms is also cubic, but two  $\text{F}^-$  are present for every  $\text{Ca}^{2+}$  (Figure 12). Although many halides exist, only halite and sylvite are common in sedimentary rocks. Except for fluorite ( $\text{CaF}_2$ ), the other halide minerals are rare in rocks of all types. Halite is typically found as rock salt in massive salt beds, often occurring with other evaporite minerals such as gypsum or anhydrite, and sometimes with sulfur. Sylvite is much less common than halite. When found, however, it is usually associated with halite.

**TABLE 3** Halide Minerals

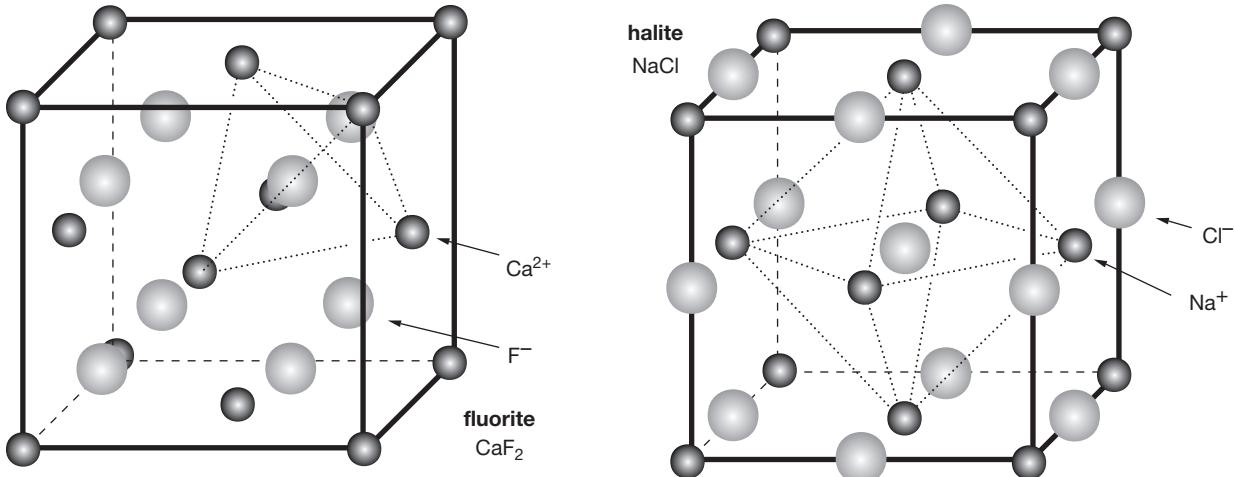
Mineral	Formula
halite	$\text{NaCl}$
sylvite	$\text{KCl}$
chlorargyrite	$\text{AgCl}$
calomel	$\text{HgCl}$
carnallite	$\text{KMgCl}_3 \cdot 6\text{H}_2\text{O}$
fluorite	$\text{CaF}_2$
cryolite	$\text{Na}_3\text{AlF}_6$

## Chert

Chert is a fine-grained (microcrystalline) form of quartz. It is also the name given to rock composed primarily of fine-grained quartz. It may be massive and well layered, and often forms as nodules or concretions in limestone. Sometimes chert seems to have formed by recrystallization of amorphous silica. Many varieties exist. Jasper is chert with a characteristic red color due to hematite inclusions. Flint,



**FIGURE 11** Fluorite ( $\text{CaF}_2$ ) and halite ( $\text{NaCl}$ ). Fluorite crystals are typically cubic, but cleavage fragments form octahedra as shown here. Halite has excellent cubic cleavage (three cleavages at  $90^\circ$ ).



**FIGURE 12** Atomic structures of fluorite and halite. Both have cations in cubic arrangement. In fluorite, the anions ( $F^-$ ) are within the cubic cell and each is surrounded by four  $Ca^{2+}$  cations (dotted lines). In halite the anions ( $Cl^-$ ) are at the center of the cell and the centers of the edges; each anion is surrounded by six  $Na^+$  cations (dotted lines).

a darker form of chert, contains organic matter. Opal and chalcedony, two other types of  $SiO_2$ , are often associated with chert deposits. From the Stone Age until the Industrial Revolution, chert and flint were highly valued as weapons, tools, and fire starters.

## COMMON SEDIMENTARY ROCKS

### Detrital Sedimentary Rocks

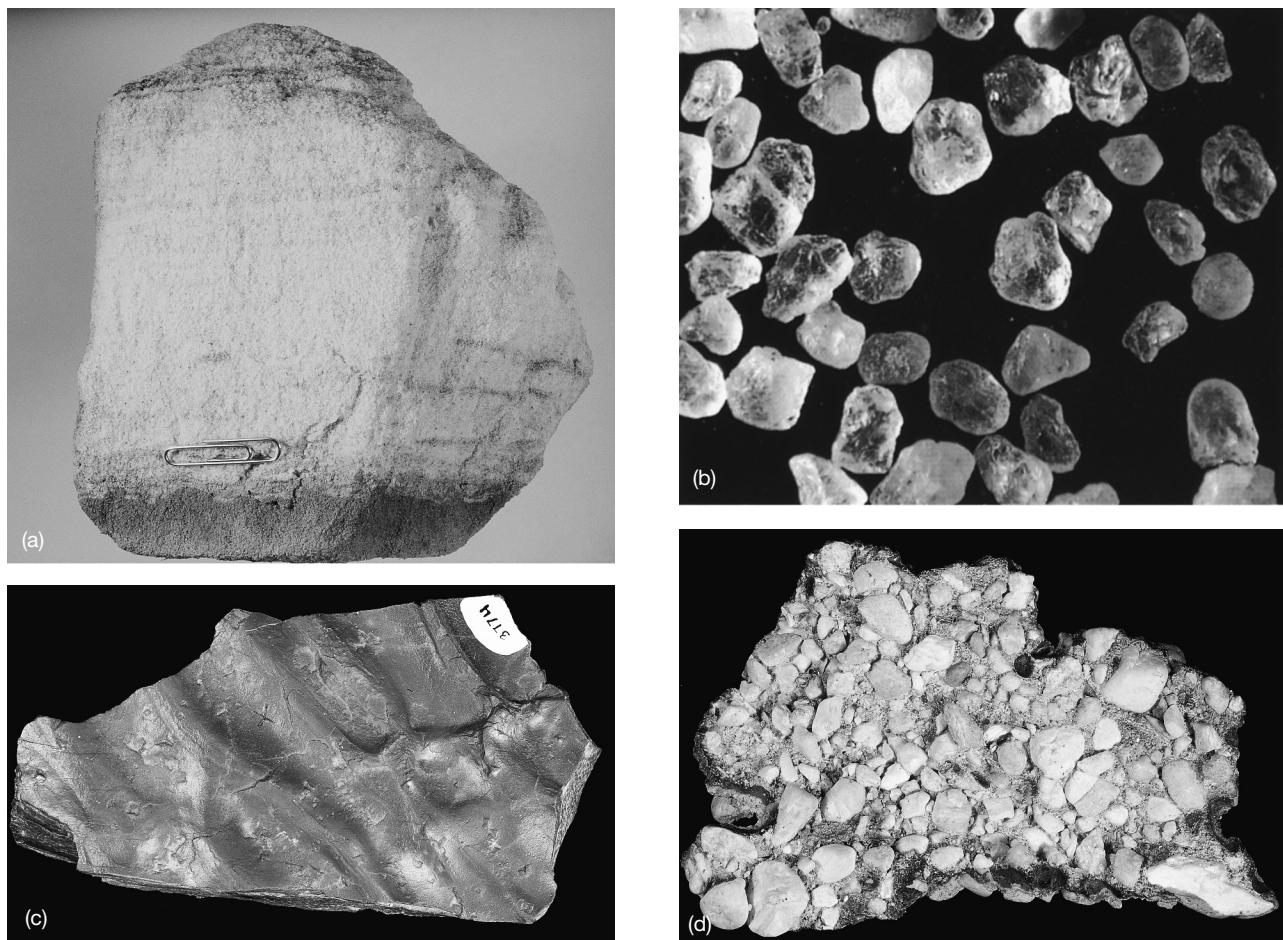
Grain size in clastic sediments and detrital rocks varies from huge clasts and boulders in gravels and conglomerates, to fine “clay size” ( $<0.004\text{ mm}$ ) particles in muds and shales (Figure 13). Table 4 gives a simple classification scheme for clastic rocks based on clast/grain size.

In the coarsest clastic rocks, a fine-grained **matrix** separates the clasts, which may be of many different types. If the clasts are angular, the rock is a *breccia*; if they are rounded, it is a conglomerate. Lithic fragments often dominate the clasts in conglomerate and breccia. Sandstones of intermediate clast size may contain both lithic fragments and individual detrital mineral grains. We call sandstones containing significant amounts of matrix material and lithic fragments *wackes* or *greywackes*, and those lacking in matrix and lithic fragments *arenites*. In the finer-grained clastic rocks, siltstone and mudstone, lithic fragments are rare or lacking. The finest grained rocks are called *shale* if they exhibit **fissility**. Fissility, the ability to cleave into very thin layers, results from parallel alignment of clay grains. Conglomerates and sandstones account for 20% to 25%

of all sedimentary rocks; the finer-grained rocks are even more common.

Since detrital sediments can be derived from any preexisting rocks, they may contain a variety of minerals and rock fragments. However, only a few are common. Quartz, feldspar, and lithic fragments containing quartz and feldspar dominate all but the finest grained rocks because they are resistant to weathering. Rocks dominated by quartz are called *quartzose*, while those containing large amounts of feldspar are termed *feldspathic*, or (if they are rich in K-feldspar) *arkosic*. In mudstones and shales, clay minerals dominate. Other minerals such as micas, magnetite, rutile, ilmenite, sphene, zircon, apatite, or garnet may occasionally be significant components of clastic sediments. Carbonate grains and organic material may be present as well. Because most minerals break down to clay and quartz if exposed at the Earth surface for sufficient time, it should be no surprise that mudstone and shale, which are composed primarily of clay and quartz, are the most abundant sedimentary rocks.

Identification of minerals in clastic rocks can be difficult if the rocks are not coarse grained. Suppose we look at a sandstone with a hand lens. Quartz, and perhaps K-feldspar, may be easy to find. However, lithic fragments can be confusing and small grains of chert or magnetite may be impossible to identify. For fine sandstones and finer-grained rocks, mineral identification can be problematic, even with a petrographic microscope; distinguishing quartz from feldspar and telling clay minerals apart can be impossible without using an X-ray diffractometer or other sophisticated equipment.



**FIGURE 13** Several detrital sedimentary rocks having different grain sizes: (a) sandstone; (b) an enlarged view of quartz grains from sandstone; the grains have been rounded by abrasion during transportation; (c) mudstone showing ripple marks on its surface; (d) a conglomerate with pebbles up to 2 cm across.

### Chemical Sedimentary Rocks

All minerals are soluble in water to some extent. Sulfates, halides, and other salts have very high solubilities. Carbonate minerals such as calcite and

dolomite have moderate solubilities (Figure 14). Silicate minerals have relatively low solubilities. If solutions become oversaturated, they precipitate chemical sediments, decreasing concentrations of dissolved

**TABLE 4** Classification Scheme for Detrital Sedimentary Rocks

Rock Type	Sediment	Grain Size	Typical Clast Material	Varieties
conglomerate or breccia	gravel	>256 mm 64 to 256 mm 4 to 64 mm 2 to 4 mm	rock fragments, quartz, feldspar rock fragments, quartz, feldspar quartz, feldspar, rock fragments quartz, feldspar	boulder conglomerate cobble conglomerate pebble conglomerate granule conglomerate
sandstone	sand	0.062 to 2 mm	quartz quartz, feldspar rock fragments, quartz, much matrix quartz, little matrix	quartzose sandstone feldspathic sandstone greywacke sandstone arenite sandstone
siltstone	silt	0.004 to 0.062 mm	quartz	siltstone
mudstone	"clay"	<0.004 mm	clays clays	shale mudstone

**BOX 5****Gypsum: Ingredient of Plaster and Sheetrock**

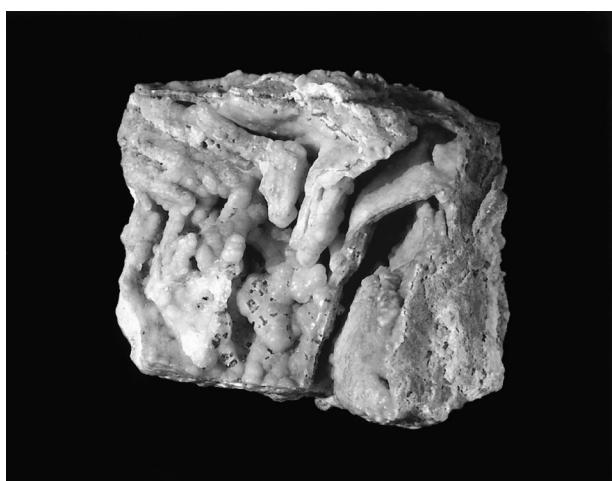
Plaster can be made from different mineral materials. Early Romans used a lime-based plaster, but **plaster of Paris**, gypsum-based plaster, was introduced around 1254. At the time, the best and most productive gypsum quarries were in Montmartre, a section of Paris. Modern plasters and sheetrock both contain plaster of Paris. Manufacturers produce it by calcining (grinding and heating) gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) to reduce its water content. Most plasters contain about 25% of the gypsum's original water. Complete dehydration of gypsum would produce anhydrite ( $\text{CaSO}_4$ ), which is not useful as a plaster because it does not recombine easily with water. However, when plaster of Paris is mixed with water, reaction occurs quickly, giving off heat and promoting drying and hardening.

material until the solution and sediments achieve equilibrium. This process produces chemical sediments and chemical sedimentary rocks (Table 5). Because of their high solubility, large amounts of evaporation may be necessary before salts, such as halite, precipitate. In contrast, carbonate minerals (calcite and dolomite) and silica (chert) often precipitate early in an evaporation event. Silica ( $\text{SiO}_2$ ), as chert, is the only silicate mineral that commonly forms a chemical sedimentary rock. Chert beds several hundred meters thick occur in much of Arkansas, Oklahoma, west Texas, and California. Thick chert beds are much more common in Precambrian rocks than in Phanerozoic rocks.

Salts such as gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ), anhydrite ( $\text{CaSO}_4$ ), halite ( $\text{NaCl}$ ), and sylvite ( $\text{KCl}$ ) have high solubilities in water, so their chemical components are common as dissolved species in natural waters. As the water evaporates, often in a closed inland basin, these minerals may precipitate to form thick beds of **evaporite minerals** (see Box 6 and

Box 7). Geologists estimate that 35% of the United States is underlain, at some depth, by thick evaporite beds. Most evaporite minerals are rare at the Earth's surface because they are so soluble that they dissolve away in all but the most arid climates. The most common evaporite mineral in outcrop is gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) because it is less soluble than others, and because it forms from any anhydrite ( $\text{CaSO}_4$ ) exposed at the surface. In the subsurface, massive gypsum and halite beds are common, as are the **salt domes** found in Texas and other Gulf Coast areas of the United States. Massive salt beds exist in many parts of the world (Figure 15). In all, petrologists have reported nearly 100 minerals from them. Less than a dozen are common (Table 6).

While *limestone* is a general term given to all carbonate rocks, we use the name *dolomite* or *dolostone* for rocks in which dolomite is the dominant mineral. Limestone and dolostone account for 10% to 15% of all sedimentary rocks. They are usually quite pure, containing mostly calcite or dolomite. Surprisingly, rocks with significant amounts of both calcite and dolomite are rare. Telling the two carbonates apart may be difficult on a fresh surface, but weathering sometimes alters dolomite to a yellow-brown color. Field geologists carry dilute hydrochloric acid—which reacts only with calcite or powdered dolomite—or chemical stains to help identification of carbonate minerals.



**FIGURE 14** Smithsonite,  $\text{ZnCO}_3$ , a carbonate mineral with relatively high solubility in water. This sample from Larium, Greece, is about 7 cm across; it precipitated with a "stalactitic" texture. See also Plates 1.2 and 1.8. The selenite in Plate 3.5 has even higher solubility than smithsonite.

**TABLE 5** Chemical Sedimentary Rocks

Rock	Major Mineral Components
limestones	calcite
dolostones	dolomite
phosphorites	phosphates such as apatite
chert	quartz
evaporites	chlorides, sulfates, carbonates, borates
iron formation	iron oxides, carbonates, silicates
travertine	calcite

**BOX 6****Disposal of Radioactive Waste in Salt Domes**

The disposal of highly radioactive wastes generated by nuclear power plants is an unsolved problem. After four decades of study, scientists still can't agree on the best disposal method. One plan is to bury the waste underground after reprocessing removes the longest-lived isotopes. To this end, the federal government investigated the possibility of disposing of nuclear waste in thickly bedded salt deposits. Salt is an attractive host because it has a high melting temperature and low porosity and permeability, and it flows under pressure rather than fracturing. Thus, the salt can be expected to help seal the waste repository. Pilot studies were conducted in New Mexico, but there are no current plans to begin disposing of radioactive waste in salt domes.

Aragonite, a polymorph of calcite, exists in some very young carbonate deposits, but never in old rocks because it changes to calcite over time. In contrast, for reasons that are not completely clear, dolomite is rare in modern carbonates but is common in Paleozoic and Precambrian rocks.

When  $\text{CaCO}_3$  precipitates to form limestones, it may be as fine-grained lime muds, resulting in microcrystalline calcite, called *micrite*. It also precipitates as coarser *sparry calcite*, which may be clear and easily visible with the naked eye. Many carbonate rocks also contain carbonate minerals that originated as clastic material or carbonate fossils (see Plate 5.1). Fossils can be of many different sorts. Pellets, mostly formed from small animal feces, are small agglomerations of microcrystalline calcite, usually well under a millimeter in longest dimension. In addition, carbonate rocks often contain detrital quartz or clay minerals and may contain authigenic minerals of many kinds.

**Other Chemical Sedimentary Rocks**

Many other types of chemical sedimentary rocks exist. They are not abundant, but they may be



**FIGURE 15** Salt crystals and Morton salt. Commercial salt is typically mined by dissolving it out of thick underground beds that formed when oceans or salt lakes evaporated.

important as sources of ore. Collophane, a cryptocrystalline form of apatite  $\text{Ca}_5(\text{PO}_4)_3(\text{OH}, \text{F}, \text{Cl})$  found in small amounts in many kinds of sedimentary rocks, has an organic origin. In rocks called *phosphorites*, apatite may comprise nearly the entire rock. Major phosphorite deposits are found in Wyoming and Idaho, where mines produce phosphate, an important component of fertilizers.

**Iron formations**, most Precambrian in age, are mined for iron in the Mesabi Range of Minnesota and elsewhere (Box 8). Fe oxides and hydroxides—hematite,  $\text{Fe}_2\text{O}_3$ ; goethite,  $\text{FeO}(\text{OH})$ ; and magnetite,  $\text{Fe}_3\text{O}_4$ —or Fe-carbonate (siderite,  $\text{FeCO}_3$ ) are the most common Fe-minerals in iron formations. Occasionally, Fe-silicates or Fe-sulfides may be present. Iron formations form from sediments originally deposited in shallow marine conditions. Young manganese deposits, similar to iron formations, have been dredged from ocean floors.

**Sedimentary Environments and Facies**

The processes that form sedimentary rock occur everywhere on Earth. In many places, however, the rate of sediment deposition is slow. In other places, erosion removes sediment as fast as it is deposited. Consequently, most of the sedimentary rocks that we see are associated with a few special

**TABLE 6** Some Minerals Common in Evaporite Deposits

Mineral	Chemical Formula
halite	$\text{NaCl}$
sylvite	$\text{KCl}$
anhydrite	$\text{CaSO}_4$
gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$
calcite	$\text{CaCO}_3$
dolomite	$\text{CaMg}(\text{CO}_3)_2$
sulfur	$\text{S}$

**BOX 7****Did the Mediterranean Sea Repeatedly Dry Up in the Past?**

Many scientists have evaporated seawater to study the precipitates that form. If seawater is evaporated, after 65% of it is gone, gypsum begins to crystallize. When 90% is gone, the first halite crystals form. When 95% is gone, sylvite and magnesium salts precipitate.

Recent deep-sea drilling and geophysical studies in the Mediterranean Basin indicate the widespread presence of thick beds of gypsum and halite. In some places the beds are up to 2,000m ( $1\frac{1}{4}$  mi.) thick. The deposits resulted from tectonic events that periodically closed and reopened the connection between the Mediterranean Sea and the Atlantic Ocean (the present-day Straits of Gibraltar) over the past six to seven million years. When the Mediterranean Basin was isolated from the Atlantic, evaporation over several thousand years led to the deposition of thick layers of gypsum followed by halite. If enough evaporation occurred, sylvite and magnesium salts also precipitated.

When connection to the Atlantic Ocean was reestablished, the briny waters of the Mediterranean were replaced by normal seawater. Recent studies suggest that refilling was much faster than evaporation, taking only hundreds of years to complete. Some of the salt and gypsum redissolved, but much was preserved. Studies indicate that the evaporation-drying cycle took place at least 30 times.

environments where the rate of deposition is relatively fast, and the volume of sediments deposited was relatively large. The most significant such environments are large basins on continents, and shallow seas. Lesser amounts of sedimentary rocks are associated with other environments such as shorelines, rivers, lakes, deserts, and glaciers. Because different environments are different physically, chemically, and biologically, the nature of sedimentary rocks is highly variable. Table 7 lists some different sedimentary environments and the types of rocks that typify them. The most significant factors that account for the differences are the energy and biology of the environment, the

distance from the source of the sediment, and the way the sediment was transported.

Most sedimentary environments vary laterally. Large basins, for example, are not the same everywhere. So different kinds of sediment can be deposited in different parts of a basin simultaneously. The term **facies** is used to refer to the different rocks that characterize a particular process or environment (Table 7). So, geologists may talk about continental, transitional, or marine facies. More specifically, they may consider reef facies, continental shelf facies, deep ocean facies, and so on. Different contemporaneous facies often grade into each other. Consider, for example, sedimentation at or near a shoreline.

**TABLE 7** Important Sedimentary Environments and Rocks

Environment	Typical Sedimentary Rocks
<i>Continental Environments</i>	
alluvial fan	breccia, conglomerate, arkose
fluvial (streams/rivers)	conglomerate, sandstone, siltstone, shale
lacustrine (lakes)	siltstone, shale, limestone, evaporites
desert	sandstone (quartz arenite), gypsum
marsh	peat, coal, black shale, siltstone
<i>Transitional Environments</i>	
delta	sandstone, siltstone, shale, coal
barrier beach	sandstone (quartz arenite), coquina
lagoon	siltstone, shale, limestone, gypsum
tidal flat	siltstone, shale, dolostone, gypsum
<i>Marine Environments</i>	
reef	fossiliferous limestone
continental shelf	sandstone, shale, siltstone, limestone
continental slope	sandstone, siltstone, shale
deep ocean	shale, chert, micrite, chalk, diatomite

**BOX 8****Iron Formation**

*Iron formation* is a general term given to iron-rich chemical sedimentary rocks. Sedimentary iron deposits, our most important source of iron, are mostly of Precambrian age. They consist of chert with variable amounts of iron oxides (hematite and magnetite), iron sulfides (pyrite), iron carbonates (siderite, ankerite), and iron silicates (greenalite, minnesotaite, stilpnomelane, chamosite). Typical iron formations are banded, having iron-rich layers and iron-poor layers. North American mining companies have produced iron from iron formations in Ontario, Minnesota, Michigan, and a few other places. Iron formations are also mined at Thabazimbi, South Africa, and in the Hamersley Range of western Australia.

The mineralogy of iron formations seems to reflect the chemistry of the oceans and atmosphere at the time of deposition. Most geologists believe deposition started because of an increase in oxygen in the Earth's atmosphere during late Archean and early Proterozoic times. Carbonate minerals were deposited from waters relatively rich in  $(CO_3)^{2-}$ , sulfide minerals from water relatively rich in S, with oxides and silicates originating elsewhere.

Coarse sediments are typically deposited on land and at beaches, somewhat finer sediments in shallow water, and the finest materials farther offshore. If the sedimentary environment changes, the nature of sedimentation changes. With rising sea level, for exam-

ple, fine deep-water sediments may be deposited over coarser shoreline sediments. With falling sea level, the opposite may occur. So, sedimentary facies vary both laterally and vertically (geographically and temporally).

**Questions for Thought**

Some of the following questions have no specific correct answers; they are intended to promote thought and discussion.

1. What are the most common minerals in clastic sediments? Why?
2. What are the most common minerals in chemical sediments? Why?
3. Why do ceramicists use clays, instead of other minerals such as quartz and feldspar, to make porcelain and other ceramics?
4. The many different carbonate minerals share some common properties. What are those properties? Why?

5. Sulfates and halides are both common evaporite minerals. Why? What physical properties do they have in common? Why?
6. Why are clastic sedimentary rocks generally classified according to grain size rather than chemistry or mineralogy?
7. When groundwater percolates down through soil, it eventually reaches the water table. As it percolates, it leaches (dissolves) soluble minerals from upper soil horizons and deposits them in lower soil horizons. Consequently, how do the mineralogical and chemical compositions of upper and lower soil horizons differ?

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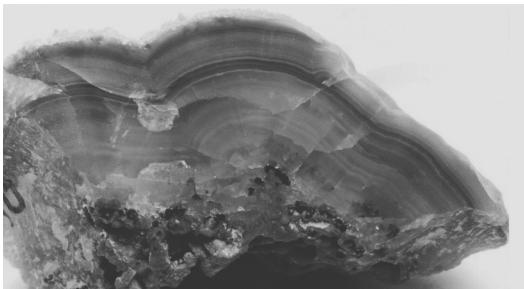
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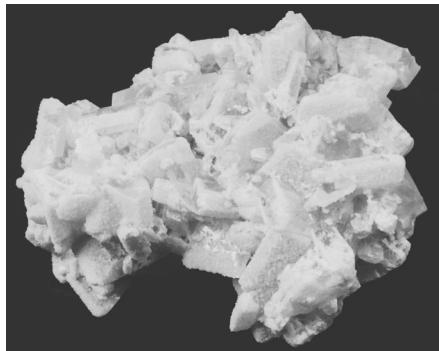
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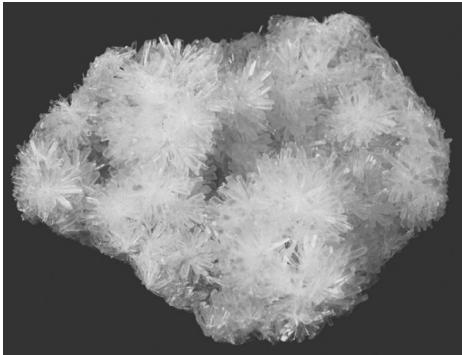
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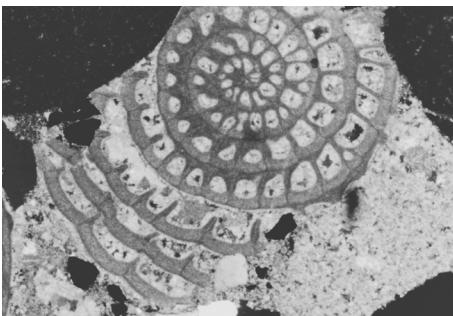
**PLATE 1.2** Smithsonite from Rush Creek, Arkansas, with colors showing compositional zonation.



**PLATE 1.6** Celestite from Lime City, Ohio.

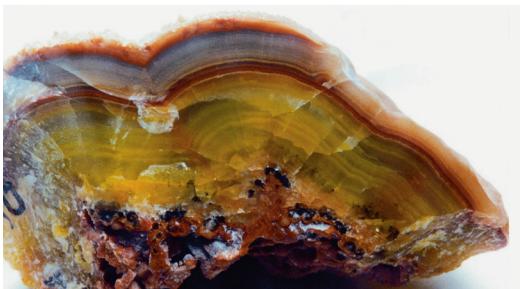


**PLATE 3.5** Green selenite, a variety of gypsum, from Mt. Gudson, South Australia.



**PLATE 5.1** Thin section view of calcite replacing a foraminifera fossil.

# Sedimentary Minerals and Sedimentary Rocks Color Plates



**PLATE 1.2** Smithsonite from Rush Creek, Arkansas, with colors showing compositional zonation.



**PLATE 1.6** Celestite from Lime City, Ohio.



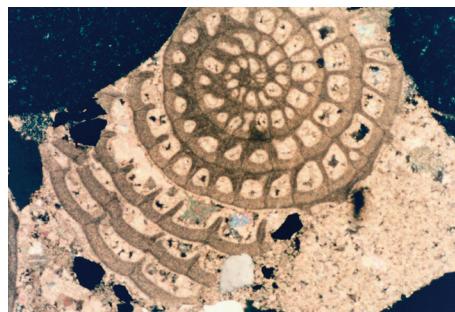
**PLATE 1.8** Botryoidal purple smithsonite from Choix, Mexico.



**PLATE 2.8** Herkimer diamonds (in reality, quartz crystals) from Herkimer, New York.



**PLATE 3.5** Green selenite, a variety of gypsum, from Mt. Gudson, South Australia.



**PLATE 5.1** Thin section view of calcite replacing a foraminifera fossil.

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# Metamorphic Minerals and Metamorphic Rocks

Metamorphic minerals and metamorphic rocks form when preexisting rocks undergo changes in chemistry, texture, or composition without melting. The changes are caused primarily by pressure and temperature. In this chapter we discuss metamorphic minerals and rocks and how they develop in response to such changes. We discuss mineral reactions and look at some of the basic laws of thermodynamics we use to interpret and predict metamorphic minerals and metamorphic reactions.

The term **metamorphism** describes a change in a rock's mineralogy, texture, or composition without melting. It occurs when minerals undergo metamorphic reactions, when texture changes due to recrystallization or realignment of minerals, or when a rock's chemistry is changed by flowing fluids. The principal agents of metamorphism are heat, pressure, and fluids composed primarily of H<sub>2</sub>O and CO<sub>2</sub>. All types of rocks can be metamorphosed. Some, such as clay-rich sediments, change greatly when metamorphosed; others, such as granite, change to a lesser extent. The nature of the changes depends on rock composition and the conditions at which metamorphism occurs.

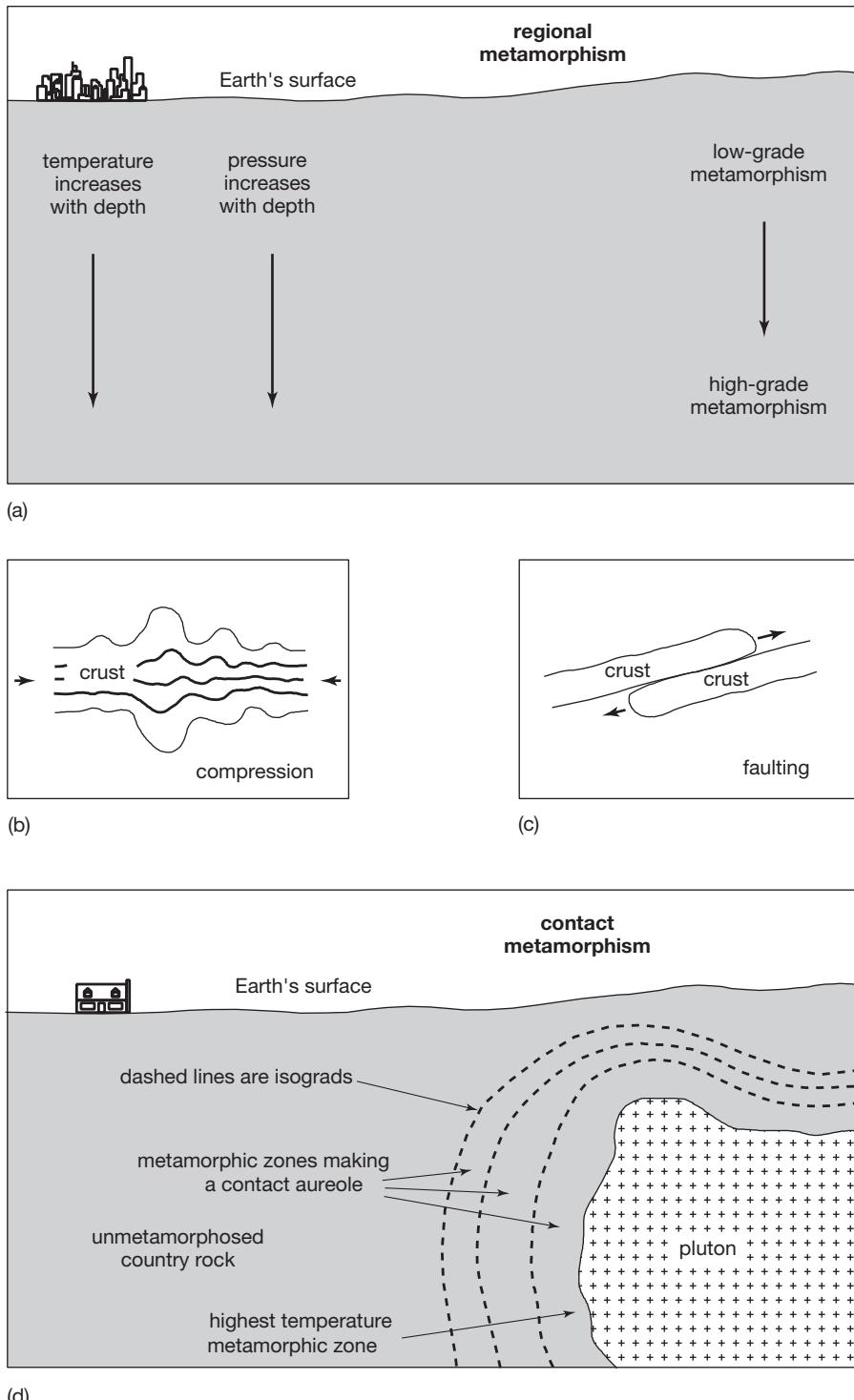
## THE CAUSES OF METAMORPHISM

A variety of tectonic processes bury and carry rocks deep into Earth, including subduction and mountain building. As they move downward or have more material piled on top of them, they experience increased temperature and increased pressure (Figure 1). This produces **regional metamorphism**, so called because it covers large regions. Today and in the past, regional

metamorphism has occurred in orogenic belts, but the most significant examples of regional metamorphic terranes are found in **Precambrian shields**, sometimes flat-lying areas that may be thousands of kilometers across.

Heat from an igneous intrusion may also cause metamorphism. We call this **contact metamorphism** because it is usually localized at the contact between the intrusion and surrounding rock called **country rock** (Figure 1). Contact metamorphism leads to the development of metamorphic zones called **contact aureoles** or **skarns**, which wrap around an intrusion and may be anywhere from a few centimeters to many kilometers thick. The formation of skarns may involve **metasomatism**, a change in rock composition due to flowing metamorphic fluids. The width of skarns mainly depends on the size of the intrusion and how much fluid (mostly H<sub>2</sub>O and CO<sub>2</sub>) it gives off. Aureoles often develop concentric zones or layers, each containing a distinct mineral assemblage that reflects the maximum metamorphic temperature attained and the degree of metasomatism.

Regional and contact metamorphism account for most metamorphic rocks. Some geologists have



**FIGURE 1** Regional and contact metamorphism: (a) regional metamorphism occurs when rocks are buried and subjected to increases in temperature and pressure; (b) crustal rocks experience regional metamorphism in tectonic belts where the crust is highly deformed; (c) high temperatures and pressures of metamorphism also result from large-scale faulting, which carries crustal rocks to great depth; (d) contact metamorphism occurs adjacent to plutons when heat and fluids from the pluton alter surrounding country rock.

described another kind of metamorphism, called **burial metamorphism**, but it is really just high-temperature diagenesis. **Dynamic metamorphism**, also called **shock metamorphism** or **cataclastic metamorphism**, is an additional unique and uncommon form of metamorphism. It occurs because of sudden pressure exerted by faults or meteorite impacts. The results are often the fracturing and granulation of

rocks and sometimes the creation of high-pressure minerals such as coesite or stishovite, polymorphs of quartz.

Metamorphism, which may affect any kind of rock, occurs over a wide range of pressure and temperature conditions. This leads to tremendous variation in metamorphic rocks and the minerals they contain. Most of the metamorphic minerals we see form at

**BOX 1****Extremes of Metamorphism**

Most metamorphic rocks we see were formed at temperatures of less than 800 to 850 °C (1,500 to 1,550 °F) and pressures less than 10 kbar. Most rocks melt above about 850 °C. So at higher temperatures they become at least partially molten. To reach pressures greater than 10 kbar it is necessary to go deep in the Earth. Although metamorphic rocks do form at higher pressure, there are few mechanisms to bring them to the surface of the Earth for examination. Petrologists do occasionally find rocks that were metamorphosed at pressures greater than 10 kbar or temperatures greater than 850 °C. The talc-kyanite schists from the Dora Maira Massif, Italy, and the metapelites (metamorphosed clay-rich sediments) of the Napier Complex, Enderby Land, Antarctica, are examples of extreme metamorphism.

The Dora Maira rocks have been called **whiteschists** because of their very light color. Besides talc and kyanite, they contain pyrope (white to pink Mg-garnet), phengite (a white mica related to muscovite), and quartz as major minerals. Coesite (a high-pressure polymorph of  $\text{SiO}_2$ ) and ellenbergite (another high-pressure mineral) are found as small inclusions in some of the pyrope crystals. A number of papers discuss the formation of these unusual rocks; most significant is the seminal paper by Chopin (1984). Chopin and others concluded that the Dora Maira rocks may have originated as shallow crustal rocks but were subsequently metamorphosed at about 35 kbar pressure and temperatures of 700 to 750 °C (1,300 to 1,400 °F). While the temperature is not extreme, the pressure is; 35 kbar is equivalent to a depth in the Earth of more than 100 km (62 mi.). There are few places where rocks metamorphosed at that depth are found at the Earth's surface—especially if they originally came from the shallow crust. The Dora Maira rocks were apparently uplifted during the Alpine Orogeny in southern Europe, but exactly how is unknown.

Rocks metamorphosed at extreme temperatures have been reported from a number of locations, including some in Uganda, South Africa, and Labrador, Canada. The best studied, however, are Mg-rich pelites from the Napier Complex of Antarctica. Carrington and Harley (1995) summarize the previous studies of the Napier rocks. The rocks contain distinctive high-temperature mineral assemblages, which include the relatively rare minerals pigeonite (a high-temperature pyroxene), osumilite, and sapphirine. Several different studies have concluded that the Napier rocks were metamorphosed at pressures of 7 to 8 kbar and temperatures of more than 1,000 °C (1,800 °F), perhaps as high as 1,075 °C (2,000 °F). How did these rocks get so hot, and how did they escape melting? The answer to the first question is not known. Some investigators believe that a magma must have been involved. The answer to the second is that the rocks are of a composition that does not melt easily when water is absent. The Napier rocks were apparently metamorphosed in the absence of water.

temperatures of 100 to 800 °C (200 to 1,500 °F) and at pressures of 1 bar ( $10^5$  Pa) to 10 kbar (10,000 atm, equivalent to  $10^9$  Pa). Exceptions, however, do exist (Box 1). The term **metamorphic grade** describes the temperature at which a particular metamorphism occurs. Low-grade metamorphic rocks form at low temperatures, generally between 150 and 450 °C (300 and 850 °F). At the lower end of this range, diagenesis overlaps metamorphism. Low-grade metamorphic rocks are often fine grained. Because they are hard to study and frequently do not represent chemical equilibrium, many metamorphic petrologists prefer to study higher-grade rocks. Medium-grade metamorphism, occurring at temperatures between 400 and about 600 °C (750 and 1,100 °F), often results in rocks containing conspicuous metamorphic minerals we can easily study with a microscope. High-grade metamorphic rocks, which form at temperatures greater than about 600 °C (1,100 °F), are usually quite coarse grained, containing minerals easily identified in hand specimen. Depending on its composition, a high-grade metamorphic rock may undergo **partial melting**, also called **anatexis**, so both metamorphic and igneous processes contribute to its evolution. We call the resulting partially melted rocks **migmatites**, which means “mixed rocks.”

**Prograde metamorphism** occurs when low-grade or unmetamorphosed rocks change mineralogy or texture in response to a temperature increase. If the metamorphism is gradual and predictable, we call it **progressive metamorphism**. During progressive metamorphism, a series of reactions occur as the degree of metamorphism increases; rock mineralogy changes multiple times before equilibrating at the highest temperature conditions. While this idea makes a convenient conceptual model, it cannot be correct for all metamorphic rocks. For example, many metamorphic rocks from deep in the Earth were initially formed at high temperature. Other rocks go from low temperature to high temperature, perhaps because of rapid intrusion of a pluton, so rapidly that they skip intermediate stages. Finally, some metamorphic rocks form by **retrograde reactions** (metamorphism in response to temperature decrease). This is especially true of basalts and other high-temperature volcanic rocks affected by low-grade regional metamorphism.

One of the most intriguing questions about metamorphic rocks is: Why do we find high-grade minerals at the surface of the Earth where theoretically

they are unstable? The laws of thermodynamics say that rocks will change mineralogy in response to increasing temperature (prograde metamorphism), so why don't they undergo opposite changes when temperature decreases (retrograde metamorphism)? Several facts help answer these questions:

- Prograde metamorphic events are usually of much longer duration than retrograde, giving minerals more time to achieve equilibrium.
- Prograde metamorphism liberates fluids not present when retrogression occurs. The fluids act as fluxes to promote prograde metamorphism; their absence may hinder retrogression.
- At low temperature, reactions are very sluggish; they may not have time to reach equilibrium.
- More complex, low-grade minerals often have difficulty nucleating and growing.

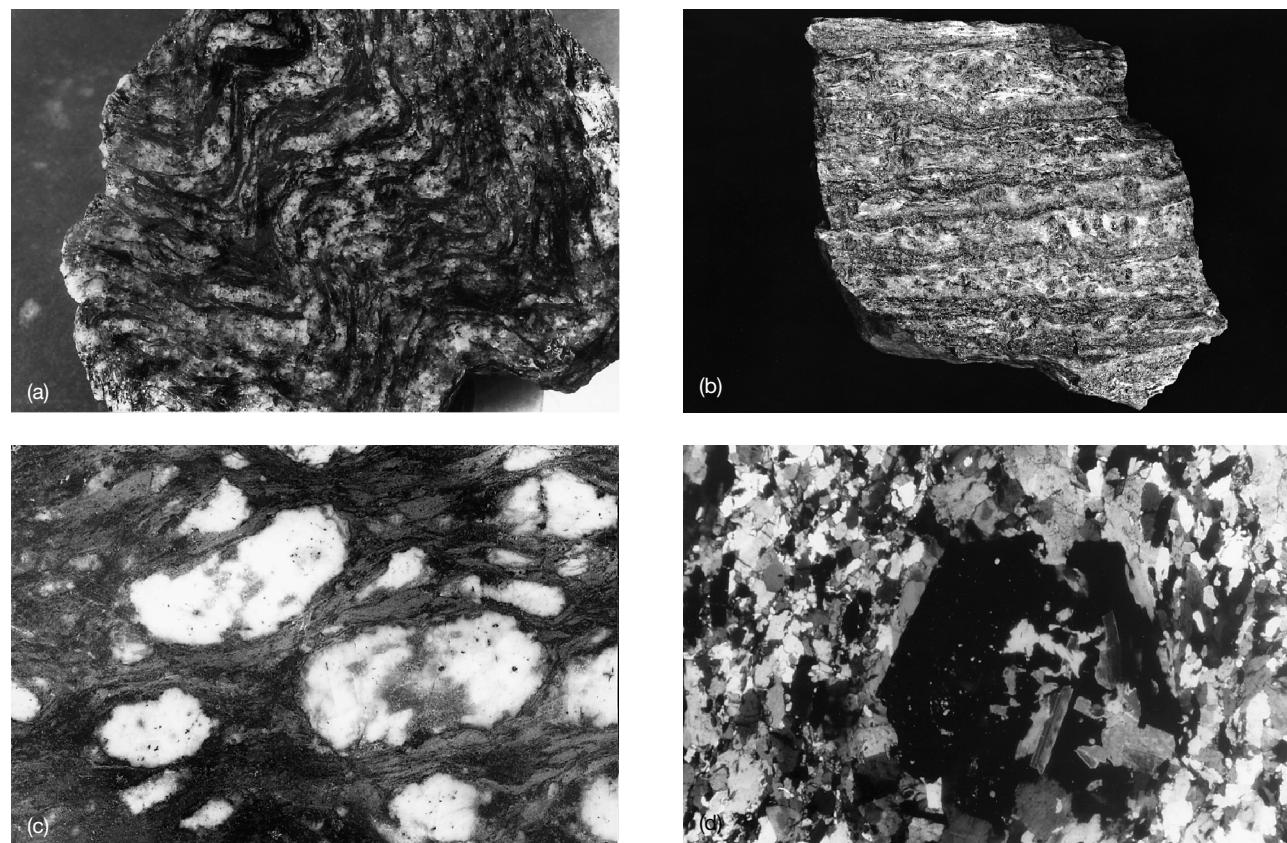
## METAMORPHIC TEXTURES

Textural changes take place as rocks undergo prograde metamorphism. Deformation fabrics may develop (Figure 2a), and a general coarsening of grain size is typical as small mineral grains recrystallize to form larger ones. Metamorphic minerals

may grow and modify rock texture. If they form large crystals and are surrounded by a sea of smaller crystals, we call them **porphyroblasts**. The garnets in Figures 2b and d are good examples of porphyroblasts. If the surrounding crystals are small and uniform in size, we call them the *groundmass* (Figure 2d). Porphyroblasts may form by recrystallization of minerals already in a rock. **Augen gneisses**, for example, contain large recrystallized **augen** (German for “eyes”) of feldspar (Figure 2c).

In some deformed rocks, mineral grains assume a distinctive arrangement that gives metamorphic rocks a **lineation**, long mineral grains all pointing in the same direction, or a **foliation**, minerals lining up to give a planar fabric (Figures 2a and b). Lineation occurs when kyanite, sillimanite, and other minerals that form long, thin crystals lie parallel in a rock. Alignment of clays, micas, graphite, or other platy minerals, or the separation of a rock into light and dark layers, leads to foliation. Rocks lacking lineation or foliation are termed **hornfels**. Hornfels typically form at low pressure from contact metamorphism.

We call foliated rocks **slates**, **phyllites**, **schists**, or **gneisses**. Slates, which normally result



**FIGURE 2** Examples of metamorphic textures in rocks: (a) a deformed biotite schist; (b) a garnet gneiss showing foliation due to alternating light and dark bands; (c) close-up view of 1- to 2-cm wide feldspars surrounded by biotite in an augen gneiss; (d) thin section photograph (XP) showing an 8-mm garnet porphyroblast (black hexagon) in a ground mass of primarily quartz and feldspar.

from low-grade metamorphism of shales, comprise primarily microscopic clay grains. Phyllites, which form at higher metamorphic grades, sparkle because clay minerals have metamorphosed to produce small grains of micas. Schists, which form under medium-grade metamorphic conditions, contain medium-to-coarse crystals of mica that we can easily see with our naked eye (Figure 2a). At higher grades, metamorphic rocks may develop compositional layering. We call such rocks *gneisses*. A gneiss is distinctive because of its alternating light and dark layers or bands (Figure 2b). The light bands contain quartz and feldspar, while the dark bands contain mafic minerals. At high temperatures ( $>700^{\circ}\text{C}$ ), some minerals in pelitic rocks (metamorphosed clay-rich sediments) may melt. Partial melting often produces a migmatite, a rock containing veins and patches composed of quartz and feldspar that crystallized from the partial melt.

## METAMORPHIC MINERALS

Metamorphic rocks may contain all the minerals common in sedimentary and igneous rocks, as well as many minerals exclusive to metamorphic rocks. The two most important factors controlling mineralogy are the composition of the rock and the grade of metamorphism. We generally describe rock composition by listing a rock's chemical composition or, more simply, by dividing the most common rock types into general compositional classes. Table 1 lists some common rock classes used by metamorphic petrologists.

Table 2 lists common metamorphic minerals for each rock class. Minerals at the top of the table are common in low-grade rocks; those at the bottom are found in high-grade rocks. Metapelites exhibit the most mineralogical variation. Before metamorphism, pelitic rocks contain a variety of low-temperature minerals, many of which become unstable

**TABLE 1** Compositional Classes of Metamorphic Rocks

Metamorphic Rock Class	Common Kinds of Metamorphic Rocks	Essential Minerals	Unmetamorphosed Equivalents
pelitic	slate phyllite schist gneiss	quartz micas	clay-rich sediments
psammitic	quartzite quartzofeldspathic gneiss	quartz	sandstones feldspathic sandstones
mafic (metabasite)	greenstone amphibolite mafic gneiss mafic granulite eclogite	amphiboles plagioclase	basaltic rocks
carbonate	marble	carbonates	limestone dolomite
marl	slate phyllite schist gneiss	micas carbonates	calcareous shale shaly limestone
iron formation	banded iron formation	quartz jasper magnetite hematite	iron-rich chemical sediments
ultramafic	serpentinite	serpentine talc Mg-rich amphiboles	ultramafic igneous rocks
granitic	granitic gneiss granulite	K-feldspar quartz micas	granitic rocks

**TABLE 2** Some Important Minerals in Metamorphic Rocks of Different Compositions

	<b>Pelitic</b>	<b>Mafic</b>	<b>Carbonate</b>	<b>Iron Formation</b>	<b>Ultramafic</b>	<b>Granitic</b>
<b>Low Grade</b>	quartz $\text{SiO}_2$	zeolites (variable Ca-Al silicates)	calcite $\text{CaCO}_3$	quartz $\text{SiO}_2$	talc $\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$	quartz $\text{SiO}_2$
	kaolinite $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	prehnite $\text{Ca}_2\text{Al}(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$	dolomite $\text{CaMg}(\text{CO}_3)_2$	hematiter $\text{Fe}_2\text{O}_3$	brucite $\text{Mg}(\text{OH})_2$	K-feldspar $\text{KAlSi}_3\text{O}_8$
	pyrophyllite $\text{Al}_2\text{Si}_4\text{O}_{10}(\text{OH})_2$	pumpellyite (similar to epidote but contains Mg and $\text{Fe}^{2+}$ )	quartz $\text{SiO}_2$	magnetite $\text{Fe}_3\text{O}_4$	serpentine $\text{Mg}_6\text{Si}_4\text{O}_{10}(\text{OH})_8$	biotite $\text{KMg}_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$
	chlorite (variable combinations of talc + brucite)	plagioclase (Ca-rich) $(\text{Ca},\text{Na})(\text{Al},\text{Si})_4\text{O}_8$	biotite (phlogopite) $\text{KMg}_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$	minnesotaite $\text{Fe}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$	olivine (forsterite) $\text{Mg}_2\text{SiO}_4$	hornblende (complex amphibole)
	muscovite $\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$	epidote $\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	tremolite $\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	actinolite $\text{Ca}_2(\text{Fe,Mg})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	anthophyllite $(\text{Mg},\text{Fe})_7\text{Si}_8\text{O}_{22}(\text{OH})_2$	garnet (almandine) $\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$
	kyanite $\text{Al}_2\text{SiO}_5$	chlorite (variable combinations of talc + brucite)	garnet (grossular) $\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	grunerite $\text{Fe}_7\text{Si}_8\text{O}_{22}(\text{OH})_2$	clinopyroxene (diopside) $\text{CaMgSi}_2\text{O}_6$	orthopyroxene $(\text{Mg},\text{Fe})_2\text{Si}_2\text{O}_6$
	andalusite $\text{Al}_2\text{SiO}_5$	actinolite $\text{Ca}_2(\text{Fe,Mg})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	clinopyroxene (diopside) $\text{CaMgSi}_2\text{O}_6$	fayalite $\text{Fe}_2\text{SiO}_4$	garnet (pyrope-almandine) $(\text{Mg},\text{Fe})_3\text{Al}_2\text{Si}_3\text{O}_{12}$	orthopyroxene (enstatite) $\text{Mg}_2\text{Si}_2\text{O}_6$
	biotite $\text{K}(\text{Mg},\text{Fe})_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$	hornblende (complex amphibole)	periclase $\text{MgO}$			
	chloritoid $(\text{Fe},\text{Mg})\text{Al}_2\text{SiO}_5(\text{OH})_2$	garnet (almandine-pyrope) $(\text{Fe},\text{Mg})_3\text{Al}_2\text{Si}_3\text{O}_{12}$	wollastonite $\text{CaSiO}_3$			
	garnet (almandine) $\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	biotite $\text{K}(\text{Mg},\text{Fe})_3(\text{AlSi}_3\text{O}_{10})(\text{OH})$				
	staurolite $\text{Fe}_2\text{Al}_9\text{Si}_4\text{O}_{23}(\text{OH})$	clinopyroxene (diopside) $\text{CaMgSi}_2\text{O}_6$				
	cordierite $(\text{Mg},\text{Fe})_2\text{Al}_4\text{Si}_5\text{O}_{18}$	orthopyroxene (enstatite) $\text{Mg}_2\text{Si}_2\text{O}_6$				
	K-feldspar $\text{KAlSi}_3\text{O}_8$					
	sillimanite $\text{Al}_2\text{SiO}_5$					
<b>High Grade</b>	orthopyroxene $(\text{Mg},\text{Fe})_2\text{Si}_2\text{O}_6$					

when heated. In contrast, granitic rocks show few mineralogical changes when metamorphosed because they comprise predominantly quartz and K-feldspar, which are stable under most metamorphic conditions.

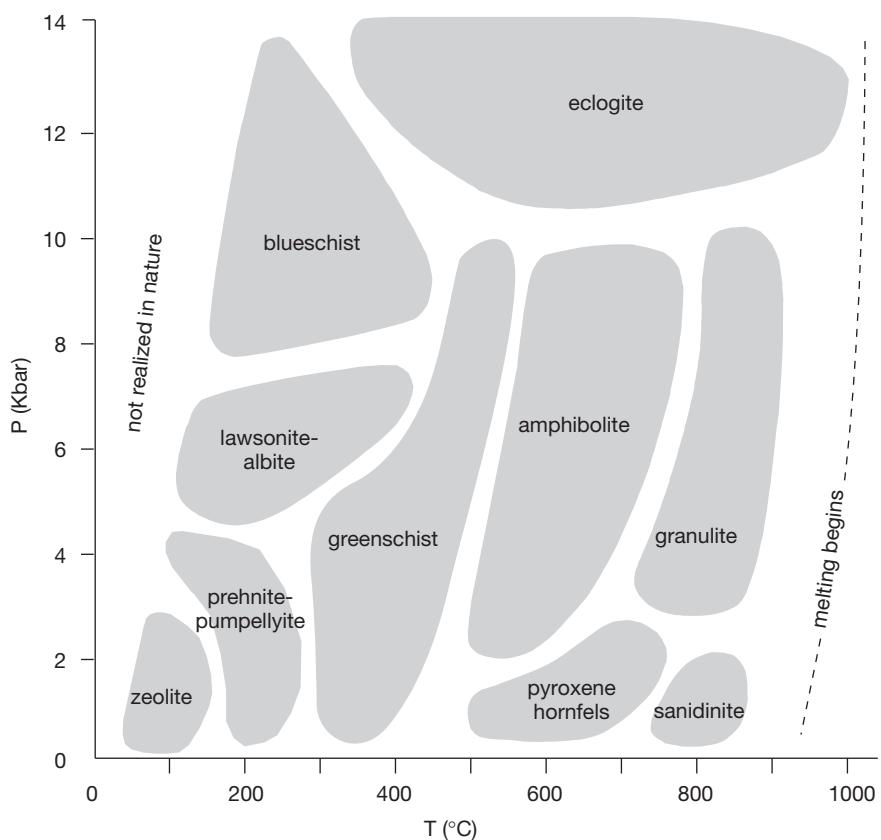
## METAMORPHIC FACIES

Pentti Eskola, a geology professor at the University of Helsinki, introduced the idea of **metamorphic facies** in 1920. He observed that the equilibrium mineral assemblage in metamorphosed mafic rocks (**metabasites**) varies with pressure and temperature. Therefore, the mineral assemblage records the pressure and temperature at which the rock was metamorphosed. Eskola defined **facies** as general ranges of pressure and temperature characterized by a distinct mineral assemblage in mafic rocks. Facies diagrams, such as Figure 3, are similar to phase diagrams because they divide P-T space into small areas associated with specific minerals or mineral assemblages. The main differences between facies diagrams and phase diagrams are that facies diagrams involve many chemical components, the locations of different facies in P-T space are not precise, and we often do not know the exact reactions that relate one facies to another.

Eskola originally identified eight facies. Other petrologists have divided some to more precisely

represent pressure and temperature ranges (Figure 3). Each facies name comes from its most characteristic metabasite minerals or rock types. Table 3 summarizes key mineral assemblages for each facies. The **zeolite facies** represents the lowest grade of metamorphism, often hard to distinguish from diagenesis. The formation of zeolite minerals and clays characterize the zeolite facies. As temperature rises, the zeolite facies gives way to the **prehnite-pumpellyite facies**, the **greenschist facies**, the **amphibolite facies**, and the **granulite facies**. Contact metamorphism produces two low-pressure, high-temperature facies, the **pyroxene-hornfels facies** and the **sanidinite facies**. The **lawsonite-albite facies**, the **blueschist facies**, and the **eclogite facies** occur at high pressure.

Although Eskola based his facies names on minerals and textures of mafic rocks, petrologists use the same names when talking about rocks of other compositions. This leads to some confusion. Table 3 lists key mineral assemblages for different metamorphic facies, but the assemblages will never be present in some rock types. For example, pelitic or calcareous rocks do not form greenschists (green mafic schists) or amphibolites (mafic rocks dominated by amphibole and plagioclase) even when metamorphosed at conditions within the greenschist or amphibolite facies. In addition, for some rock classes, several different mineral assemblages may



**FIGURE 3** Metamorphic facies. The labeled fields indicate relative pressure-temperature ranges for each of the 10 facies, but their locations vary somewhat with rock composition. There are no facies at very low temperatures and high pressures because those conditions are not reached in nature. The upper temperature limit corresponds to conditions at which most rocks melt. The upper pressure limit has been arbitrarily chosen; some eclogites and other rocks form at pressures in excess of 14 kbar.

**TABLE 3 Key Mineral Assemblages in Metamorphic Facies**

Kind of Metamorphism	Metamorphic Facies	Key Mineral Assemblages in Metabasites
contact metamorphism (very low pressure)	pyroxene hornfels facies	orthopyroxene + clinopyroxene + plagioclase + quartz (without garnet)
	sanidinite facies	sanidine or tridymite or pigeonite or glass
low-pressure metamorphism	zeolite facies	zeolite + quartz
	prehnite-pumpellyite facies	prehnite or pumpellyite + quartz (without zeolite)
	greenschist facies	chlorite + epidote + albite + quartz (without prehnite or pumpellyite)
	amphibolite facies	hornblende + plagioclase + quartz
high-pressure metamorphism	granulite facies	orthopyroxene + clinopyroxene + garnet + plagioclase + quartz
	lawsonite-albite facies	lawsonite + albite + quartz (without glaucophane or jadeite)
	blueschist facies	glaucophane
	eclogite facies	omphacite + garnet + quartz

be stable within a single facies. Further confusion arises because petrologists use some facies names in a more restricted sense, referring to particular rock types with important tectonic significance. The greatest confusion derives from the rock *granulite*, which is an orthopyroxene-bearing, coarse-grained, high-temperature rock, and the rock *eclogite*, a rock dominated by garnet and Na-rich clinopyroxene called *omphacite*. Despite these problems, the facies concept provides a convenient way to discuss general ranges of pressure and temperature, and it receives wide use. Sometimes, however, the number and name of facies are different from those in Figure 3, depending on who is using them.

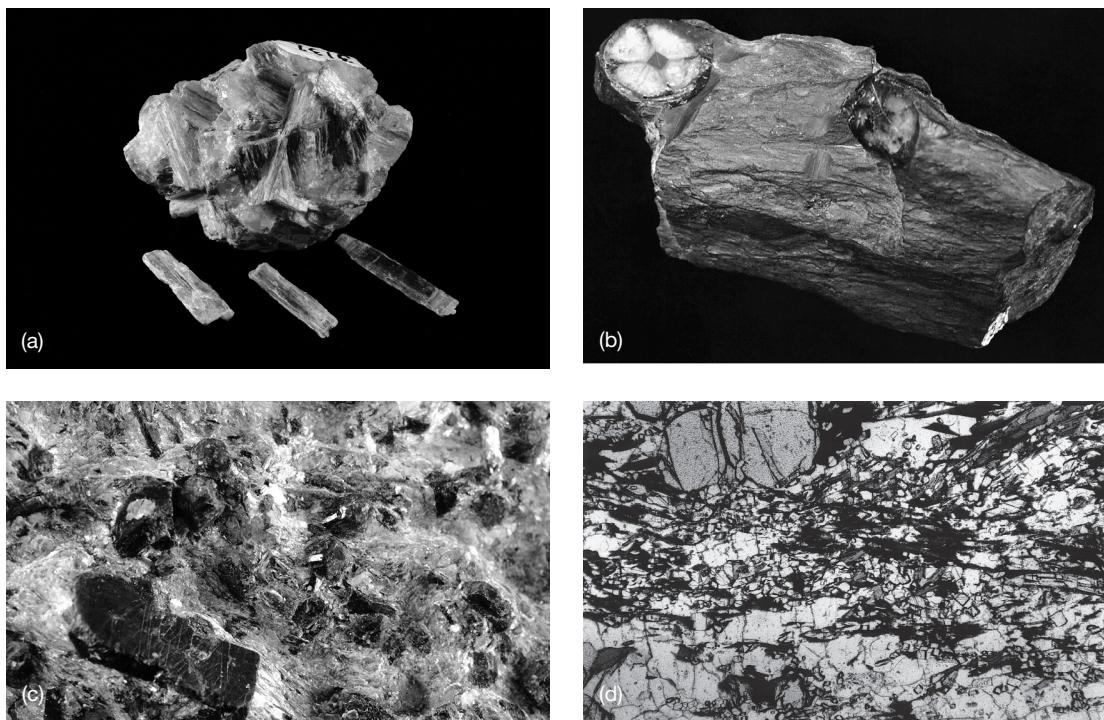
As a model for progressive metamorphism, petrologists consider different **metamorphic series**, the sequences of metamorphic rocks that would form in different metamorphic environments. Rocks experiencing only contact metamorphism experience only low pressure. They pass through the zeolite, prehnite-pumpellyite, low-pressure greenschist, pyroxene hornfels and sanidinite facies with increasing temperature. Such rocks are common anywhere there have been intrusions of magma into shallow crustal rocks. Rocks subjected to regional metamorphism during mountain building experience a significant increase in both pressure and temperature. They progress through the zeolite, prehnite-pumpellyite, greenschist, amphibolite, and granulite facies. The most classic example of such metamorphism is in the Scottish Highlands where George Barrow mapped a large zone of progressive metamorphism in the late 1800s. Barrow recognized that the higher-grade

metamorphic rocks he was mapping were once unmetamorphosed shales. Rocks, similar to the ones described by Barrow, are found worldwide. They are said to have followed a **Barrovian facies series**, a tribute to Barrow. In North America, Barrovian metamorphism is particularly well exposed and studied in the Appalachian Mountains, and in the Canadian Shield. During regional metamorphism, some rocks are metamorphosed at slightly lower pressures than the classic Barrovian Facies Series. Such rocks follow the **Buchan facies series**. Notable occurrences are in Japan and Spain, but they are found worldwide. At subduction zones, relatively cool rocks may be carried to depth and experience high pressures. So, some rocks related to subduction zones follow the **blueschist facies series** (zeolite, prehnite-pumpellyite, lawsonite-albite, blueschist, and possibly eclogite facies). We find them, typically, as blocks in fault contact with greenschist facies rocks. Blueschists have been described from many places, but the two classic blueschist facies series are defined on the basis of rocks from the Sanbagawa metamorphic belt of Japan and the Franciscan Complex of California.

## SOME COMMON TYPES OF METAMORPHIC ROCK

### Metamorphosed Pelitic Rocks (Metapelites)

- slate
- phyllite
- schist
- gneiss



**FIGURE 4** Metapelitic rocks; (a) kyanite forms bladed crystals. The crystals seen here are about 3 cm long; (b) andalusite, a polymorph of kyanite, sometimes displays chiastolite crosses; (c) a close-up of a metapelite reveals rounded equant garnets and long rectangular staurolite in a sea of fine grained micas; (d) Thin-section view (PP light) of a metapelite. The blocky mineral at the top of the photo is garnet; the small grains with square cross sections are end views of sillimanite needles; the dark grains are biotite; the white minerals are plagioclase and quartz.

Metapelites are rich in Al, Si, and K and may contain substantial amounts of Fe and Mg, so minerals containing these elements dominate metapelitic rocks. Many metapelitic rocks contain an  $\text{Al}_2\text{SiO}_5$  polymorph: andalusite, kyanite, or sillimanite. Plate 3.6 shows a spectacular example of kyanite from Minas Gerais, Brazil. Besides aluminosilicates, many other minerals are common in metapelites (Table 2). Often they form large porphyroblasts with micas and other minerals packed around them; the garnet in Plate 8.4 is an example.

Between 1890 and 1910, George Barrow studied metapelites in Scotland and showed that the presence of certain **index minerals** correlated with the temperature of metamorphism. From low temperature to high, these minerals are chlorite, brown biotite, almandine, staurolite, kyanite, and sillimanite. Barrow showed that the occurrences of these minerals allow a metamorphic terrane to be divided into **metamorphic zones**, separated by lines called **isograds** (see dashed lines in Figure 1d). Each zone is a different metamorphic grade.

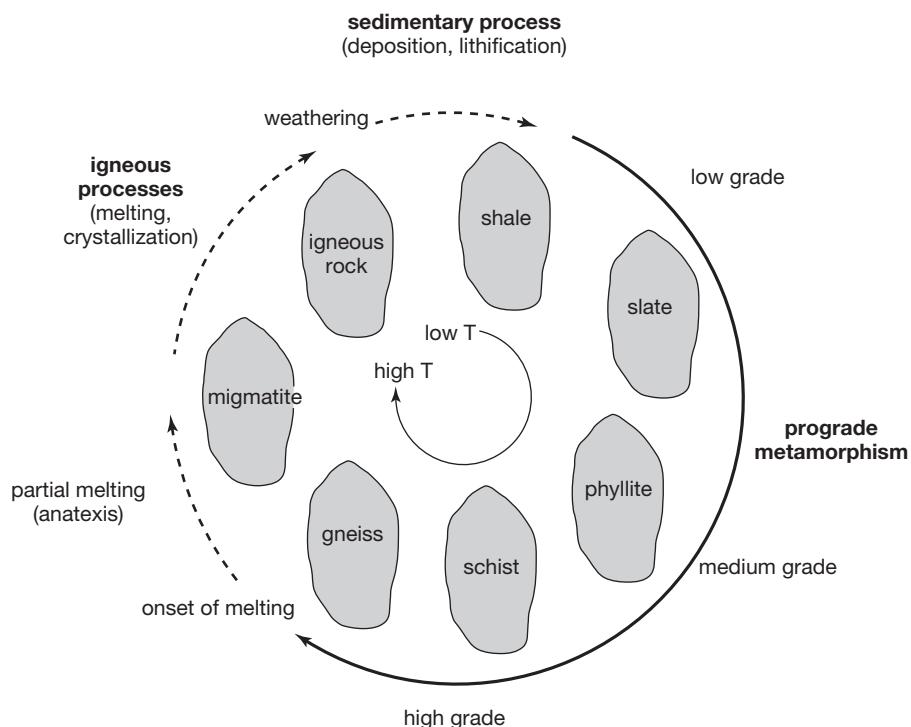
Metapelites derive from the metamorphism of shale and other clay-rich sediments, and less commonly from aluminous igneous rocks. Quartz is an essential mineral, and either muscovite or biotite is

always present (Figure 4). When metamorphosed, clay minerals dehydrate to produce new minerals containing less  $\text{H}_2\text{O}$ . At low grade this leads to the formation of pyrophyllite and muscovite, and at medium grades to biotite. As micas form from the breakdown of clays, foliated textures develop. Figure 5 illustrates how shale may be metamorphosed and eventually melted to produce an igneous rock.

### Metamorphosed Psammitic Rocks (Metapsammites)

quartzite  
quartzofeldspathic rocks

**Psammites** are rocks rich in quartz and alkali feldspar, containing more alkalis and less Al than metapelites (Figure 6). So, **metapsammites** are formed by metamorphism of sandstones and feldspathic sandstones. Because quartz and feldspar are stable at all metamorphic grades, metapsammites may undergo few obvious metamorphic reactions. Sometimes small amounts of clay minerals in sandstones produce aluminous minerals through dehydration reactions, as in pelites. Foliation, typical of metapelitic rocks, is usually lacking because of a lack



**FIGURE 5** A modified portion of the rock cycle showing how progressive metamorphism may change shales to slate, phyllite, schist, and gneiss before melting begins and, eventually, the cycle starts over again.

of micas. At low grades, metapsammites typically appear massive and homogeneous, containing light-colored quartz and feldspar with small micas and other dark minerals scattered evenly throughout. At higher grades they may recrystallize and become coarser, sometimes becoming gneisses.

### Metamorphosed Mafic Rocks (Metabasites)

- greenstone
- amphibolite
- mafic gneiss
- mafic granulite
- eclogite

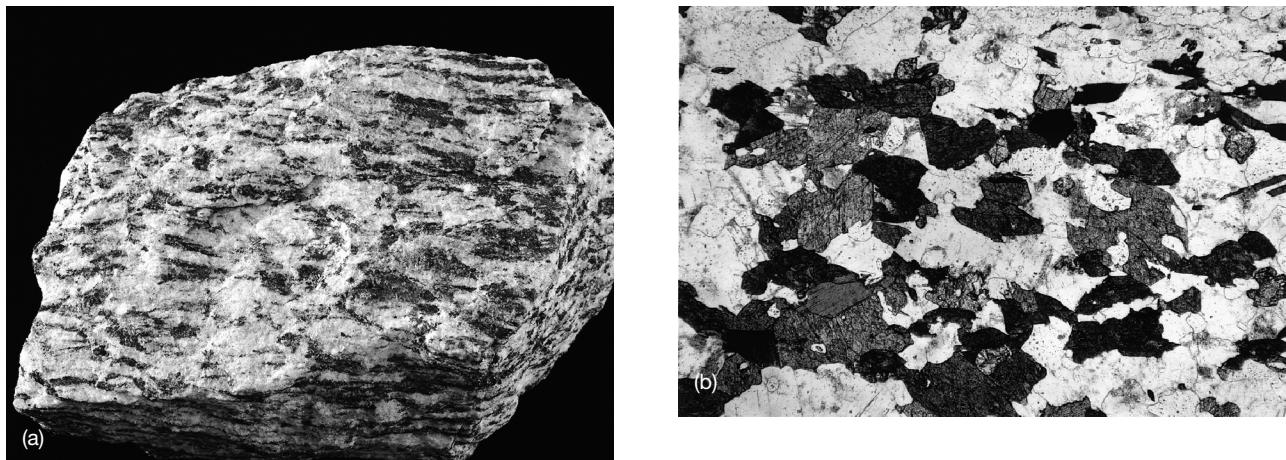


**FIGURE 6** Metapsammite cut by a granitic dike: the fine-grained rock contains primarily quartz, plagioclase, and biotite with minor garnet. The granitic dike contains K-feldspar and quartz. Note the dark selvage, the dark layer where the two rock types meet, caused by contact metamorphism.

Compared to metapsammites and metapelites, metabasites are relatively poor in Al and Si and rich in Ca, Mg, and Fe. They are equivalent to mafic igneous rocks such as basalt. Many different minerals may form, and metamorphic reactions are complex (Figure 7), but the most important metamorphic minerals are Ca and Mg silicates (Table 2). Metabasites tend to be more massive and less foliated than pelitic rocks, but at higher grades they do form schist and gneiss.

We call fine-grained, very low-grade metabasites **greenstones** because of their conspicuous light- to dark-green color. The characteristic green color comes from fine-grained chlorite and epidote. They also may contain Na-rich plagioclase (albite), quartz, carbonates, and zeolites. At grades equivalent to the greenschist facies, they become greenschists, obtaining schistosity from parallel arrangements of the green amphibole actinolite and chlorite.

In the amphibolite facies, chlorite, epidote, and actinolite break down, producing a specific kind of rock called an **amphibolite**. Amphibolites contain large grains of black hornblende and whitish plagioclase in subequal proportions. Garnet, biotite, and light-colored amphiboles such as anthophyllite or cummingtonite may also be present. At the highest grades, all amphiboles become unstable. Assemblages including garnet and clinopyroxene, or orthopyroxene, are diagnostic of the granulite facies. Minor minerals at all grades include many that are present in mafic igneous rocks.



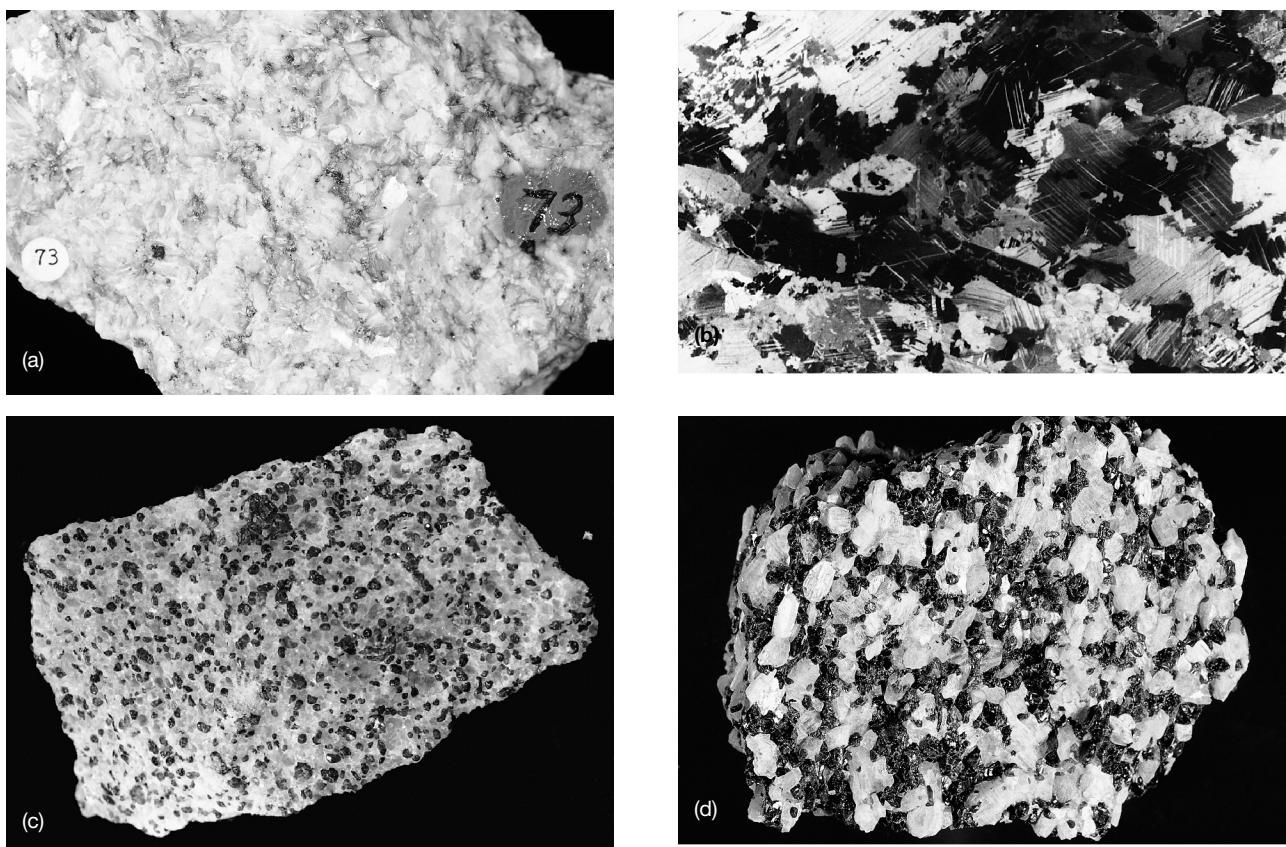
**FIGURE 7** (a) This finely layered mafic gneiss is composed almost entirely of hornblende (dark mineral) and plagioclase (light mineral). The sample is 8 cm across; (b) thin section of a mafic gneiss (PP light) showing white plagioclase, dark gray hornblende (with two cleavages at  $60^{\circ}$ ), and biotite (with one cleavage parallel to the edges of the flakes).

### Metamorphosed Limestones and Dolostones (Marbles)

marble  
skarn

To building contractors, marble refers to any kind of rock that can be slabbed and polished. Commercial

marble is made from many different rock types, including intrusive igneous rocks such as gabbro. To geologists, however, marble refers only to metamorphosed limestone or dolostone (Figure 8; Plate 6.3). Marbles are usually massive, lacking in conspicuous lineation, foliation, or compositional layering.



**FIGURE 8** Marble in-hand specimen and thin section: (a) dolomite marble from Franklin, New Jersey (10 cm across); (b) 3-mm crossed polars view of a marble in thin section showing conspicuously twinned calcite (striped pattern); (c) marble from the Adirondack Mountains, New York, containing abundant dark colored diopside; (d) marble from the Adirondack Mountains, New York, containing wollastonite (white tabular mineral) and garnet (darker mineral).

The metamorphism of a limestone or dolostone composed only of carbonate minerals produces few mineralogical changes at any but the highest grades. A general increase in grain size may take place, but no diagnostic minerals can form because of the limited chemical composition and the high stabilities of both calcite and dolomite. However, most limestones contain some quartz and other minerals besides carbonates. In such rocks, a series of interesting Ca-silicates, Ca-Mg-silicates, and Ca-Al-silicates form as metamorphism progresses (Table 2). Talc, tremolite, forsterite, diopside (Figure 8c; Plate 6.3), and grossular (garnet) are common in marbles. At very high grades, periclase, wollastonite, and several other diagnostic minerals may appear (Figure 8d). Some sedimentary rocks are rich in carbonates but contain appreciable amounts of pelitic or mafic minerals. We call such rocks *marls*. Many of the same reactions and minerals that characterize metapelites, metabasites, and marbles also occur when marls are metamorphosed.

The metamorphic reactions in marbles frequently involve the breakdown of carbonates to release CO<sub>2</sub>. If a pluton intrudes a limestone or dolostone, H<sub>2</sub>O often flows out of the pluton and into the surrounding carbonate, forming a skarn. The presence of both H<sub>2</sub>O and CO<sub>2</sub> and their relative proportions control the formation of many key minerals. Flowing CO<sub>2</sub>-H<sub>2</sub>O fluids may result in significant **metasomatism** (a change in rock chemistry)

in contact aureoles, so different zones in the aureole may have significantly different compositions. Metasomatism is responsible for the formation of many spectacular mineral specimens and some important ore deposits.

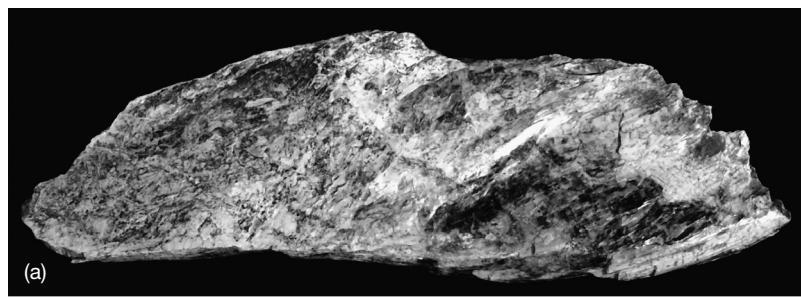
### Metamorphosed Ultramafic Rocks and Iron Formations

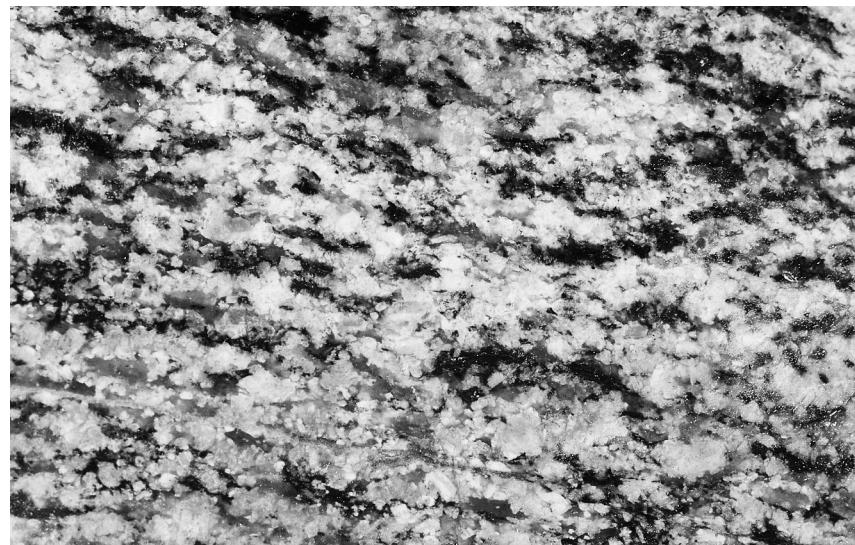
Because of their chemistry, Mg-silicates such as talc, serpentine, anthophyllite, forsterite, diopside, and enstatite dominate ultramafic rocks (Table 2, Figure 9). Through metamorphism, magnesium oxides, hydroxides, and carbonates may form. Because ultramafic compositions usually start as high-temperature igneous rocks, they do not normally undergo progressive metamorphism. Unless metamorphic temperatures are very high, metamorphism produces retrograde, rather than prograde, minerals in ultramafic rocks.

Low-grade metamorphism or alteration of olivine-bearing rocks often produces one of the serpentine polymorphs (Plate 3.7). We call rocks rich in serpentine **serpentinites**. Talc, brucite, and chlorite are common low-temperature minerals as well. At higher grades, olivine, anthophyllite, enstatite, periclase, and spinel may be found.

Iron formations are rich in iron and silicon. When metamorphosed, they commonly contain the iron equivalents of the magnesium minerals

**FIGURE 9** (a) Metamorphosed ultramafic rock (serpentinite) about 30 cm across. This sample is made of serpentine, chlorite, and talc; it is impossible to tell what it was before metamorphism; (b) close-up of serpentinite (field of view is 1 cm).





**FIGURE 10** Close view (5 cm across) of a granitic gneiss. The black mineral is biotite, the white mineral is K-feldspar, and the gray mineral is quartz. Note the foliation (parallel alignment of grains).

found in metamorphosed ultramafics (Table 2). These include Fe-amphibole, Fe-pyroxene, and Fe-garnet.

### Metamorphosed Granitic Rocks

granitic hornfels  
granitic gneiss

Metamorphism of granites may be boring because the quartz, K-feldspar, and plagioclase that make up most granites and intermediate igneous rocks are stable at all grades of metamorphism (Figure 10). However, mafic minerals common in granites, such as biotite and hornblende are not; they may react to produce metamorphic minerals at medium and high grade. These minerals include garnet and orthopyroxene. Accessory minerals found in unmetamorphosed granites and intermediate igneous rocks may also be present after metamorphism. At high grade, granitic rocks sometimes develop gneissic banding, even if mineralogy has not significantly changed.

### High-Pressure Metamorphic Rocks

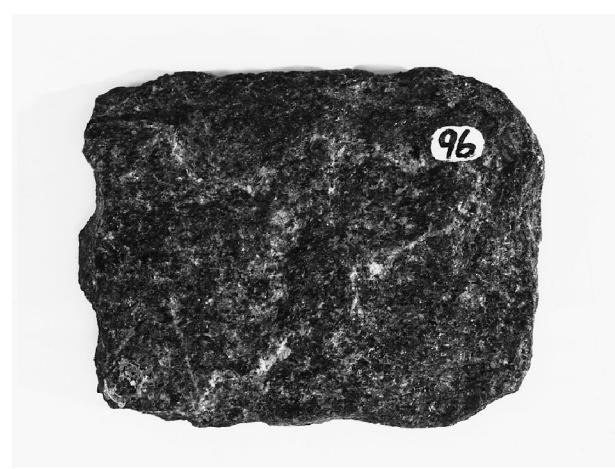
blueschist  
eclogite

Because of their special significance, high-pressure metamorphic rocks are often classed by themselves. They include mainly blueschists and eclogites, both quite rare (Figure 11). Special tectonic conditions are required to create them and bring them to Earth's surface.

*Blueschist* is a name given to one type of rock that forms at conditions within the blueschist facies, a facies characterized by high pressure and relatively low temperature. Compositionally, blueschists are variable, lying

somewhere between pelitic sediments and metabasites. They have conspicuous mineralogy. A blue amphibole, called *glaucomophane*, is responsible for the name of the facies. Other diagnostic minerals include a colorless to green Na-pyroxene called *jadeite* ( $\text{NaAlSi}_2\text{O}_6$ ), green or white lawsonite ( $\text{CaAl}_2\text{Si}_2\text{O}_7(\text{OH})_2 \cdot \text{H}_2\text{O}$ ), and pale aragonite (the high-pressure polymorph of calcite). Epidote, garnet, zoisite, quartz, and other accessory minerals may also be present. Because they form at low temperature, blueschists are often fine grained, poorly crystallized, and difficult to study.

Eclogites are mafic rocks metamorphosed at high pressure and moderate-to-high temperature. They contain the essential minerals pyrope (Mg-rich garnet) and the green Na-rich clinopyroxene called *omphacite*. Orthopyroxene may also be present in significant quantities. Accessory minerals include kyanite, quartz, spinel, titanite, and many



**FIGURE 11** Glaucophane schist (a kind of blueschist) from Sonoma County, California. This rock is sufficiently fine grained so mineral identification is difficult in hand specimen.

others. Eclogites originate in the deep crust or in the mantle. Many mantle **xenoliths**, carried up as nodules within magma, are eclogites. Eclogites are also found as layers or bands associated with some peridotites.

## METAMORPHIC REACTIONS

Under any pressure and temperature, the most stable mineral assemblage is the one with the lowest **Gibbs free energy**. Similarly, the most stable arrangement of crystals is the one with the lowest **strain energy**. If temperature, pressure, or composition of a rock changes, the mineralogy or texture, or both, may change so that energy remains minimized. When metamorphosed at high pressure, graphite reacts to form diamond. When a mica-bearing rock is stressed, micas line up parallel to one another. In these ways, rocks attain chemical and textural equilibrium. In this chapter, we are mostly concerned with chemical equilibrium and the formation of metamorphic minerals.

Box 2 gives examples of different types of metamorphic reactions. **Solid-solid reactions** are those that involve no H<sub>2</sub>O, CO<sub>2</sub>, or other vapor phase. Reaction 1 involves only two minerals, both Al<sub>2</sub>SiO<sub>5</sub> polymorphs. Reaction 2 involves four minerals, but is a solid-solid reaction. The example **dehydration reactions** and **decarbonation reactions** in Box 2 liberate H<sub>2</sub>O and CO<sub>2</sub>, respectively. **Hydration reactions**

and **carbonation reactions** consume H<sub>2</sub>O and CO<sub>2</sub>, respectively. Most metamorphic reactions involve more than two minerals, and many involve H<sub>2</sub>O or CO<sub>2</sub>.

Mineralogical equilibrium is easier to interpret and model than textural equilibrium. The laws of thermodynamics (Box 3) allow us to predict which minerals are stable under particular conditions. Conversely, we can sometimes estimate the pressure and temperature at which a rock formed from the minerals it contains. In contrast, textural changes often involve recrystallization, causing a change in grain size and shape that may be difficult to interpret. Nevertheless, textural changes can reveal information about deformation and stress that is otherwise unavailable. Consequently, textures are important to structural geologists and others interested in mechanical processes and tectonism, while mineralogists and many petrologists generally focus on the minerals present rather than rock texture or mineral appearance.

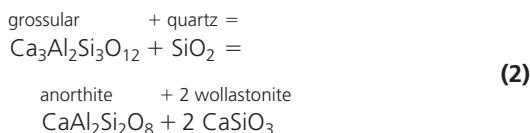
## EQUILIBRIUM

Metamorphic reactions involve changes in mineralogy or in mineral composition. A mineral assemblage is at chemical equilibrium if no such changes are occurring. If the assemblage has the lowest Gibbs free energy possible for the given conditions, it is at **stable**

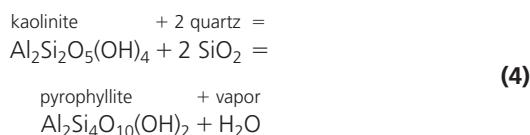
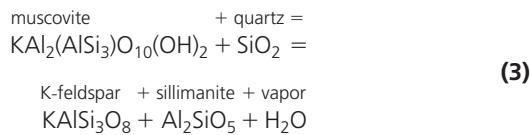
### BOX 2

#### Examples of Metamorphic Reactions

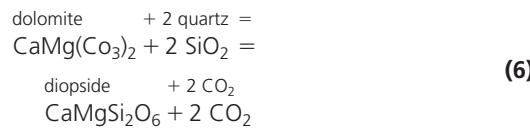
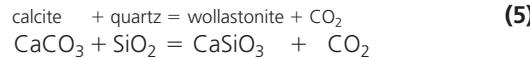
##### Solid-solid reactions:



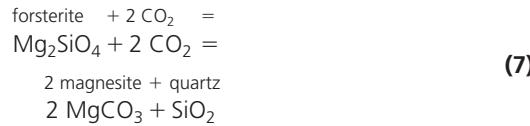
##### Dehydration reactions:



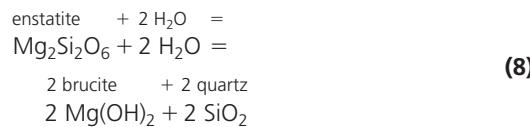
##### Decarbonation reactions:



##### Carbonation reaction:



##### Hydration reaction:



**BOX 3****Thermodynamic Laws and Definitions**

**The First Law of Thermodynamics:** The first law of thermodynamics defines the **internal energy ( $E$ )** of a chemical system. If the composition of a system does not change (the system is closed),  $E$  is constant unless heat flows or work is done.  $E$  is usually expressed in units of energy/mole: joules/mole (J/mol) or calories/mole (cal/mol or Kcal/mol). One calorie is equivalent to 4.184 joules.

**The Second Law of Thermodynamics:** The second law of thermodynamics defines **entropy ( $S$ )**. Entropy is a thermodynamic value expressing the degree of disorder of a system. Minerals with simple atomic structure and simple chemistry have low entropy. Those with complex structure or chemistry have high entropy.  $S$  is usually expressed in units of energy/mole-degree: joules/mole-K (J/mol-K) or calories/mole-K (cal/mol-K or Kcal/mol-K).

**The Third Law of Thermodynamics:** Entropy varies with temperature. The third law of thermodynamics states that the entropy of crystals tends toward zero as the absolute temperature approaches 0 K ( $-273^{\circ}\text{C}/-460^{\circ}\text{F}$ ).

**Molar Volume (V):** The **molar volume** is the volume occupied by one mole of a compound. It is usually expressed in units of  $\text{cm}^3/\text{mole}$  (cc/mol). For some calculations, it is expressed in units of joules/bar-mole (J/bar-mol). ( $1\text{J}/\text{bar} = 10\text{cc}$ .)

**Molar Entropy (S):** The molar entropy is the entropy of one mole of a compound. It is usually expressed in units of joules/Kelvin-mole (J/K-mole) or calories/Kelvin-mole.

**Enthalpy (H):** Minerals of high volume are less stable at high pressure than at low pressure. Conversely, minerals of low volume are less stable at low pressure than at high pressure. **Enthalpy (H)** is a thermodynamic quantity that reflects this concept. It includes the internal energy ( $E$ ) and energy associated with the volume of a substance:

$$H = E + PV \quad (9)$$

$H$  and  $E$  are usually expressed in units of energy/mole: joules/mole (J/mol) or calories/mole (cal/mol or Kcal/mol).

**Gibbs Free Energy (G):** Minerals of high entropy ( $S$ ) are more stable at high temperature than at low temperature. Minerals of low entropy are more stable at low temperature than at high temperature. The Gibbs free energy reflects this relationship by adding an entropy term ( $TS$ ) to enthalpy ( $H$ ):

$$G = H - TS = E + PV - TS \quad (10)$$

As with  $H$  and  $E$ ,  $G$  is usually expressed in units of energy/mole: joules/mole (J/mol) or calories/mole (cal/mol or Kcal/mol).

**Clausius-Clapeyron Equation:** The Clausius-Clapeyron equation relates the volume and entropy of a reaction to its slope on a pressure-temperature phase diagram:

$$\frac{dP}{dT} = \Delta S / \Delta T \quad (11)$$

**Gibbs Phase Rule:** The Gibbs phase rule says that the number of minerals that may stably coexist is limited by the number of chemical components:

$$p + f = c + 2 \quad (12)$$

where  $p$  is the number of mineral phases,  $c$  is the number of chemical components, and  $f$  is the number of degrees of freedom. On a phase diagram,  $f = 0$  corresponds to a point,  $f = 1$  corresponds to a reaction line, and  $f = 2$  corresponds to a general area.

**equilibrium.** In principle, all rocks tend toward stable equilibrium. Whether they reach it depends on many things, including temperature, grain size, and reaction kinetics. If reactions cease before a rock has reached stable equilibrium, the rock is at **metastable equilibrium**.

We call a stable mineral assemblage representative of a given set of pressure-temperature conditions a **paragenesis**. When conditions change, metamorphic reactions may create a new paragenesis as some minerals disappear and others grow. Such reactions

may be prograde or retrograde. Most of the reactions in Box 2 are prograde, but Reactions 7 and 8 are examples of retrograde reactions that often affect mafic rocks.

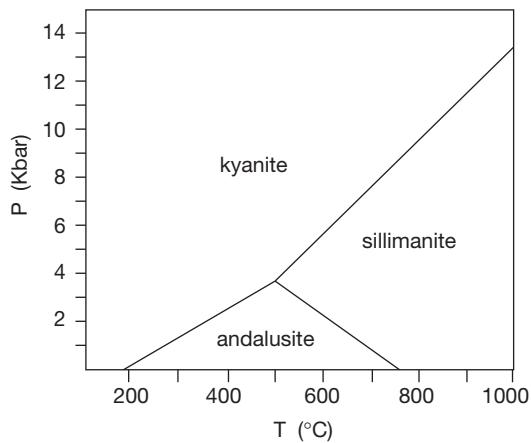
Prograde metamorphism involves the breakdown of minerals stable at lower temperature to form minerals stable at higher temperature. Some prograde reactions are solid-solid reactions, but most involve vapors of  $\text{H}_2\text{O}$  or  $\text{CO}_2$  that flow along cracks or grain boundaries. As temperature increases,

minerals containing  $H_2O$  or  $CO_2$  become increasingly unstable, causing dehydration or decarbonation, and the release of  $H_2O$  or  $CO_2$  as intergranular fluid. If we ignore  $H_2O$  and  $CO_2$ , we find that most prograde metamorphism is nearly **isochemical**, meaning that the rock is the same composition before and after metamorphism. In some cases, however, flowing fluids and metasomatism can be the dominant forces controlling metamorphism.

Retrograde metamorphism is in many ways just the opposite of prograde metamorphism.  $H_2O$ - and  $CO_2$ -free minerals react with fluids to produce hydrous or carbonate minerals. Mg-silicates such as forsterite,  $Mg_2SiO_4$ , and enstatite,  $Mg_2Si_2O_6$ , for example, may react to form talc,  $Mg_3Si_4O_{10}(OH)_2$ ; serpentine,  $Mg_6Si_4O_{10}(OH)_8$ ; brucite,  $Mg(OH)_2$ ; or magnesite,  $MgCO_3$ , at low temperature. In contrast with prograde reactions, retrograde reactions are often quite sluggish. They may not go to completion and frequently do not reach stable equilibrium. Sometimes retrogression only affects parts of a rock or parts of some grains in a rock.

## METAMORPHIC PHASE DIAGRAMS AND THE PHASE RULE

Pressure-temperature (P-T) **phase diagrams** show the pressures and temperatures at which metamorphic reactions occur. Phase diagrams for simple chemical systems with few stable minerals may only contain a few reactions. Figure 12 shows a phase diagram depicting the phase relationships for a one-component chemical system. The chemical component is  $Al_2SiO_5$ ; the system includes only polymorphs of  $Al_2SiO_5$



**FIGURE 12**  $Al_2SiO_5$  phase diagram. The diagram shows the general P-T conditions under which kyanite, sillimanite and andalusite are stable. Kyanite is found in high-pressure pelitic rocks, andalusite is found in low-pressure pelitic rocks, and sillimanite is typical of high-grade pelitic rocks.

(andalusite, kyanite, sillimanite). Solid lines in Figure 12 show the location of three reactions:



Reactants and products are stable on separate sides of the reaction lines, which separate P-T space into small areas called **stability fields**, each characterized by a specific  $Al_2SiO_5$  mineral. The phase diagram shows us that each of the three polymorphs has its own stability field: Rocks containing kyanite form at low temperature and high pressure, rocks containing andalusite form at low pressure, and those containing sillimanite form at high temperature. The diagram also allows us to make predictions: If a rock containing andalusite is metamorphosed at high temperature, the andalusite will change into sillimanite (Figure 12).

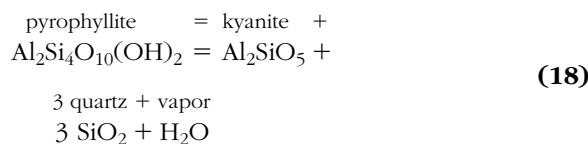
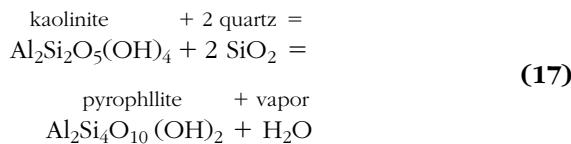
Pressure and temperature are the two most important **intensive variables** (variables controlled by factors outside a rock) that determine the mineral assemblage in a metamorphic rock. Sometimes if pressure or temperature change, the mineral assemblage will change; other times it will not. We can think of a rock as a chemical system. If pressure and temperature can change independently without a change in mineral assemblage, the rock system has 2 **degrees of freedom**. If neither pressure nor temperature can change without a change in mineral assemblage, the rock system has 0 degrees of freedom. If the two intensive variables must change together to maintain a mineral assemblage, the rock system has 1 degree of freedom. The Gibbs phase rule relates the number of possible stable minerals to the number of chemical components and the degrees of freedom of a system:

$$p + f = c + 2 \quad (16)$$

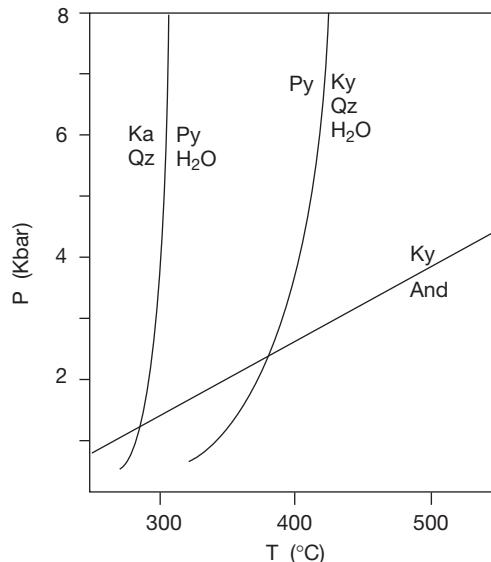
where  $p$  is the number of phases (number of minerals plus fluid species),  $c$  is the number of components (in the case of andalusite-kyanite-sillimanite,  $c = 1$ ), and  $f$  is the number of degrees of freedom. The constant 2 in the phase rule refers to the two intensive variables, pressure and temperature, that normally vary and control mineralogy. At an **invariant point**, a point where two or more reactions intersect on a phase diagram,  $f = 0$ . All three  $Al_2SiO_5$  polymorphs can coexist at about 4 kbar

and 500 °C (930 °F), the invariant point at which Reactions 13, 14, and 15 intersect (Figure 12). Along a **univariant line** ( $f = 1$ ) corresponding to a reaction line on a phase diagram, two of the three polymorphs may be stable. In a general region of P-T space,  $f = 2$ , and only one  $\text{Al}_2\text{SiO}_5$  mineral is stable.

Figure 13 depicts more complicated reactions in the three-component ( $c = 3$ ) system  $\text{Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$ . The reactions are univariant ( $f = 1$ ), involving four phases ( $p = 4$ ):



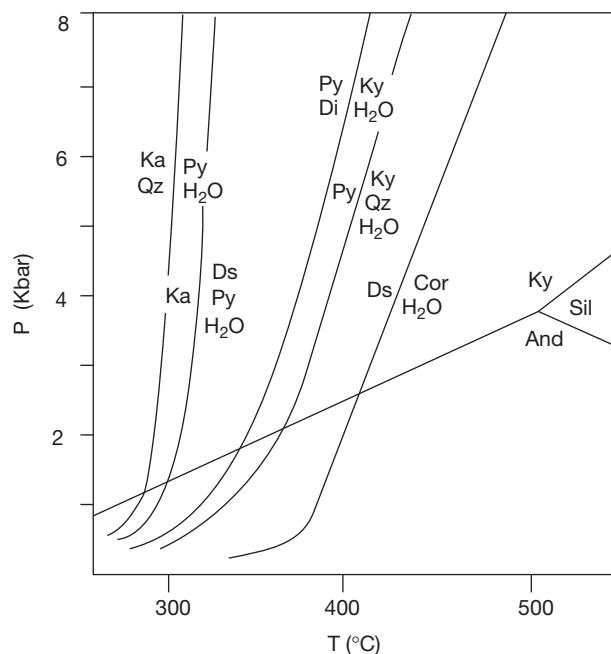
Reaction 17 is a dehydration reaction that takes place in some metapelitic rocks at low temperature. At low temperature, kaolinite and quartz are stable together, but as temperature increases, kaolinite and quartz react to produce pyrophyllite and  $\text{H}_2\text{O}$  vapor. Pyrophyllite itself breaks down at slightly higher temperatures by Reaction 18, so pyrophyllite may only be stable over a range of about 100 °C (Figure 13). It is important to emphasize that Reaction 17 does not limit the stability



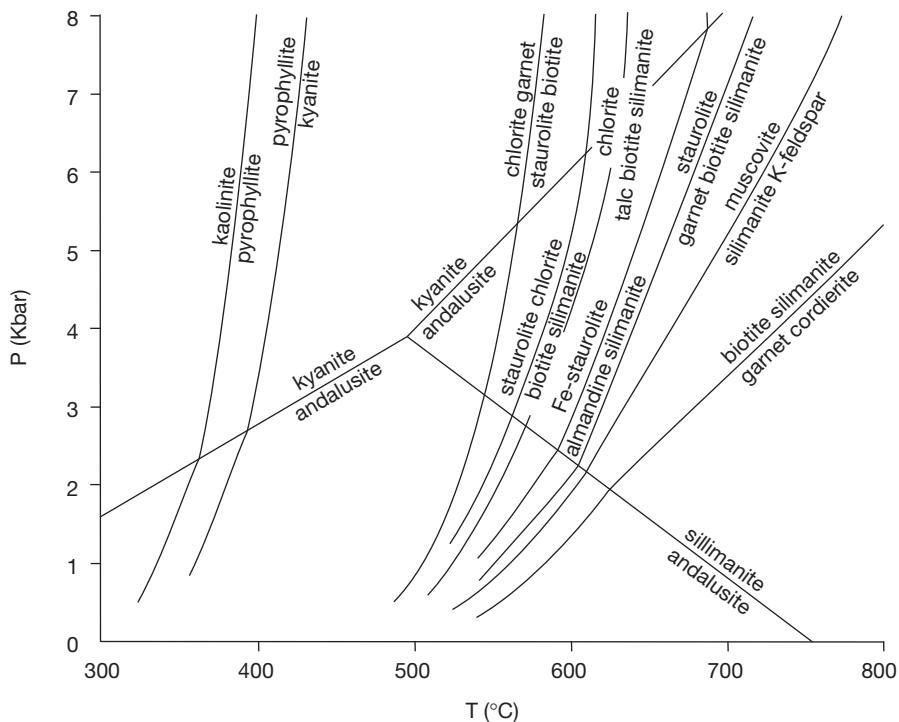
**FIGURE 13** Phase diagram showing some reactions involving kaolinite (Ka), quartz (Qz), pyrophyllite (Py), kyanite (Ky), and andalusite (And). The two nearly vertical reactions, both dehydration reactions, limit pyrophyllite stability to 300 to 400 °C when water is present.

of kaolinite if quartz is not present. When a rock containing kaolinite + quartz reacts according to Reaction 17, reaction will cease when either kaolinite or quartz is completely consumed. The resulting assemblage will be kaolinite + pyrophyllite + vapor or quartz + pyrophyllite + vapor unless both kaolinite and quartz are exhausted at the same time.

The reactions in Figure 13 are only three of many that can take place in the  $\text{Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$  system. Figure 14 is a more complete phase diagram for the system, including all stable minerals and reactions. Eight minerals are involved but they cannot all be stable together. At temperatures over about 450 °C (850 °F), the stable minerals are corundum ( $\text{Al}_2\text{O}_3$ ), quartz ( $\text{SiO}_2$ ), and the three  $\text{Al}_2\text{SiO}_5$  polymorphs (andalusite, kyanite, sillimanite), but corundum and quartz cannot be found together. The phase diagram permits prediction of the pressures and temperatures at which individual minerals and specific mineral assemblages will form. Conversely, it allows us to estimate the pressure and temperature of formation for some metapelitic rocks containing those minerals and assemblages. For example, rocks containing kaolinite and quartz are constrained to have formed at temperatures below about 300 °C (570 °F). If andalusite accompanies the kaolinite and quartz, pressure is restricted to less than 1 kbar (Figure 14).



**FIGURE 14** Phase diagram for the  $\text{Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$  system. Abbreviations: Ka—kaolinite; Qz—quartz; Py—pyrophyllite; Ds—diasporite; Ky—kyanite; Cor—corundum; Sil—sillimanite; And—andalusite. Diagrams of this sort allow petrologists to estimate the conditions at which a rock formed based on the minerals present.



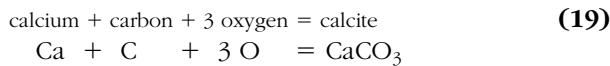
**FIGURE 15** Phase diagram showing reactions limiting the stability of common minerals in metapelitic rocks. Some of the reactions involve quartz or H<sub>2</sub>O, which are generally present in pelitic rocks and, so, have not been labeled in this diagram. Diagrams like this allow petrologists to interpret the history of metamorphic rocks.

Figure 15 is a more complex diagram showing other important reactions that take place in metapelitic rocks. Although quartz and water vapor are involved in some of the reactions, they have not been labeled in this diagram because they are always present in pelites. The minerals shown are the ones that change when a pelitic rock is metamorphosed. We can use Figure 15 to estimate the P-T conditions of formation of metapelitic rocks based on the minerals they contain. We could construct similar diagrams for other composition metamorphic rocks.

## THE THERMODYNAMICS OF REACTIONS

### The Gibbs Free Energy

In the preceding discussions, we said that the mineral or mineral assemblage with least energy is more stable than others of the same composition. The Gibbs free energy (often just called *Gibbs energy*) of a mineral is the numerical value describing a mineral's stability (see Box 3). Minerals do not have absolute values of Gibbs energy; values are always relative, usually referenced to the elements that comprise a mineral. The Gibbs free energy of formation of calcite from the elements ( $\Delta G_f^\circ$ ), for example, is the Gibbs energy released by the reaction of Ca, C, and O to produce calcite:



Gibbs energies can be used to calculate the Gibbs free energy of a reaction ( $\Delta G_{\text{rxn}}$ ), the difference in Gibbs energy between the products and the reactants, to determine if the reaction will take place. The Gibbs free energy of formation of calcite from the elements is the Gibbs free energy of Reaction 19:

$$\Delta G_{f, \text{elements}}^\circ (\text{calcite}) = G_{\text{calcite}} - G_{\text{Ca}} - G_{\text{C}} - 3 G_{\text{O}} \quad (20)$$

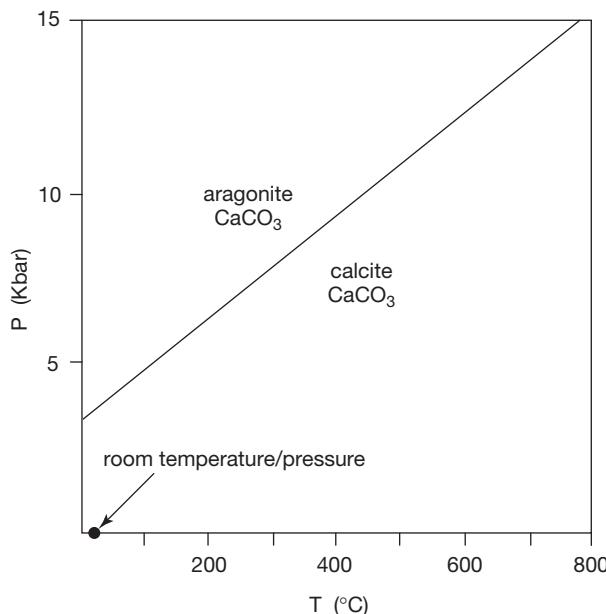
As another example, consider the equilibrium between aragonite and calcite, both having composition CaCO<sub>3</sub>. The reaction relating the two is:



The Gibbs energy of this reaction is:

$$\Delta G_{\text{rxn}} = G_{\text{aragonite}} - G_{\text{calcite}} \quad (22)$$

Under most P-T conditions, the Gibbs energies of aragonite and calcite are not equal; the one with the least Gibbs energy is stable. If  $G_{\text{aragonite}} < G_{\text{calcite}}$ , then  $\Delta G$  for Reaction 21 is negative and aragonite is stable. If equilibrium is maintained, calcite will react to produce aragonite as the reaction goes to the right. If  $G_{\text{calcite}} < G_{\text{aragonite}}$ , then  $\Delta G$  for Reaction 21 is positive and calcite is stable. The reaction goes to



**FIGURE 16** Phase diagram showing the reaction calcite = aragonite. Calcite is the stable calcium carbonate mineral under normal Earth surface conditions. Aragonite is found in some high-pressure rocks, especially blueschists.

the left. Calcite and aragonite may stably coexist only when  $G_{\text{calcite}} = G_{\text{aragonite}}$  and  $\Delta G_{\text{rxn}} = 0$ , conditions represented by the line in Figure 16. At Earth surface conditions,  $G_{\text{calcite}} < G_{\text{aragonite}}$ , so most  $\text{CaCO}_3$  is calcite. Some metastable aragonite can be found, most notably in seashells and other biogenic material, but given enough time, it will change into calcite.

Thermodynamic tables in reference books list Gibbs free energies and other thermodynamic values of minerals and related compounds (Box 3). We can use the values to calculate phase diagrams and to predict mineral stability. We usually give Gibbs free energies in units of joules per mole (J/mol) or, in older books, kilocalories per mole (kcal/mol). A reference might say  $\Delta G_f^\circ(\text{calcite}) = -1,128,842 \text{ J/mol}$ , meaning that 1,128,842 joules of energy are released when pure elements react to produce one mole of calcite. Further, because  $\Delta G_f^\circ(\text{calcite})$  is negative, calcite is more stable than the elements by themselves. We can combine equations such as 20 with 22 to verify that we can calculate the Gibbs free energy of any reaction ( $\Delta G_{\text{rxn}}$ ) from the  $\Delta G_f^\circ$  values of the products and reactants:

$$\Delta G_{\text{rxn}} = \sum \Delta G_f^\circ(\text{products}) - \sum \Delta G_f^\circ(\text{reactants}) \quad (23)$$

and therefore for Reaction 21:

$$\Delta G_{\text{rxn}} = \Delta G_f^\circ(\text{aragonite}) - \Delta G_f^\circ(\text{calcite}) \quad (24)$$

## Changes in Gibbs Energy with Pressure and Temperature

Gibbs energy values vary with pressure and temperature (Box 3). The variations depend on the internal energy ( $E$ ), molar volume ( $V$ ), and molar entropy ( $S$ ), and are directly related to pressure ( $P$ ) and temperature ( $T$ ):

$$G = E + PV - TS \quad (25)$$

Equation 25 describes the Gibbs energy of any mineral. A similar equation describes the Gibbs energy of a reaction:

$$\Delta G_{\text{rxn}} = \Delta E_{\text{rxn}} + P\Delta V_{\text{rxn}} - T\Delta S_{\text{rxn}} \quad (26)$$

where the internal energy of reaction ( $\Delta E_{\text{rxn}}$ ) is:

$$\Delta E_{\text{rxn}} = \sum \Delta E_f^\circ(\text{products}) - \sum \Delta E_f^\circ(\text{reactants}) \quad (27)$$

the volume of reaction ( $\Delta V_{\text{rxn}}$ ) is:

$$\Delta V_{\text{rxn}} = \sum \Delta V_f^\circ(\text{products}) - \sum \Delta V_f^\circ(\text{reactants}) \quad (28)$$

and the entropy of reaction ( $\Delta S_{\text{rxn}}$ ) is:

$$\Delta S_{\text{rxn}} = \sum \Delta S_f^\circ(\text{products}) - \sum \Delta S_f^\circ(\text{reactants}) \quad (29)$$

Equations 25 and 26 have some important implications. If the molar volume of a mineral is large and the pressure is high,  $G$  will be large and the mineral will be relatively unstable. Therefore, at high pressure, minerals of low molar volume (high density) are most stable. Similarly, at high temperature, high-entropy minerals are most stable because high entropy and high temperature lead to low  $G$ . These observations explain why graphite reacts to form diamond—a denser polymorph—at high pressure, and why sillimanite—a high-entropy polymorph of kyanite—is only stable at high temperature.

If a reaction is at equilibrium, the minerals on both sides of the reaction are stable simultaneously. So, when calcite and aragonite coexist stably, they have equal Gibbs energies and the Gibbs energy of Reaction 21 is zero:

$$0 = \Delta E_{\text{rxn}} + P\Delta V_{\text{rxn}} - T\Delta S_{\text{rxn}} \quad (30)$$

Equation 30 must hold at all points along any reaction curve on a P-T phase diagram. Application of calculus to Equation 30 yields a relationship, called the *Clausius-Clapeyron equation*, used for calculating the slope of a reaction on a P-T diagram:

$$\text{slope} = \frac{dP}{dT} = \frac{\Delta S_{\text{rxn}}}{\Delta V_{\text{rxn}}} \quad (31)$$

Volumes and entropies of minerals depend mostly on chemical composition, and, to a lesser extent, on temperature and pressure. Variations with temperature and pressure are predictably small and similar in most minerals. Thus, for solid-solid reactions, the volume and entropy of reaction are nearly constant over a wide range of pressure and

temperature, and the Clausius-Clapeyron equation tells us the slopes of reaction lines are nearly constant; they often plot as straight lines. Dehydration and decarbonation reactions, however, usually plot as curves because the volumes and entropies of fluids like H<sub>2</sub>O and CO<sub>2</sub> vary greatly with pressure and temperature, leading to great variation in  $\Delta V_{\text{rxn}}$  and  $\Delta S_{\text{rxn}}$ .

The example considered above (Reaction 21) involved only two minerals. We can analyze more

#### BOX 4

##### Using Phase Diagrams to Interpret Rocks

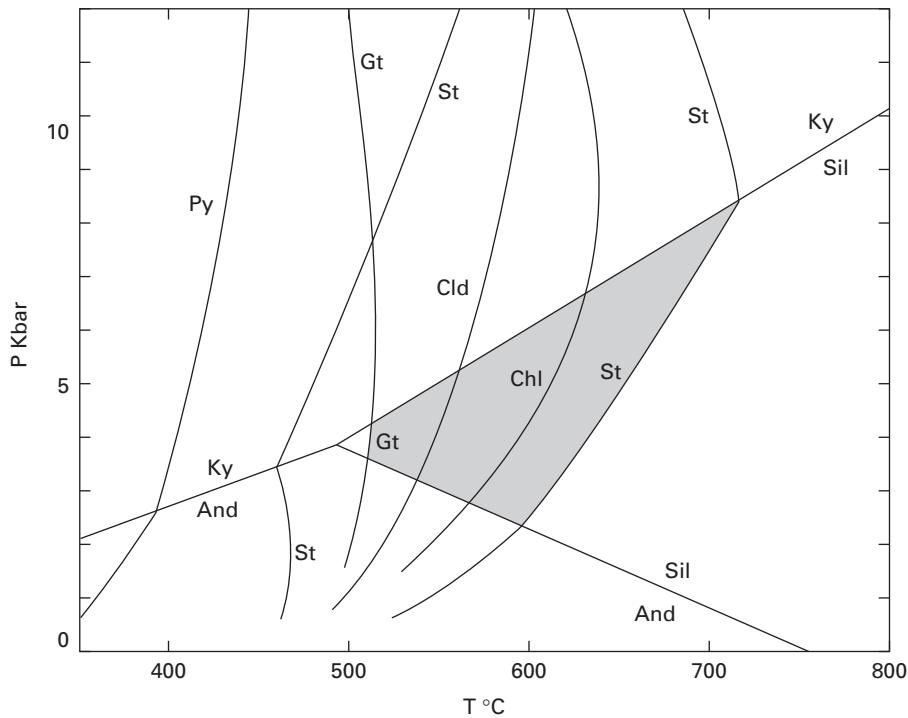
In this chapter we have talked mostly about metamorphic minerals and mineral stability in metamorphic rocks. We have described how minerals change with metamorphism and we have discussed thermodynamics and how we can predict mineral changes.

Petrologists often look at metamorphism and metamorphic minerals in a slightly different way. They find a rock containing a certain mineral or mineral assemblage, and they want to know what the conditions were when that rock formed. Such information allows them to reconstruct the geological history of the rock and, by extension, of the area from which it comes.

Figure 17 shows a schematic phase diagram depicting the stability fields for some key minerals in pelitic rocks. Reactions that limit the stabilities of pyrophyllite (Py), chloritoid (Cld), chlorite (Chl), garnet (Gt), staurolite (St), kyanite (Ky), sillimanite (Sil) and andalusite (And) can give us information about the metamorphic conditions when the rock formed. For simplicity, we have not shown the products for some reactions. They involve multiple minerals and would needlessly complicate this discussion.

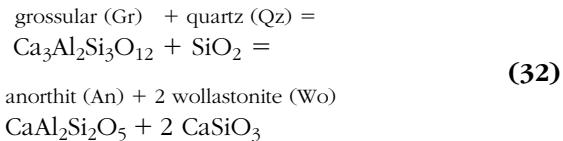
Consider a rock that contains garnet. The phase diagram shows that the rock must have formed at temperatures greater than about 500 °C (930 °F). Garnet does not, however, have an upper temperature limit. On the other hand, if a rock contains staurolite, it must have formed in the temperature window between about 460 and 700 °C (750 and 1,300 °F), depending on pressure, because staurolite has both a lower and an upper temperature limit. Suppose a rock contains the common assemblage garnet, staurolite, and sillimanite. It must have formed in the shaded window between reactions limiting those minerals.

Figure 17 shows only reactions limiting the stability of individual minerals. If we considered reactions that limit the stability of mineral assemblages (two or more minerals together) the diagram would become very complex and would include many more reactions. Such diagrams, which petrologists call *petrogenetic grids*, divide P-T space into small areas. They allow petrologists to use mineral assemblages to estimate the conditions at which a rock formed.



**FIGURE 17** P-T diagram for pelites. This diagram shows the conditions under which some key pelitic minerals form. These minerals, termed index minerals, are good indicators of metamorphic grade. Abbreviations: Py—pyrophyllite; Ky—kyanite; Sil—sillimanite; And—andalusite; St—staurolite; Gt—garnet; Chl—chlorite; Cld—chloritoid.

complex reactions in the same way. For example, consider the following reaction:

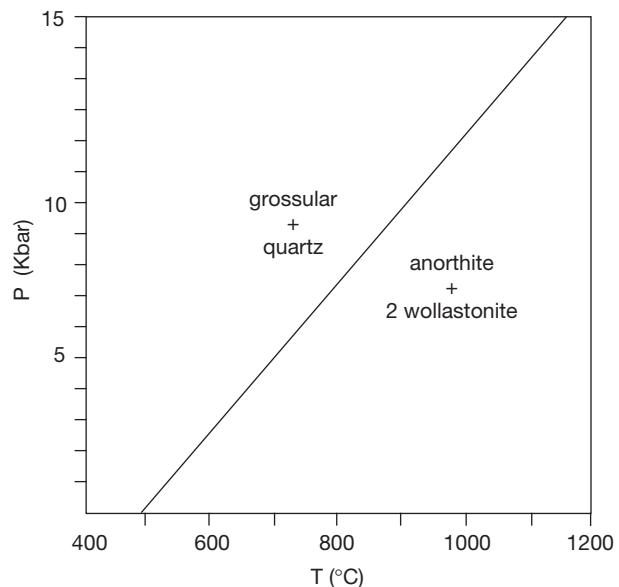


For this reaction, we may calculate  $\Delta G_{rxn}$  as

$$\begin{aligned} \Delta G_{rxn} = & \Delta G_f^\circ(\text{An}) + 2 \Delta G_f^\circ(\text{Wo}) \\ & - \Delta G_f^\circ(\text{Gr}) - \Delta G_f^\circ(\text{Qz}) \end{aligned} \quad (33)$$

Note that we multiply the Gibbs energy of wollastonite by 2 because the reaction involves 2 moles of wollastonite. We can calculate  $\Delta V_{rxn}$ ,  $\Delta S_{rxn}$ , and other thermodynamic quantities for Reaction 32 the same way we did for  $\Delta G_{rxn}$ . As with most solid-solid reactions, Reaction 32 plots as a straight line in P-T space (Figure 18).

If we knew the thermodynamic properties of all minerals, we could program computers to calculate phase diagrams for any chemical system. Many programs exist for this purpose. For simple systems involving simple minerals, the calculations are relatively straightforward, and all programs yield



**FIGURE 18** The reaction grossular + quartz = anorthite + 2 wollastonite plotted on a phase diagram. This reaction, like almost all solid-solid reactions, plots as a straight, or nearly straight, line.

similar results. However, for some complex systems and minerals, we have inadequate thermodynamic data at present.

## Questions for Thought

Some of the following questions have no specific correct answers; they are intended to promote thought and discussion.

1. If a rock contains quartz and feldspar prior to metamorphism, it will often contain quartz and feldspar after metamorphism. Why? How can we tell, then, that a granitic rock has been metamorphosed?
2. Many of the same minerals characterize both regional and contact metamorphic terranes. Why? On the other hand, some minerals such as sanidine or pigeonite are generally thought to characterize only contact metamorphic terranes. Why are such minerals generally absent from regional metamorphic terranes?
3. Why do many ultramafic rocks experience retrograde metamorphism? What are some of the typical retrograde minerals found in ultramafic rocks? What chemical characteristics do they share?
4. What evidence might you look for in a rock to determine that progressive metamorphism has occurred?
5. What evidence might you look for in a rock to determine that retrograde metamorphism has occurred?
6. When granites are metamorphosed, they rarely develop schistosity. Why?  
Why is it convenient to divide metamorphic rocks into classes based on chemistry?
8. Most metapelites are formed by metamorphism of clay-rich sediments. They are rarely formed by metamorphism of aluminous igneous rocks. How can they form from both? How can you distinguish the two?
9. What is the significance of Eskola's facies? Why is the facies concept widely used today?
10. Metamorphism of a basalt, or of a greywacke, produces many different minerals. The stable minerals vary depending on the pressure and temperature of metamorphism, so the minerals in such rocks can be used as indicators of metamorphic grade. On the other hand, metamorphism of a sandstone or of a granite produces less varied mineralogy; consequently, the minerals are not good indicators of metamorphic grade. Why?
11. If all metamorphic rocks represented equilibrium, we could theoretically enter their chemical and mineralogical compositions into a computer program, and the program could tell us the conditions at which the rock formed. However, we don't do this, and we can't do this. Why?
12. Consider the P-T diagram in Figure 17. Under what conditions did a rock form if it contains:
  - a. staurolite and andalusite
  - b. kyanite and chloritoid
  - c. garnet and chloritoid

Use words, or make a sketch of the phase diagram with appropriate shading, to explain your answers. What does the diagram tell you about the likelihood of finding pyrophyllite and sillimanite together?

## Resources

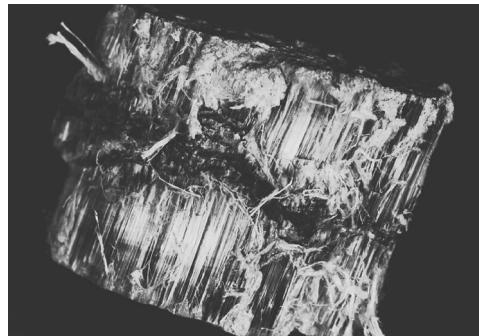
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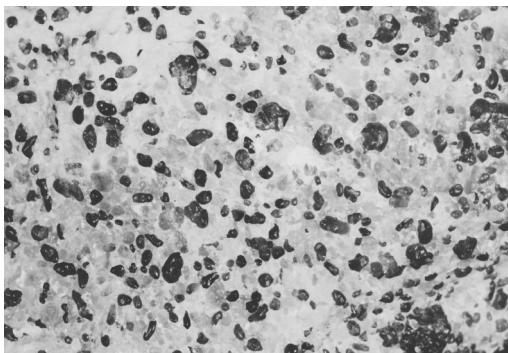
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**PLATE 3.6** Bladed blue kyanite from Minas Gerais, Brazil.



**PLATE 3.7** Chrysotile, the asbestosiform variety of serpentine, from Waldheim, Saxony.



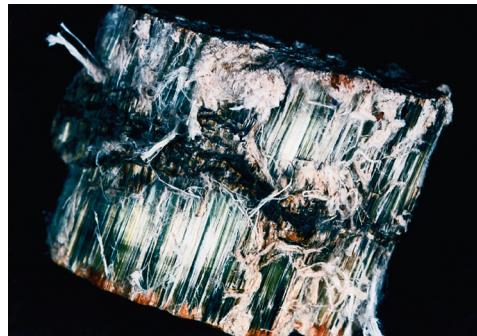
**PLATE 6.3** Marble from Lake Placid, New York, containing green diopside and white calcite.

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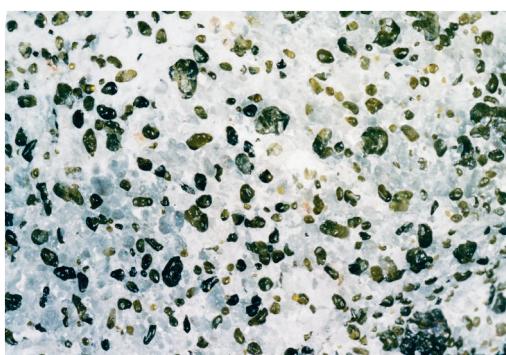
# Metamorphic Minerals and Metamorphic Rocks Color Plates



**PLATE 3.6** Bladed blue kyanite from Minas Gerais, Brazil.



**PLATE 3.7** Chrysotile, the asbestosiform variety of serpentine, from Waldheim, Saxony.



**PLATE 6.3** Marble from Lake Placid, New York, containing green diopside and white calcite.



**PLATE 8.4** Almandine in a schist from western Massachusetts.

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# Ore Deposits and Economic Minerals

We mine many minerals from the Earth. They include industrial minerals of many sorts, ore minerals that are processed to recover elements they contain, and gems. The best ore deposits are those that contain large amounts of ore minerals. The best ore minerals are those that contain large amounts of elements of interest. Most ore minerals are native elements, sulfides, sulfosalts, oxides, or hydroxides. In this chapter we discuss the many kinds of ore deposits and the minerals they contain. We also consider gems, beautiful and rare varieties of (often common) minerals.

The Earth gives us many mineralogical resources (Figure 1). We mine industrial minerals such as halite, gypsum, clays, calcite, asbestos, micas, and zeolites to make salt, plaster, ceramics, construction materials, electronic components, chemical filters, and many other things (Table 1). We mine gems for jewelry and a few industrial applications, and we mine many minerals for the elements they contain. We value industrial minerals and gems for their mineralogical properties, but we value most ores because they produce elements that we can use to make other things.

## MINERAL USE AND PROFITABILITY

Less than a dozen minerals and eight or nine elements dominate the crust. We use most of them in our daily lives. Other elements and minerals that exist only in small amounts and have uneven distributions are equally vital to our society (Box 1). If a rock or deposit contains a mineral or element in an amount sufficient to be mined at a profit, we call it an **ore deposit**. **Ore**, then, is an economic term describing anything that we can profitably take from the ground. Sometimes we mine ores from quarries or from open pits, sometimes we mine them

underground, and sometimes we remove them from the Earth by drilling holes and circulating water through beds of soluble minerals.

People have practiced mining and quarrying since ancient times. The first mineral known to be mined was flint, a fine-grained variety of quartz used to make weapons. Early peoples mined other things, such as ochre, for use as pigment in art and religious ceremonies. Egyptians mined native metals, including gold, silver, and copper, from stream beds as early as 3700 to 3000 B.C. Around 2600 B.C. they began to quarry stone to build the Great Pyramids. By the Middle Ages, mining was common in Europe. Georgius Agricola, a German physician, wrote the first widely read book about mining, *De re metallica*, published in 1556. Agricola's work is said by some to represent the beginning of the science of mineralogy.

We mine some ores because they contain elements that have the metallic properties of conductivity, strength, or shiny appearance, but many ores are valuable for other reasons. We conveniently divide ore minerals into several main commodity groups: metallic, semimetallic, and nonmetallic elements; gems; construction and manufacturing materials; fertilizer and chemical minerals; and energy resources (Table 1). We take energy resources and

**BOX 1****Strategic Minerals and Metals**

We use many different minerals and metals to maintain our lifestyles and provide military security. Some of these commodities are not found or produced in the United States in sufficient quantities to meet demand. Consequently, we must import them from other nations. These minerals and metals are not only important to industry and the military, but they also have vast applications in manufacturing. During the Cold War, many important commodities came from the former Soviet Union, its allies, and other nations that were politically unstable, and supplies were often problematic. At various times since the Cold War ended, for political reasons, the United States has stopped importations from Cuba, Iran, Iraq, Libya, and North Korea. So, sources of strategic metals are controlled by politics as well as geology. Further complicating the picture is that the United States is both an importer and an exporter of some key metals and minerals.

The table below lists some of the key commodities imported by the United States, and their sources and uses today. This is only a partial list. The Federal Emergency Management Agency has identified more than 60 commodities that are crucial for our country but must, for the most part, be imported.

**Mineral Commodities and Their Sources (2008)\***

Metal or Mineral	% Imported	Source Nations	Some Important Uses
niobium	100	Brazil, Canada, Estonia, Germany	steel and other alloys
muscovite	100	India, Belgium, China, Brazil	electronics
bauxite	100	Guinea, Jamaica, Australia, Brazil	abrasives, chemicals, refractories
tantalum	100	Australia, Brazil, China, Germany	specialty alloys, electronics
manganese	100	South Africa, Gabon, Australia, China	steel, batteries
strontium	100	Mexico, Germany	fireworks, specialty metals
fluorite	100	China, Mexico, South Africa, Mongolia	chemical manufacturing, metallurgy
graphite (natural)	100	China, Mexico, Canada, Brazil	metallurgy, lubricants, brake linings
platinum	94	South Africa, United Kingdom, Germany, Canada	catalysts
diamonds (industrial)	88	Botswana, Ireland, Namibia, South Africa	computer chips, construction, grinding/polishing
barite	83	China, India	oil-drilling muds
potash	81	Canada, Belarus, Russia, Germany	fertilizer
tin	79	Peru, Bolivia, China, Indonesia	cans/containers, electronics
cobalt	78	Norway, Russia, Finland, China	alloys and chemical manufacturing
tungsten	70	China, Canada, Germany, Portugal	metal working, mining, filaments
chromium	62	South Africa, Kazakhstan, Russia, Zimbabwe	stainless steel
silver	55	Mexico, Canada, Peru, Chile	coins, jewelry, electronics
copper	37	Chile, Canada, Peru, Mexico	building construction, electronics, transportation
aluminum	26	Canada, Russia, Brazil, Venezuela	transportation, packaging, buildings
nickel	17	Canada, Russia, Norway, Australia	stainless steel
iron	12	Canada, European Union, Mexico, Brazil	steel, other manufacturing

\*U.S. Geological Survey: Mineral Commodity Summaries 2008

construction materials from the Earth in the greatest quantities. We also mine large amounts of salt and fertilizer components. Of the metals, only iron is removed from the Earth in comparable amounts. In this chapter we focus on ore minerals that contain metallic, semimetallic, and nonmetallic elements, and on gems, because mineralogy is perhaps the most significant factor determining their value.

Many factors control the profitability of an ore deposit. We call the amount of known ore in a deposit the **reserves**. The concentration of a commodity in the ore (the “richness” of the ore) determines the **ore grade**. When calculating the profitability, amount of reserves and ore grade are the most significant geological factors, although economic factors such as extraction costs, processing

costs, and market price are often more decisive. A high-grade ore deposit may be uneconomical to mine if the reserves are low, because start-up costs could consume all profits. A large high-grade deposit may be uneconomical to mine if it is in a remote area. Even large, developed deposits can become uneconomical if the market price falls, perhaps due to the discovery of a better deposit somewhere else.

The elements oxygen, silicon, aluminum, iron, calcium, sodium, potassium, magnesium, and titanium make up 99% of Earth's crust. It is no wonder, then, that humans have developed processes so we may use these elements in industry, agriculture, and manufacturing. Less abundant elements have also become important to modern society. These include



**FIGURE 1** Miner working on a gold-bearing quartz vein in the Hishikari mine, Japan, one of the richest gold mines in the world. The vein, which is slightly less than a meter wide here, consists of thin layers of quartz, some of which contain gold. Photo from S. E. Kesler (1994), *Mineral Resources, Economics and the Environment*, MacMillan, New York.

metals, radioactive elements such as uranium or thorium, and fertilizer components such as nitrogen and phosphorous. As shown in Table 2, some of these elements make up very small percentages of Earth's crust; nevertheless, natural processes concentrate

them in particular minerals and in particular places. The term **concentration factor** refers to the ratio of minimum economical ore concentration to average crustal concentration (Table 2). For example, the average crustal abundance of chromium is about 0.01 wt %. Chromium ore can sometimes be profitable if it contains 30 wt % Cr. The necessary concentration factor is therefore 3,000—chromium must be concentrated at least 3,000 times to create profitable ore.

Because profit is related to volume, the minimum concentration factor necessary to make an element economical to mine is generally inversely proportional to crustal abundance. Elements that occur in high abundance do not need a high concentration factor to make mining economical. Iron deposits, for example, are profitable if concentration factors are 5 or 6. In contrast, economical tin, chromium, and lead mining require concentration factors of 2,500 or more. We mine relatively common elements, such as iron and aluminum, in many places worldwide; rarer elements, such as tin, chromium, or lead, are mined in far fewer places. Exceptions to the inverse relationship between abundance and economical grade are precious metals such as gold, silver, and platinum. High market value ensures large profits even when the concentration factor is low. Many gold mines can remain profitable in spite of a concentration factor of less than 750, which amounts to less than 0.1 ounces of gold in a ton of rock. Table 2 compares economical concentration factors and lists ore minerals of some important metals.

Ores and ore minerals vary greatly in quality. Ideal ores contain 100% of the commodity of interest. Native copper, for example, is an ideal copper ore. Ideal ores are, however, uncommon. Ores containing lots of a commodity of interest, and in a form that can be processed inexpensively, are considered good ores. Sulfide minerals often comprise good ores because they contain large amounts of the metals of interest, and are easily separated into metal and sulfur. For example, we mine Cu and Cu-Fe sulfides for their copper content. Silicate minerals, in contrast, are poor ore minerals. Although aluminum is found in many common silicates, tight bonding makes producing metallic aluminum from silicates uneconomical. We obtain most aluminum from Al-hydroxides found in bauxite deposits.

After mining, ore goes through a process to separate the valuable minerals from others. This involves crushing the ore, followed by gravity and chemical separation. The unwanted minerals are called **gangue**. Along with other processing and mining waste, gangue is usually discarded in **tailings** piles (Figure 2). In some mines, miners return wastes to abandoned portions of a mine to fill voids left by ore removal. Disposal of mine waste sometimes leads to

**TABLE 1 Groups of Ore Commodities**

Group	Examples
metallic and semimetallic elements	gold, silver, copper, iron, manganese, nickel, aluminum
nonmetallic elements	potassium, sodium, phosphorous, sulfur
gems	diamond, sapphire, agate
industrial materials: construction and manufacturing	sand, clay, building stone, asbestos, diatomite, talc, pyrophyllite, mica, zeolites
industrial materials: fertilizer and chemicals	limestone, dolomite, phosphate, potash, salt, nitrates, fluorite
energy resources	coal, oil, gas, uranium

**TABLE 2** Mineral Commodities: Minable Grade and Ore Minerals

Element	Average Crustal Abundance (wt %)	Average Minimum Economical Grade	Average Minimum Economical Concentration Factor	Some Important Ore Minerals	
Al	8	30	3.75	gibbsite boehmite diaspore	$\text{Al(OH)}_3$ $\text{AlO(OH)}$ $\text{AlO(OH)}$
Fe	5	25	5	magnetite hematite goethite siderite pyrite	$\text{Fe}_3\text{O}_4$ $\text{Fe}_2\text{O}_3$ $\text{FeO(OH)}$ $\text{FeCO}_3$ $\text{FeS}_2$
Cu	0.005	0.4	80	chalcopyrite bornite chalcocite covellite	$\text{CuFeS}_2$ $\text{Cu}_5\text{FeS}_4$ $\text{Cu}_2\text{S}$ $\text{CuS}$
Ni	0.007	0.5	71	pentlandite garnierite	$(\text{Ni}, \text{Fe})_9\text{S}_8$ $(\text{Ni}, \text{Mg})_3\text{Si}_2\text{O}_5(\text{OH})_4$
Zn	0.007	4	571	sphalerite wurtzite zincite franklinite	$\text{ZnS}$ $\text{ZnS}$ $\text{ZnO}$ $\text{ZnFe}_2\text{O}_4$
Mn	0.09	35	389	hausmannite polianite pyrolusite	$\text{Mn}_3\text{O}_4$ $\text{MnO}_2$ $\text{MnO}_2$
Sn	0.0002	0.5	2,500	cassiterite	$\text{SnO}_2$
Cr	0.01	30	3,000	chromite	$\text{FeCr}_2\text{O}_4$
Pb	0.001	4	4,000	galena cerussite	$\text{PbS}$ $\text{PbCO}_3$
Au	0.0000004	0.0001	250	gold calaverite	$\text{Au}$ $\text{AuTe}_2$

**FIGURE 2** Abandoned mine and tailings pile (behind the buildings, to the left).

environmental problems, including water, air, and soil contamination. For example, sulfides in mine wastes can react with water and oxygen in air to produce acid mine drainage. The resulting sulfuric acid may kill vegetation and fish in nearby lakes and streams. (See Box 6)

### TYPES OF ORE DEPOSITS

The geological processes that concentrate ore are unusual, so good ore deposits are rare. If they were not, market prices would fall, decreasing profits and putting some mines out of business. Because the geology of the Earth varies, the distribution of ore deposits

around the globe is uneven. For example, in North America, we could produce the silver, tungsten, sulfur, zinc, and gold to meet our needs. But nickel, chromium, aluminum, and tin must be imported from elsewhere (Box 1). Furthermore, we can import many mineral commodities at less than it would cost us to mine them in our own country; tungsten is a good example. Some regions contain most of the supply of certain commodities, which can affect international politics. The United States controls about half the world's molybdenum, Australia about a quarter of the world's aluminum, and Zaire half the cobalt. South Africa, a country rich in mineral commodities, controls 90% of the world's platinum, half the world's gold, and 75% of the chromium. Much of the world's tin comes from Bolivia and Brazil.

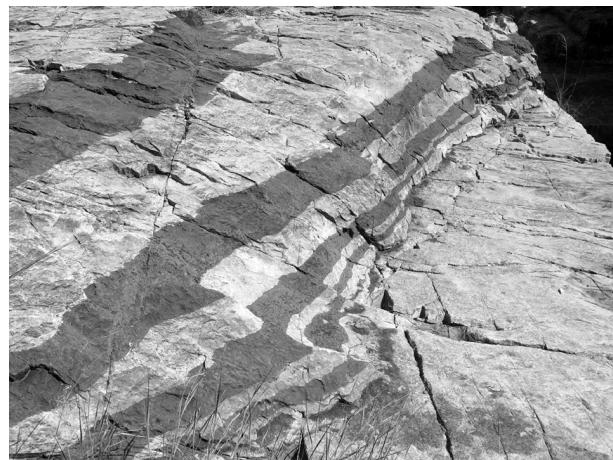
Most South African ore deposits are associated with terranes called Precambrian **greenstone belts**, ancient volcanic terranes. Similar greenstone belts in Canada account for many of North America's metallic ore deposits. Various other types of geological terranes are associated with ore deposits. Most economical metal and semimetal deposits are found near margins of continents, or the former margins of continents, where igneous activity has occurred. Many other types of deposits are found in continental interiors.

Ore deposits form in many different ways, and we find them in many different rock types. Some high-temperature ore deposits form in igneous rocks by direct crystallization of a magma, but most metal ores precipitate from **hydrothermal fluids**. These solutions of hot water and dissolved metals deposit minerals in **host rocks**, which may be igneous, metamorphic, or sedimentary.

### Magmatic Ore Deposits

In igneous rocks, elements of economic value are often concentrated in **accessory minerals**. In some rare circumstances, these same minerals exist in sufficient abundance to make mining profitable. If the minerals are scattered throughout a host rock, we call the deposit a **disseminated deposit**. Disseminated deposits produce most of the world's diamonds, copper, and molybdenum and also large percentages of the available tin, silver, and mercury. Often, disseminated ores consist of minerals scattered randomly in a host rock. If ore is distributed in many small veins, geologists call the deposit a **lode deposit**.

Magmatic processes can concentrate minerals in different ways. During crystallization of a magma, early forming, dense minerals sometimes sink and accumulate at the bottom of magma chambers (Figure 3). **Cumulate** ore deposits form in this way, typically associated with magmas of mafic or ultramafic composition. Chromite, magnetite, and



**FIGURE 3** Chromite layers (black) in anorthosite of the Bushveld Complex, South Africa. The origin of the layering is debated: some geologists believe it is due to settling of chromite grains in a magma chamber to make a cumulate, others associate these layers with intrusions of crystal slurry. The Bushveld chromite deposits provide not only chromium, but much of the world's supply of platinum group elements.

platinum are examples of minerals mined from cumulates. Perhaps the most famous of such deposits are found in South Africa. There, chromite cumulates produce not only significant amounts of chrome, but also very large amounts of platinum and other elements.

During crystallization, some minerals crystallize before others. Consequently, the late-stage magma may not be the same composition as the original magma. Often, this final late-stage melt results in **pegmatites**, late-stage coarse-grained igneous rocks that may concentrate economic minerals (Plate 1.4). After much crystallization has occurred, residual magmas often become enriched in **incompatible elements** (those that don't easily fit into crystal structures). These magmas, often water-rich, crystallize as pegmatites, forming dikes or tabular intrusions. Elements of value in pegmatites include lithium, cerium, beryllium, tin, and uranium.

Sometimes a magma becomes immiscible and separates into two different compositions. This process concentrates some minerals and elements in dikes or pockets within the original magma body. Sulfide and oxide ores may form this way, especially if gravity helps concentrate the dense ore minerals. The world-class nickel and platinum ores at Sudbury, Ontario, formed this way. A final type of igneous ore deposit is associated with **kimberlites**, fine-grained ultramafic rocks of unusual chemistry. Kimberlites are the primary source of diamonds at Earth's surface. If they weather and erode, the diamonds may later be concentrated in sedimentary deposits. Kimberlites occur in pipe-like deposits that are thought to have reached the surface during short, violent, intrusion.

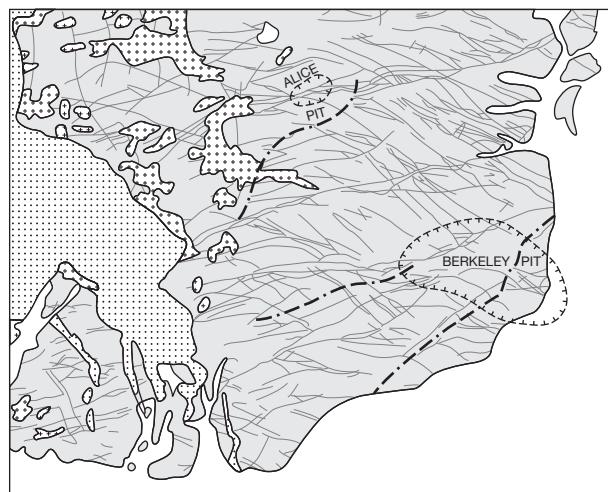
They occur in all parts of the world but the most famous are near Kimberly, South Africa.

### Hydrothermal Ore Deposits

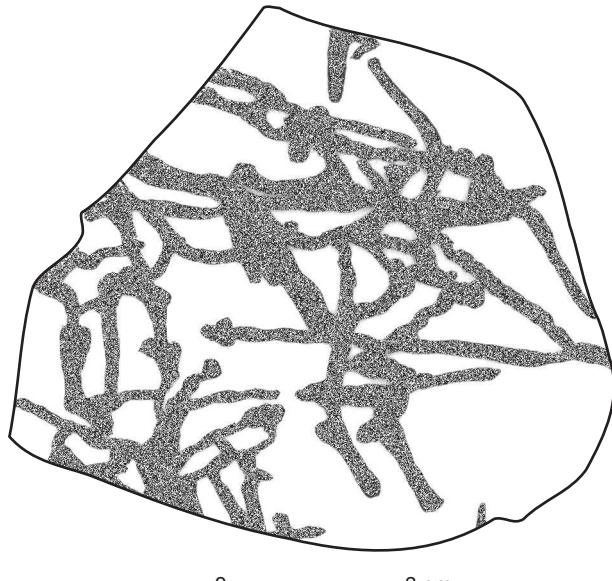
As magmas crystallize, hot, water-rich hydrothermal fluids may be released from the melt. The fluids are rich in sulfur, sodium, potassium, copper, tin, tungsten, and other elements with relatively high solubilities. Hydrothermal fluids dissolve other elements as they flow through rocks and eventually cool to deposit minerals in **hydrothermal deposits**. Hydrothermal fluids may travel long distances before they deposit ore. So, determining the source of the fluid and of the ore elements is often very difficult or impossible. Deposition, however, is more easily explained. It usually occurs in response to cooling, pressure changes, or changes in pH or other chemical factors. Hydrothermal deposits vary in size from huge networks of veins covering many square

kilometers to small veinlets only centimeters in width (Figure 4). Hydrothermal ore deposits typically form at mid-ocean ridges, in subduction zone, or adjacent to plutons. These environments provide a source of heat and of hydrothermal fluids. Large copper and molybdenum deposits, called **porphyries**, are good examples of deposits associated with plutons. Some of the world's largest porphyry copper deposits formed when hydrothermal fluids flowed through fractures, dissolving and altering oxide minerals and replacing them with sulfides. **Skarn deposits**, formed by fluids associated with contact metamorphism, may develop when fluids given off by a crystallizing pluton react with adjacent carbonate rocks. When hydrothermal fluids create ore deposits at the Earth's surface, we call the deposits **exhalitives**.

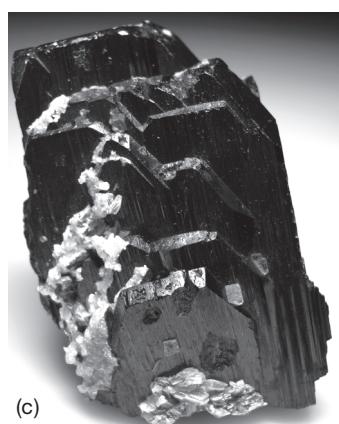
When a hydrothermal deposit is not directly associated with a pluton, we call it an **epigenetic** deposit. Often, the hydrothermal fluids have traveled



(a) Sediment cover  
 Rhyolite  
 Aplite  
 Granodiorite  
 500 km  
 Fault  
 Veins



(b) 0 3 cm



(c)

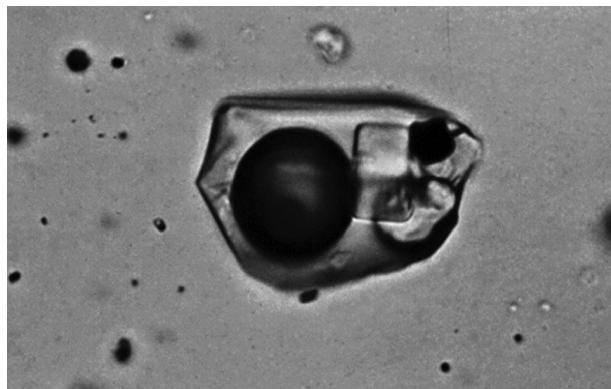
**FIGURE 4** Hydrothermal deposits and ores come in all sizes: (a) schematic map of the Butte, Montana, district showing the many hydrothermal veins; (b) close-up of molybdenite-bearing veins in a granite hand sample from Climax, Colorado; (c) crystals of wolframite (up to 6 cm in longest dimension), with some quartz crystals on top. Wolframite is a common hydrothermal tungsten ore mineral.

Illustrations modified from those in Evans, 1980.

**BOX 2****Fluid Inclusions and Hydrothermal Ore Deposits**

Many minerals formed in a variety of environments contain fluid inclusions, small bubbles that are typically 0.1 to 1 mm in diameter. Usually we need a microscope to see them. Inclusions are found in igneous, sedimentary, and metamorphic rocks, and are of particular importance when studying hydrothermal ore deposits. Fluid inclusions are also found in deep ice cores from Greenland and the Arctic. By studying their composition climatologists gain information that helps them reconstruct the past climate record.

In hydrothermal ore deposits, fluid inclusions are trapped in a crystal at the time it forms, or later along fracture zones. When trapped, the fluids are at relatively high temperatures. As the fluid cools, it contracts and a gas bubble may form (Figure 5). So, many fluid inclusions contain both a liquid and a vapor bubble. If the fluid contained abundant dissolved ions, minerals such as halite, sylvite, or hematite may precipitate as well. By heating an inclusion slowly and measuring the temperatures at which any gas bubble disappears and salts dissolve, ore petrologists can often determine the conditions under which an ore deposit formed.



**FIGURE 5** This fluid inclusion contains a liquid, a vapor bubble, and crystals of halite, sylvite, and hematite. The bubble and the crystals formed as originally hot ore fluid cooled, exsolving vapor and precipitating crystals.  
<http://minerals.cr.usgs.gov/gips/na/fluid.html>

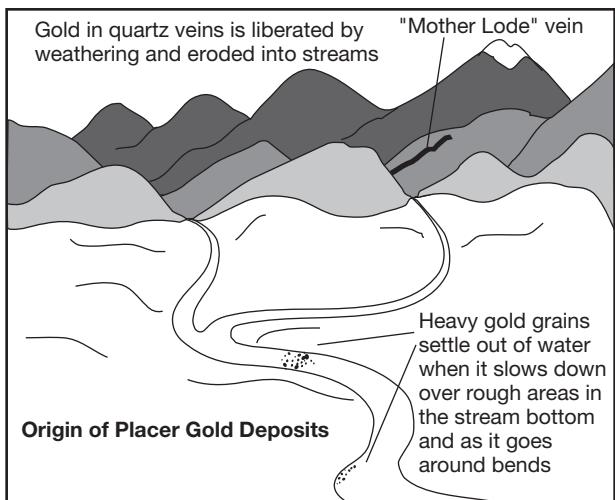
so far that their original source is unknown. Many gold and antimony deposits formed in this manner. The lead-zinc deposits of limestones in the central United States, called *Mississippi Valley-type deposits*, are epigenetic (Figure 6).

**Sedimentary Ore Deposits**

Gravity may be an important force concentrating economic minerals. Heavy minerals, weathered from igneous, sedimentary, or metamorphic rocks, often become concentrated in stream or valley bottoms. Rivers may transport them long distances before they become concentrated in **placers** (Figure 7). Placer deposits set off the historically important California Gold Rush of 1849. The original sources of minerals in placer deposits are often difficult to determine. The California gold was weathered from



**FIGURE 6** Galena, PbS, is one of the principal ore minerals in Mississippi Valley deposits. This sample is typical of galena, containing intergrown cubes slightly modified by octahedral faces (triangles at corners).



**FIGURE 7** Origin of placer deposits, which are concentrations of heavy clastic grains in stream, lake, or ocean sediment. As shown here, minerals liberated from veins by weathering and erosion are carried downstream and deposited where the water slows. From S. E. Kesler, *Mineral Resources, Economics and the Environment*, New York: Macmillan, 1994. Used by permission.

extensive vein deposits in the Sierra Nevada Mountains, called the **mother lode**. Many prospectors told stories of finding and mining the mother lode, but in actuality, most of it eroded away long before the “Forty-Niners” arrived. Tin, titanium, zirconium, and diamond are examples of other placer-mined commodities.

Sedimentary ore deposits also form by chemical precipitation; **banded iron formations (BIF)**, found in Precambrian shields, are examples (Figure 8). Banded iron formations include oxides, silicates, and carbonates of iron. They were deposited because of changes in the Earth’s

atmosphere more than two billion years ago and contain very old fossil algae. Iron is not the only commodity deposited by shallow seas. When a body of seawater is trapped, evaporation leads to precipitation of halite and other salts. Thick **evaporite deposits** of halite, sylvite, gypsum, and sulfur have formed in this way. Chemical precipitation of such salts is occurring today around the margins of the Great Salt Lake in Utah and other inland seas. In the past, evaporation of seas has led to economical borate deposits in California’s Mojave Desert and elsewhere. Nitrates and, more rarely, phosphates may also be deposited from water.

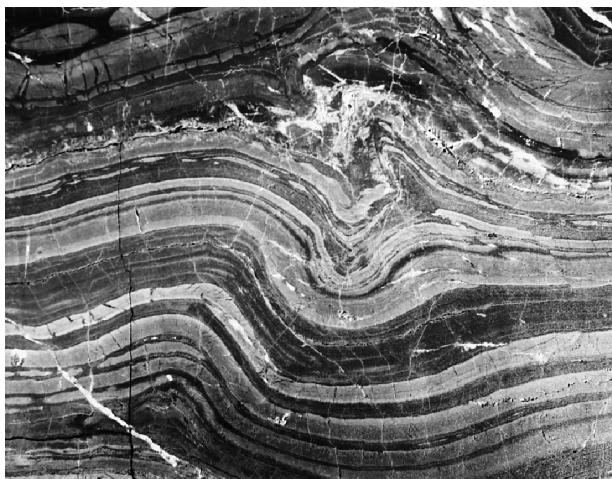
The weathering of preexisting rock may expose and concentrate valuable minerals. Over time, water leaches rocks and soils, dissolving and carrying away soluble material. The remains, called **residuum**, may be rich in aluminum, nickel, iron, or other insoluble elements. In tropical climates extreme leaching has produced soils called **laterites**, which are rich in aluminum or, sometimes, nickel. If aluminum-rich laterite lithifies to become rock, we term it *bauxite*. We mine laterites and bauxites from open pits to produce nickel and aluminum and, sometimes as a secondary commodity, iron. Leaching of rocks at great depth in the Earth may lead to deposition of economic minerals at shallower depths. We mine such deposits, called **supergene** deposits, for gold, silver, and sometimes copper.

## ORE MINERALS

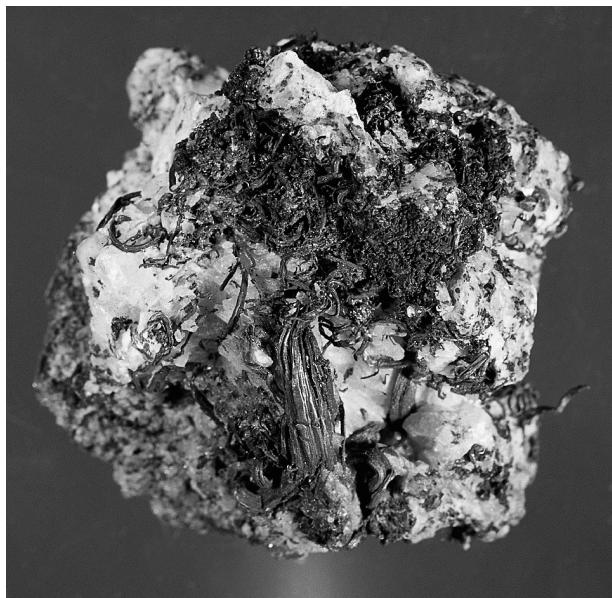
Most ore minerals fall into just four classes: native elements, sulfides and sulfosalts, oxides, and hydroxides. Table 2 contains examples of each. Minerals in these four classes contain relatively large amounts of elements of value. Furthermore, processing and element extraction are usually straightforward and relatively inexpensive.

### Native Elements: Metals, Semimetals, and Nonmetals

Native elements are highly valued because they may require no processing before being used in manufacturing, as currency, or for other purposes. The first metals ever used by humans were native minerals. Only later did humans develop refining techniques for the extraction of elements from more complex minerals. Ore geologists divide native elements into metals, semimetals, and nonmetals based on their chemical and physical properties.



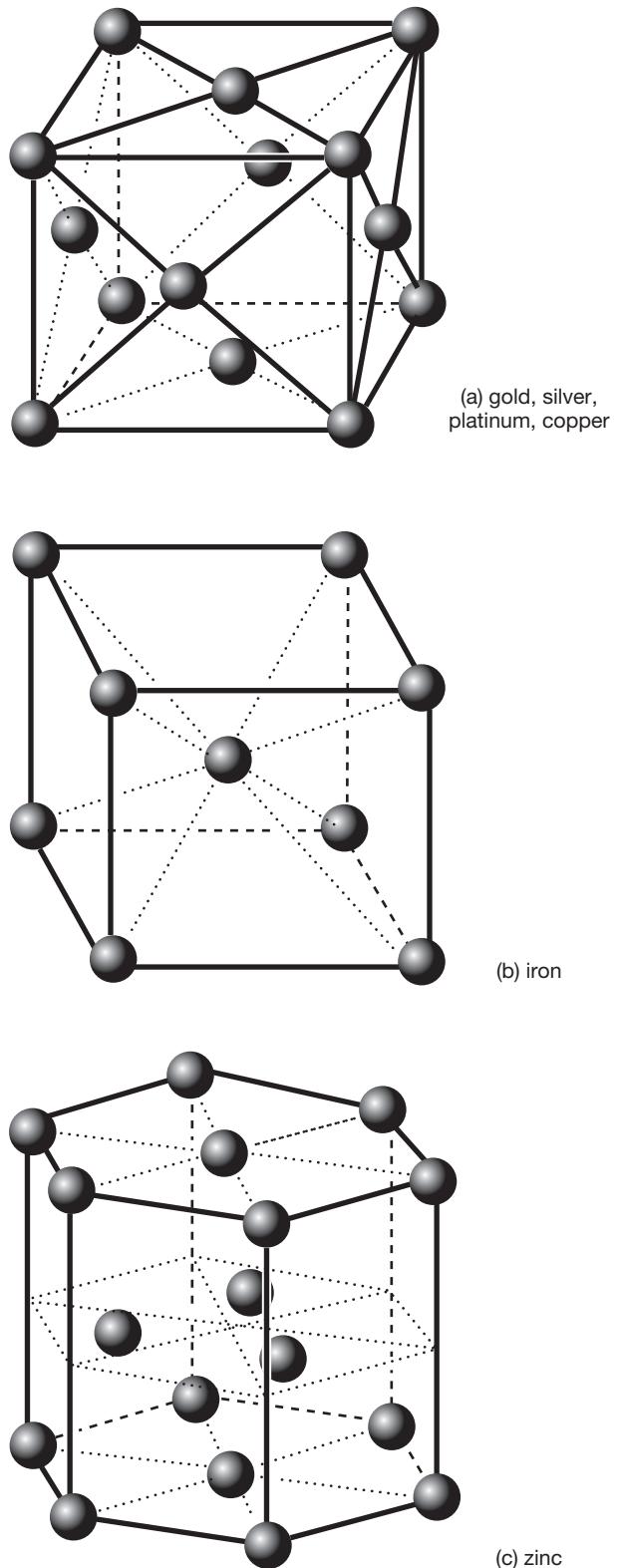
**FIGURE 8** Banded iron formation from near Hibbing, Minnesota. This sawn slab is about 20 cm wide.



**FIGURE 9** A 5-cm-wide sample with conspicuous arborescent native silver on quartz.

Within the metal group, the principal native minerals are gold, silver, copper, and platinum (Plates 7.7 and 8.7, Figure 9). These four minerals all contain weak metallic bonds. Gold, silver, and copper have further commonality in their chemical properties and are in the same column of the periodic table. One mineral, an Au-Ag solution called *electrum*, can even vary in composition from pure gold to pure silver. Since copper atoms differ in size from gold and silver atoms, solutions are limited between copper and the precious metals. Native gold, silver, and copper may contain small amounts of other elements. Native copper frequently contains arsenic, antimony, bismuth, iron, or mercury. Native platinum may contain small amounts of other elements, especially palladium. Native platinum is much rarer than gold, silver, or copper. The native semimetals arsenic, antimony, and bismuth are also rare.

Native copper, gold, silver, and platinum have atomic structures with atoms arranged in a cubic pattern (Figure 10). Iron does, too, although native iron is rare except in meteorites. Consequently, euhedral crystals may be cubic or octahedral. More typically, however, these minerals crystallize in less regular shapes (Figure 9). Copper is found as branching sheets, plates, and wires, and as massive pieces (Plate 7.7). Silver sometimes occurs in a wirelike or **arborescent** (tree-like) form (Figure 9). Gold, sometimes mined as nuggets or flakes (Plate 8.7), is also found as wires or scales. These are, however, unusual examples; most precious metals in ores are fine subhedral grains, often microscopic. Gold, silver, platinum, and copper all have similar



**FIGURE 10** The atomic structures of some native metals: (a) gold, silver, platinum, and copper have cubic structures with an extra atom at the center of each face; (b) iron has a cubic structure with an extra atom at the center of the cube; (c) zinc has a hexagonal structure.

**BOX 3****The Witwatersrand Gold Deposits**

Gold occurs in many different ore deposits. The world's largest, the Witwatersrand deposits of northeastern South Africa, dominate world production. The Witwatersrand deposits are paleo-placer deposits, meaning that they were placers when originally deposited. They occur in an area about 100 by 40 km (60 by 25 mi.). The size of the Witwatersrand deposits is puzzling because placers form when hard-rock deposits are eroded and sedimentary processes concentrate ore. Yet today there are no hard-rock gold deposits of anywhere near sufficient size to account for the volume of the Witwatersrand placers.

The Witwatersrand deposits were discovered in 1886. The discovery led to the founding of Johannesburg, a central town in frontier South Africa. When miners reached a zone of pyrite in 1889, the new town began to die because it was not known how to extract gold from sulfides at that time. In the early twentieth century, three Scotsmen discovered the **cyanide method** for gold extraction, and Johannesburg flourished once more.

atomic structures; iron's is different, although still cubic. In contrast, native zinc, a very rare mineral, has a hexagonal atomic arrangement (Figure 10).

Most hard-rock gold and silver deposits are in quartz-rich hydrothermal veins. Pyrite (fool's gold) and other sulfides are often associated with native gold and silver in the veins (Figure 11). Besides hard-rock deposits, gold and silver are also found in placers (Box 3), and native silver is found in several other types of deposits. We mine native platinum primarily from ultramafic igneous rocks, but platinum is also found in placers or is produced as a secondary product of Cu- or Ni-sulfide refining. Native copper occurs in a variety of ore deposits associated with mafic volcanics and in some sandstones.

Graphite, diamond, and sulfur are examples of nonmetallic native elements; both graphite and diamond consist of carbon. Graphite (Figure 12a) is common as a minor mineral in many kinds of metamorphic rocks, including marbles, schists, and gneisses. The origin of the carbon is usually organic

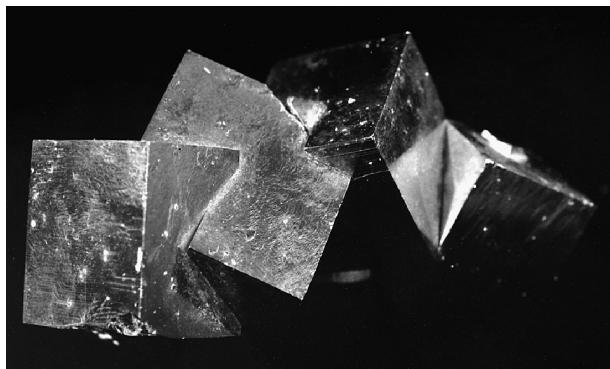
material in the original sediments. Graphite also occurs in some types of igneous rocks and in meteorites. Native sulfur is associated with volcanoes, often concentrated by fumaroles. It is also found in veins associated with some sulfide deposits and in sedimentary rocks associated with halite, anhydrite, gypsum, and calcite. Native sulfur deposits only account for about half the world's supply. Most of the rest is separated from sulfides during processing to recover metals.

Diamond (Figure 12b) only forms at very high pressures associated with the lowermost crust or mantle of the Earth. We mine it from kimberlite pipes, where rapidly moving, sometimes explosive, mafic magmas have carried it up to the surface. After formation, diamond sometimes concentrates in river and streambeds where we mine it from placer deposits. Although some diamonds are of gem quality, most are not. We call lower-quality diamonds **bort**.

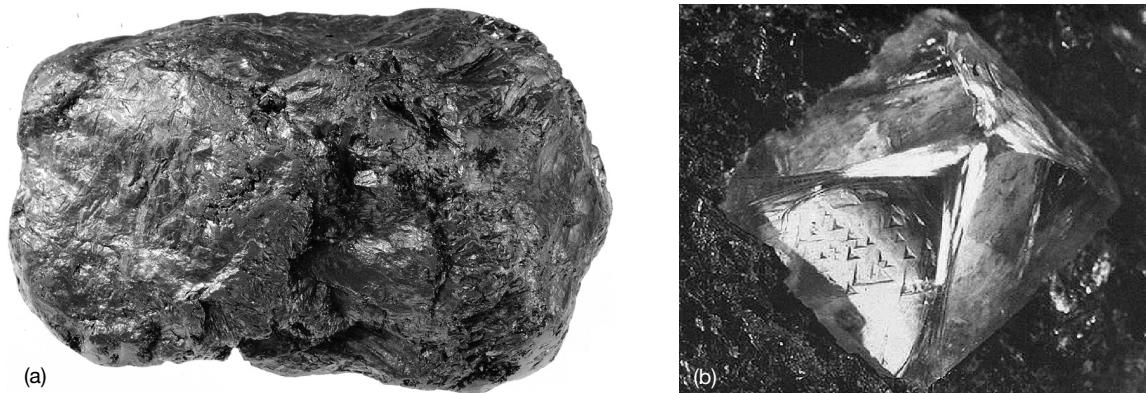
**Sulfides and Sulfosalts**

True sulfide minerals (such as pyrite, Figures 11 and 13) contain one or several metallic elements and sulfur as the only nonmetallic element. Some examples are shown in Plates 7.1 through 7.6, 7.8, 8.1, and 8.2. Bonding is either covalent, metallic, or a combination of both. Other minerals grouped with the sulfides, because of similar properties, contain selenium (the selenides), tellurium (the tellurides), or bismuth instead of sulfur. A related group of minerals, the sulfosalts, contain the semimetals arsenic and antimony in place of metal atoms. Many of the sulfides and related minerals have similar atomic structures, so solid solutions are common. Although many sulfides and sulfosalts are found in nature, only a few are abundant.

Sulfide minerals often form distinct **associations**. Pyrite, sphalerite, and pyrrhotite are frequently found together, as are chalcopyrite, pyrite, and bornite or pyrrhotite. In some carbonate-hosted deposits, sphalerite and galena occur together. We can depict sulfide associations using triangular composition diagrams such as the diagram shown in Figure 14.



**FIGURE 11** Pyrite crystals. Although called "fool's gold," pyrite can be distinguished from gold because gold has a duller, more butter-yellow color than pyrite. Spectacular samples of pyrite, such as the one shown here, contain perfect cubic crystals, often twinned (multiple crystal domains sharing atoms) or in aggregates.



**FIGURE 12** Both graphite (a) and diamond (b) are essentially pure carbon. They are different minerals, because the carbon atoms are not bonded together in the same way in both.  
Diamond photo from J. Banfield, used by permission.

The tie lines (straight lines joining two compositions, such as the line from sphalerite to pyrite) in that figure indicate that in Fe-Zn-S ore, the ore-mineral association will be either pyrite-sphalerite-sulfur, pyrite-sphalerite, or pyrite-pyrrhotite-sphalerite, depending on the amount of elemental sulfur present. Box 4 presents a more detailed discussion of Cu-Fe-S ore minerals and explains how we can use triangular diagrams to show solid solution compositions.

### Oxides and Hydroxides

We often group oxides and hydroxides together because they have similar compositions and atomic structures (Table 3). They often have similar properties, and most have relatively simple and related formulas. Oxide minerals consist of one or several metal ions bonded to  $\text{O}^{2-}$ . Hydroxide

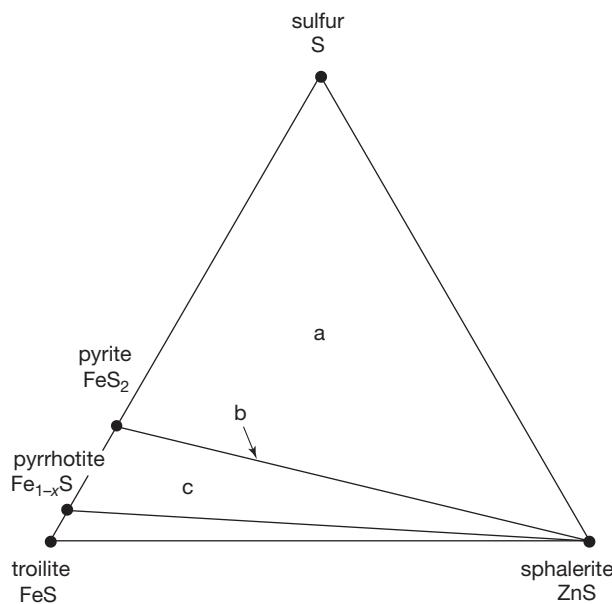
minerals contain  $(\text{OH})^-$  anions in place of all or some of the  $\text{O}^{2-}$ .

A primary difference between oxides and hydroxides is the temperatures at which they form and are stable. Hydroxides are unstable at high temperature; they exist in low-temperature environments and are commonly products of alteration and weathering. We usually group quartz, the most common oxide, with silicate minerals. Other oxide minerals—magnetite and ilmenite, for example—are high-temperature minerals generally associated with igneous or metamorphic rocks. In fact, most igneous and metamorphic rocks contain oxide minerals. Typically they are present in minor amounts, are easily overlooked, and may be difficult to identify.

Oxides and hydroxides have properties distinct from silicates and sulfides. They are dominated by ionic bonding, and anions ( $\text{O}^{2-}$  or  $\text{OH}^-$ ) do not



**FIGURE 13** Pyrite is one of the most common sulfide minerals and often forms spectacular cubic crystals. In this photo, the cubes (about 1 cm on a side) have growth striations on their faces. Prismatic quartz crystals can also be seen.



**FIGURE 14** Triangular diagram for the system FeS-ZnS-S showing the principal end-member minerals (solid dots). Triangles and lines indicate possible mineral assemblages. Most Fe-Zn-S ores contain assemblages of sulfur-pyrite-sphalerite (triangle a), pyrite-sphalerite (line b), or pyrite-pyrrhotite-sphalerite (triangle c). Troilite is rare in terrestrial rocks but is common in some meteorites.

control their structure and properties as they do for other mineral groups. Oxides and hydroxides also have properties distinct from carbonates, sulfates, and other ionic minerals that have high solubilities in water.

Examples of oxide and hydroxide minerals are given in Table 3. Simple oxides contain one metal element and have formulas  $R_2O$ ,  $RO$ , or  $R_2O_3$ , where R is the metal cation. The different formulas reflect different valences of the metals. More complex oxides contain two different metal cations and have formulas  $XYO_3$  or  $XY_2O_4$ , where X and Y denote the metals. Oxides with general formula  $XY_2O_4$  (spinel, chromite, and franklinite in Table 3) belong to the spinel group; they all have similar atomic structures. Magnetite, with a formula that can be written  $FeFe_2O_4$ , also has a spinel structure and belongs to this group.

## GEMS AND GEM MINERALS

**Gems** are precious or semiprecious stones and related substances that can be cut or polished to be used for ornamentation. Gems may be natural or synthetic; the term *gemstone* is sometimes used to refer to gems that are minerals. It is not the composition of gems that makes them valuable, but rather their appearance. Most gems are varieties of common minerals, but they exhibit spectacular color, clarity, brilliance, or fire. Some gems, such as opal, show a **play of color**. Cutting and polishing enhance these desirable features. We value gems such as amber or pearls—which we call gems although they are not minerals—for their unique lusters. The hardest gems are most highly valued because they are most durable. Others are prized because of their rarity.

**TABLE 3 Examples of Oxide and Hydroxide Minerals**

Oxide Minerals		Hydroxide Minerals		
Oxides/Hydroxides Containing One Metal Element				
Al minerals	corundum	$Al_2O_3$	gibbsite diaspore	$Al(OH)_3$ $AlO(OH)$
Mg minerals	periclase	$MgO$	brucite	$Mg(OH)_2$
Fe minerals	magnetite hematite	$Fe_3O_4$ $Fe_2O_3$	goethite lepidochrosite	$FeO(OH)$ $FeO(OH)$
Mn minerals	pyrolusite	$MnO_2$	manganite	$MnO(OH)$
Zn minerals	zincite	$ZnO$		
Ti minerals	rutile	$TiO_2$		
Sn minerals	cassiterite	$SnO_2$		
Oxides Containing Two Metal Elements				
Fe-Ti oxide	ilmenite	$FeTiO_3$		
Mg-Al oxide	spinel	$MgAl_2O_4$		
Fe-Cr oxide	chromite	$FeCr_2O_4$		
Zn-Fe oxide	franklinite	$ZnFe_2O_4$		

**BOX 4****Another Look at the Phase Rule and Cu-Fe-Sulfide Minerals**

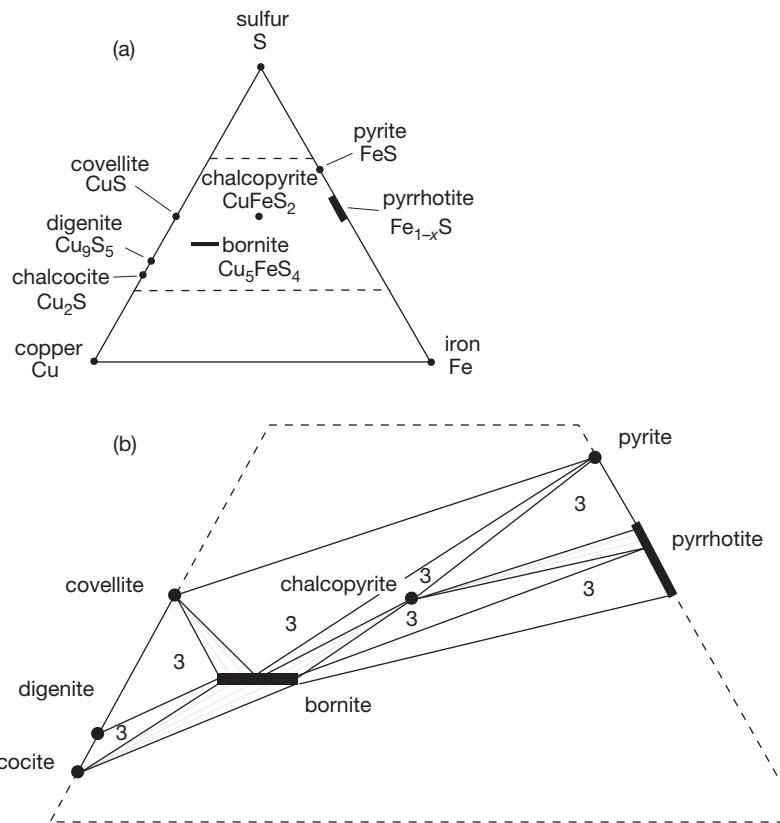
We use triangular diagrams to plot the compositions of ore minerals and to show ore mineral assemblages, just as we did for metamorphic and igneous minerals. The phase rule tells us that the number of chemical components ( $c$ ) in a system is related to the number of degrees of freedom ( $f$ ) and the number of minerals ( $p$ ) by:

$$c + 2 = p + f$$

Figure 15a is a ternary diagram showing the Cu-Fe-S system ( $c = 3$ ), and the 10 principal minerals within that system. The center of the diagram is enlarged in Figure 15b. Minerals such as chalcopyrite that do not vary much in chemical composition appear as points on the diagrams. Bornite and pyrrhotite, which have variable compositions, appear as bars. The lengths of the bars indicate the range of compositions possible for each mineral.

Tie lines connect minerals that coexist in ore deposits formed at a variety of pressures and temperatures. Normally,  $P$  and  $T$  may vary,  $f = 2$ , and the phase rule tells us that up to three minerals may be stable together. Possible three-mineral assemblages are shown as triangles (with "3" inside) in Figure 15b. Several two-mineral assemblages are also stable. For example, several tie lines connect chalcopyrite with the pyrrhotite bar, showing that chalcopyrite may coexist with different pyrrhotite compositions to make a two-mineral assemblage. Other possible two-mineral assemblages are chalcopyrite-bornite, bornite-chalcocite, and covellite-bornite.

Cu-Fe sulfide mineralogy is complex because many minerals have similar compositions. Figure 15b shows there are more than 10 possible assemblages. The assemblage present in a specific deposit depends on the Cu:Fe:S ratio. In Fe-poor ore deposits, for example, sulfide assemblages will include covellite, digenite, or chalcocite, but not pyrite or pyrrhotite. Diagrams such as Figure 15 are useful ways to describe complex mineral relationships without words, and we use them to predict and interpret ore deposit mineralogy.



**FIGURE 15** (a) A ternary diagram showing the Cu-Fe-S system and the 10 principal minerals within that system; (b) an enlargement of part of the ternary diagram. See text for explanation.

Many natural materials, including minerals and nonminerals, have been used as gems. Because gemstones have different appearances than common minerals, many have names different from the mineral names. Diamond, emerald (a variety of beryl), and ruby

(a variety of corundum) have been, historically, the most valuable gemstones. Sapphire (another variety of corundum) and alexandrite (a variety of chrysoberyl) are nearly as valuable. Table 4 presents a list of some common gems and the countries that produce them.

**TABLE 4** The Most Common Gemstones in Approximate Order of Importance

Mineral	Gem	Most Important Producing Countries
diamond	diamond	Australia, South Africa, Namibia, Russia
beryl	emerald aquamarine	Colombia, Brazil, Russia, Egypt, East Africa Brazil, Afghanistan, Pakistan
corundum	ruby sapphire	Cambodia, Myanmar, Afghanistan, India Australia, Thailand, Sri Lanka, Brazil
opal	opal	Australia, Hungary, Mexico
jadeite	jade	Myanmar, China
chrysoberyl	alexandrite	Russia, Brazil
quartz	amethyst citrine	Russia, Sri Lanka, India, Uruguay, Brazil Many locations
topaz	topaz	Brazil, Sri Lanka, Russia, India
tourmaline	tourmaline	Namibia, Brazil, United States, Russia
turquoise	turquoise	United States, Egypt, Australia
tremolite-actinolite	nephrite jade	Russia, China, Taiwan, Canada
olivine	peridot	Egypt, Myanmar, Australia
zircon	zircon	Sri Lanka

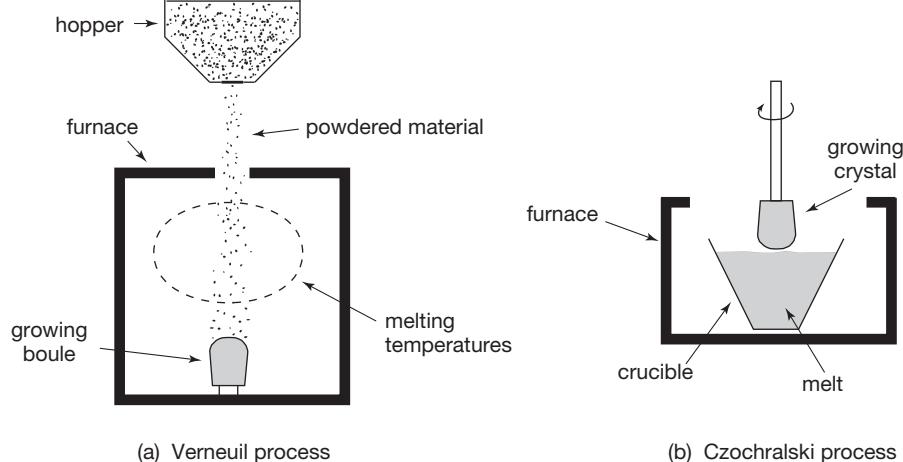
Only one or two countries dominate production of many gems, including diamond (Box 5). Plate 8.5 shows some examples of minerals that are gems.

### Synthetic Gems and Color Alteration

Although by definition minerals must be natural, we can synthesize equivalents of them in the laboratory. However, most “synthetic minerals” are so fine grained they are unusable as gems. The exceptions to this are some synthetic beryl, chrysoberyl, corundum, diamond, garnet, opal, quartz, rutile, spinel, and turquoise. Several synthetic compounds with no natural equivalents are

also used as gems. Foremost among them are yttrium aluminum garnet (YAG) and cubic zirconia (CZ), both used as imitation (or “genuine *faux*” from the French for “fake”) diamonds. Besides their value as gems, synthetic minerals are often important in such industrial applications as laser optics.

Synthetic minerals are made by several different methods. The Verneuil technique and the Czochralski process both involve crystallizing gems from molten material (Figure 16). In the more common Verneuil technique, powdered chemicals pass through a hot flame and crystallize as a **boule**, a single elongated crystal. This technique produces large synthetic rubies,



**FIGURE 16** (a) Verneuil process: Fine powder passes from the hopper through a sieve with the aid of a tapper and then is melted in a flame fed by oxygen and hydrogen. The melt falls on a boule and, as the boule crystallizes, it is slowly lowered in the furnace. (b) Czochralski process: A crucible is filled with powder and heated in a furnace so the powder melts. A rod with a seed crystal attached to the bottom end is lowered until it touches the melt and is rotated and slowly withdrawn, “pulling” the crystal from the melt.

**BOX 5****The World's Major Diamond Producers**

Until recently, the largest diamond-producing countries were in Africa. During the last decade, diamond production has increased in Australia and Russia; both now produce more diamonds than any African nation. Most diamonds are mined from **alluvium** (sediments deposited by flowing water), some from glacial tills, and some from igneous intrusions called *kimberlite pipes*. Diamonds have also been identified in some rare high-pressure metamorphic rocks, but generally in uneconomical quantities. Geologists believe that kimberlites were the primary sources of most of the world's diamonds; they infer that diamonds in alluvium and glacial till originated in kimberlites that were subsequently weathered, transported, and deposited.

Besides Australia and Russia, other major diamond producers are Zaire, Botswana, and South Africa. Together, these five countries produce about 111 million carats a year, equivalent to 22,000 kg (49,000 lbs.). About half the diamonds they produce are gem quality; the other is of a low quality called *bort*, which is used as an abrasive and grinding agent in industrial applications.

The largest producers of *gem-quality* diamonds are Australia, Russia, Angola, South Africa, and Namibia. In South Africa some of the diamond production comes from volcanic pipes, including the pipe at Kimberley (from which the rock name *kimberlite* is derived). Gem-quality diamonds are mined from pipes in many other places, including Tanzania, which has the largest pipe mine in Africa. In recent years there has been a renewed interest in diamond mining in North America, mostly in Canada's Northwest Territories where the Ekati Mine, North America's first diamond mine, started operations in 1999.

sapphires, spinels, and other gems. The synthetic rubies are used in lasers. In the Czochralski process, a seed crystal is placed in contact with a melt and allowed to grow. Rubies up to 40 cm (16 in.) long have been grown using the Czochralski process.

A third approach, the **flux method**, has sometimes yielded large synthetic crystals, notably quartz, ruby, sapphire, alexandrite, and emerald. Flux is a material that promotes reaction and crystal growth but is not incorporated in crystal structures. A mixture of chemicals—including those needed to make the desired mineral and others to act as the flux—is ground together and heated above its melting point. As the temperature is lowered, crystals begin to grow. After the melt solidifies, water or other reagents remove the flux, leaving the desired crystals. Most synthetic rubies and emeralds are created this way.

Mineralogists use other synthesis techniques, but with a few exceptions they do not produce gems of great value. Synthetic minerals may be grown from hydrothermal solutions in high-pressure reactor vessels called **bombs**. Synthetic quartz, ruby, and emerald have all been made this way. Synthetic diamond and a few other high-pressure crystals are made using a **solid state** (no melt or water) approach. A cylinder of starting material, enclosed in a graphite heater, is squeezed between two pistons. Electricity passing through the graphite heats the material to temperatures at which crystals will grow. Chemists at General Electric have perfected this technique for making gem-quality synthetic diamonds.

Gems and other minerals derive their color from many different things. Common minerals may have little value as gems, but if we can alter or enhance colors, even common quartz may become valuable. Gemologists, therefore, often treat gems and

minerals, natural or synthetic, to change their color and increase their value. For instance, quartz crystals from the Hot Springs area of Arkansas are irradiated to disrupt their atomic structure and give them a smoky or black coloring (Figure 17). Irradiation is also used to induce color changes in diamond and topaz. Gem color can also be changed through dyeing or heat treatment, although dyeing only affects gems that are porous, such as jade and chalcedony. Gemologists have successfully used heat treatment—which changes elemental valences or alters atomic structures—on quartz, beryl, zircon, and topaz, although the results are not always predictable.

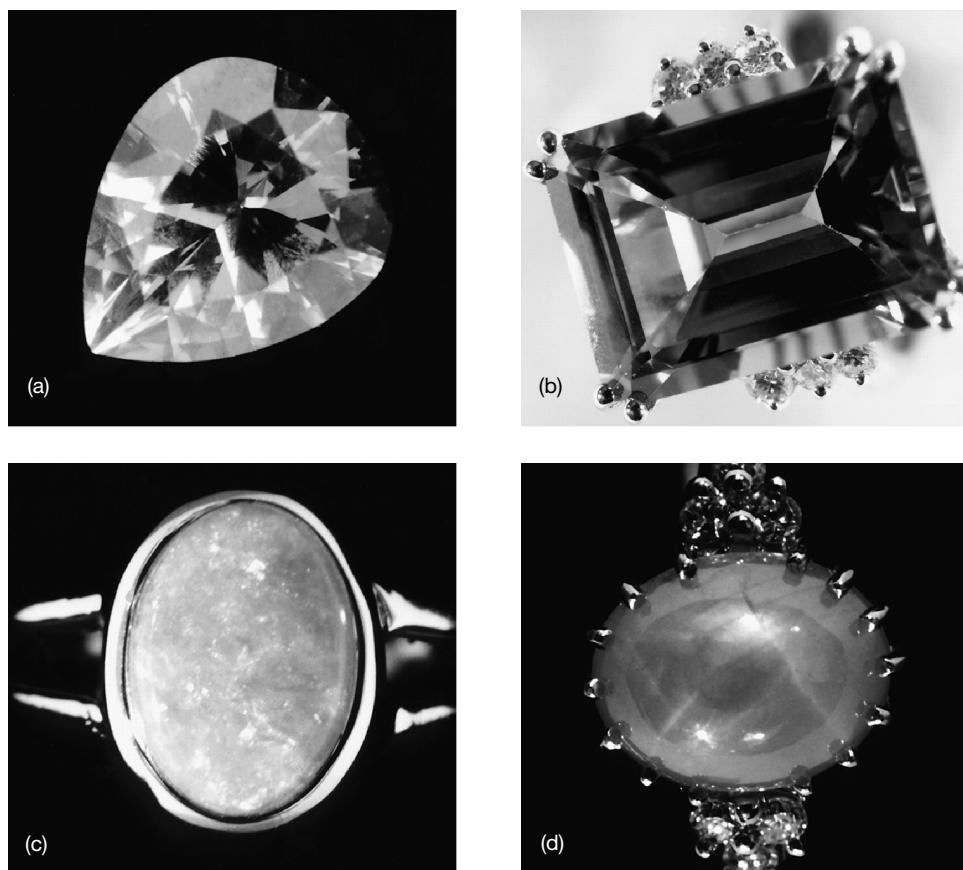
**Cutting and Polishing Gems**

Most gems are sold in shapes that do not resemble natural crystals (Figures 18a and b). Ruby, a red variety of corundum, generally grows as hexagonal crystals, but when rubies are incorporated into jewelry, gem cutters shape and polish them to increase their beauty and value. The cutting of a gem affects its value as much as the quality of the raw material. Cutting and polishing takes place in many parts of the world. Israel and Belgium dominate diamond cutting; the United States, India, Hong Kong, Thailand, and Brazil also cut significant amounts of various gems.

Gemologists shape and cut gems in several ways. Some minerals, including agate, opal, chalcedony, and onyx, are **tumbled** in a cylinder with a polishing/abrading agent. The cylinder rotates until the stones have smooth surfaces. They become polished, but often have irregular shapes. Alternatively, gemologists shape gemstones using a **cabochon** cut, with a smooth, domed top and, usually, a flat base (Figures 18c and d). Cabochons are shaped using a wet



**FIGURE 17** Quartz from near Hot Springs, Arkansas. The quartz is colorless and clear when mined (left) but after irradiation it becomes artificially smoky or black quartz (right).



**FIGURE 18** (a) Tourmaline faceted to produce a pear shape; (b) topaz faceted with an "emerald" cut; (c) an opal cabochon showing play of light; (d) a star sapphire cabochon showing play of light. These photos are black and white, but the tourmaline is really pink, the topaz is blue, the opal has rainbow colors, and the sapphire is grey.

**BOX 6****Mining, the Environment, and Politics**

Mining, especially public land mining, is a controversial environmental issue. The 1872 Mining Law gives U.S. citizens and corporations the right to stake claims and mine public lands if they can show that the mining is profitable. The claims last forever, provided miners invest \$100 in the property each year. Claim holders have the right to purchase the surface and mineral rights at very low cost through a process called *patenting*, often at \$5 an acre or less. Miners pay no royalties, in contrast with those who develop coal, oil, or gas on public lands. In 1999, mining corporations took more than \$1 billion worth of minerals from public lands without paying anything back to taxpayers. So, the 1872 law really is a federal subsidy for mining.

Many environmental groups want to see Congress change the 1872 law. They argue that public lands are for the public, not mining corporations, and they point out that mining is incompatible with other uses such as wildlife habitat, hiking, and camping. Furthermore, mining leaves scars on the land and may cause long-term environmental degradation. According to a 1998 article in the journal Environmental Law, "there are over 550,000 abandoned hard-rock mines, most of which have been left for government-funded clean-up efforts at an estimated cost of \$32 to \$72 billion."

The mining industry argues that we need the 1872 law to ensure a flow of mineral resources to our citizens. They point out the importance of mining to some local western economies, and say they can mine in an environmentally friendly way. They also accuse many mining opponents of having a "NIMBY" (not in my backyard) mentality.

The mining industry is correct when they argue that we need mineral resources and they have to come from somewhere. Despite industry's claims, however, mining always has a cost to the environment. A visit to active or abandoned mines confirms this. Besides scars on the land, less obvious problems include air, water, and soil pollution. All these problems can be limited, but not eliminated, by following the best mining practices.

In today's industrial world we need mineral resources. The real questions are where are they going to come from and how much are we willing to pay? Those who seek reform of the 1872 law argue that some areas should be off limits to mining, that mining companies should pay more in royalties, and that there should be strict antipollution and land reclamation requirements. If enacted by Congress, these changes might affect the price of mineral commodities, but most economists think the effect would be very small.

grinding wheel. Softer minerals are ground with a quartz sandstone wheel; harder ones require wheels impregnated with diamonds. As a final step, cabochons are finely polished. Until the Middle Ages, most gems were cut *en cabochon* (Figures 18c and d).

While most soft gemstones receive a cabochon cut, many hard gemstones are faceted. **Facets** are small, polished, planar surfaces that give the stones

attractive shapes and light properties. With proper cutting, originally dull stones can sparkle. Facets are usually symmetrically arranged in geometric shapes (Figures 18a and b). Gemologists create them by mounting the stones on a holder, called a **dop**, and grinding the stone with a diamond-impregnated wheel. As with cabochons, they are polished after being ground.

### **Questions for Thought**

*Some of the following questions have no specific correct answers; they are intended to promote thought and discussion.*

1. Why are some minerals valuable as ore minerals, while others are not? In particular, why do many ore minerals belong to the sulfide, oxide, and native element groups?
2. In comparison with many other elements, such as tin, aluminum requires a low concentration factor to be economically mined. Why? What are the main factors that dictate economical concentration factors?
3. Why are actively mined ore deposits unevenly distributed around the world?
4. What kinds of minerals would you expect to find in cumulate deposits? Give examples. Why these minerals and not others?
5. What kinds of minerals would you expect to find in hydrothermal deposits? Give examples. Why these minerals and not others?
6. What kinds of minerals would you expect to find in placer deposits? Give examples. Why these minerals and not others?
7. What kinds of minerals would you expect to find in evaporite deposits? Give examples. Why these minerals and not others?
8. The crystal structures of copper, gold, silver, platinum, and iron are all similar. Why?
9. Most diamonds are not mined from the original rocks in which they formed. Where do diamonds come from and how do they become concentrated where we mine them?
10. Why do ore deposits typically contain few ore minerals?
11. What are the properties that make a gem valuable?
12. Some mineralogists would argue that synthetic gems are inferior to natural ones. Are they just being snobs? What, if any, real differences are there between synthetic and natural gems? What is the origin of such differences?

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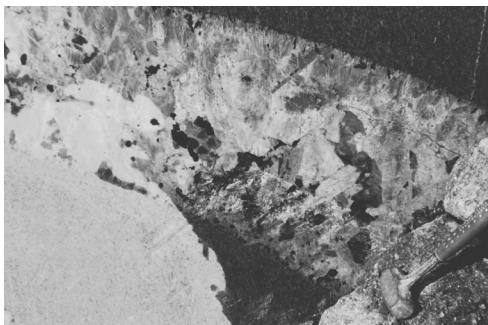
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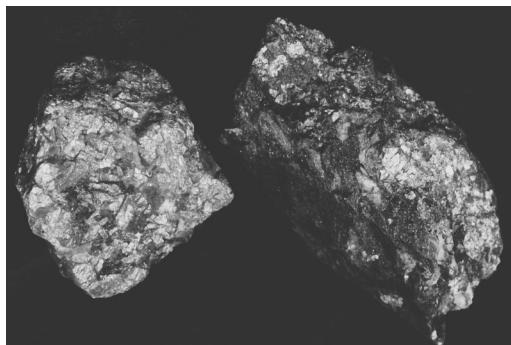
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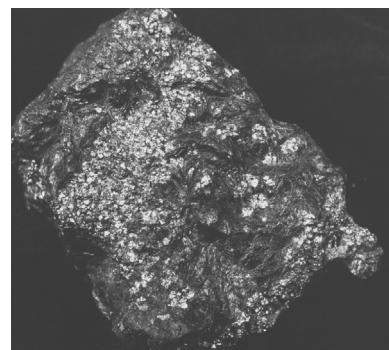
**PLATE 1.4** Small pegmatite exposed in Larvikite quarry near Larvik, Norway.



**PLATE 7.1** Acicular boulangerite from the Noche Buena Mine, Zacatecas, Mexico.



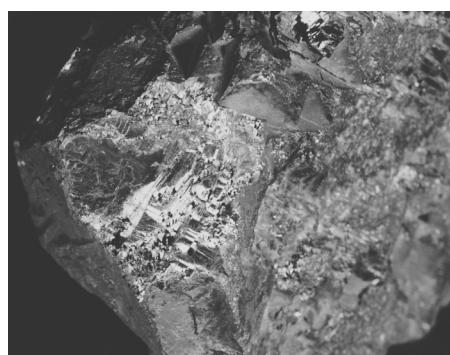
**PLATE 7.2** Arsenopyrite in a biotite schist from the Homestake Mine, Lead, South Dakota.



**PLATE 7.3** Covellite (purple tarnish) and pyrite (gold) from Sudbury, Ontario, Canada.



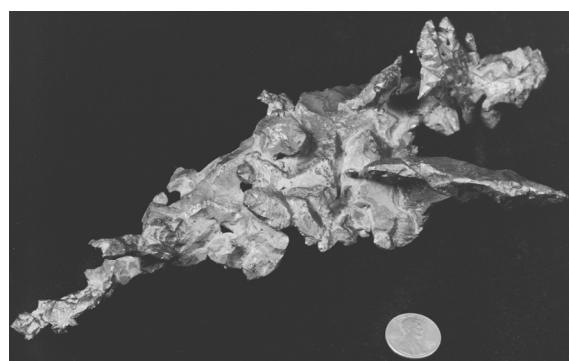
**PLATE 7.4** Sphalerite from Tennessee.



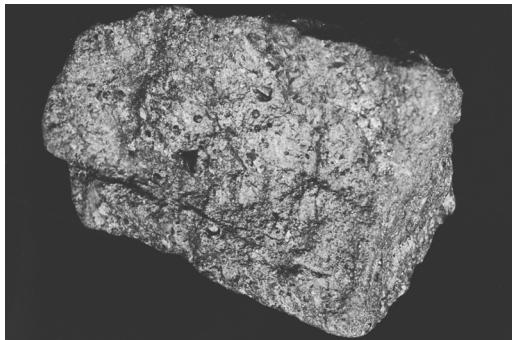
**PLATE 7.5** Galena in ore from Joplin, Missouri.



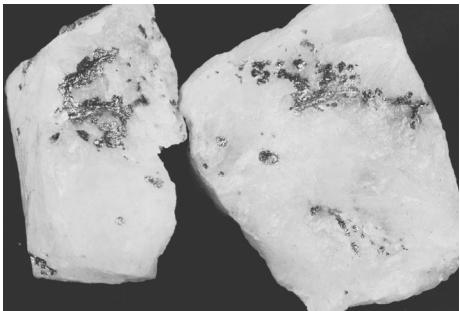
**PLATE 7.6** Orpiment (yellow) and realgar (orange-pink).



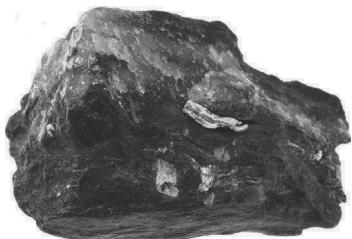
**PLATE 7.7** Native copper from the Keweenaw Peninsula, Michigan.



**PLATE 7.8** Chalcopyrite from Timmins, Ontario, Canada.



**PLATE 8.2** Molybdenite in quartz.



**PLATE 8.7** Gold ore from Montana. This specimen, 5 cm across, contains visible gold flakes, wires and stringers. It is exceptionally high-grade gold ore.

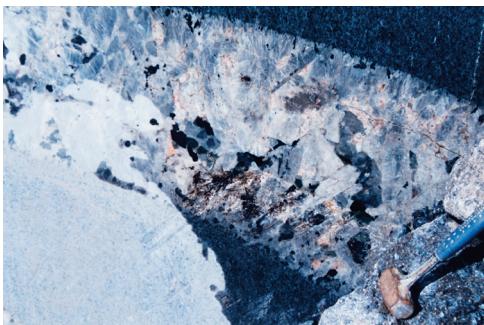


**PLATE 8.1** Pentlandite (silver) with minor pyrrhotite (yellow-gold) from Cobalt, Ontario, Canada.



**PLATE 8.5** A collection of gem minerals. Back row, left to right: blue aquamarine (beryl), topaz, pink tourmaline; middle row: yellow beryl, blue-green tourmaline, red ruby (corundum); front row: emerald (beryl), kunzite (a variety of spodumene), yellow sapphire, blue sapphire.

# Ore Deposits and Economic Minerals Color Plates



**PLATE 1.4** Small pegmatite exposed in Larvikite quarry near Larvik, Norway.



**PLATE 7.1** Acicular boulangerite from the Noche Buena Mine, Zacatecas, Mexico.



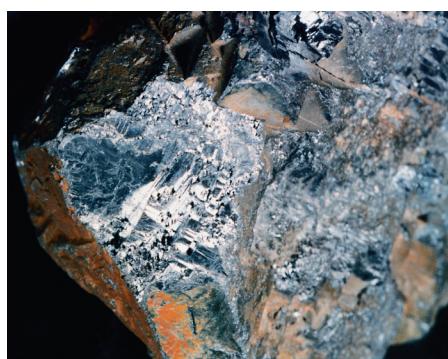
**PLATE 7.2** Arsenopyrite in a biotite schist from the Homestake Mine, Lead, South Dakota.



**PLATE 7.3** Covellite (purple tarnish) and pyrite (gold) from Sudbury, Ontario, Canada.



**PLATE 7.4** Sphalerite from Tennessee.



**PLATE 7.5** Galena in ore from Joplin, Missouri.



**PLATE 7.6** Orpiment (yellow) and realgar (orange-pink).



**PLATE 7.7** Native copper from the Keweenaw Peninsula, Michigan.



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# Crystal Morphology and Symmetry

This chapter is about symmetry. The symmetry of an entity is the relationship between its parts. The symmetry of a crystal is a reflection of internal atomic arrangement. The way in which atoms are arranged in an atomic structure dictates the way a crystal's properties are distributed. If a crystal has symmetry, the symmetry is common to all of its properties. Crystal faces, magnetic properties, optical properties, and others must all be distributed in the same way. Consequently, by studying physical properties to determine crystal symmetry, crystallographers can make inferences about internal atomic order. Although crystals may have any of an infinite number of shapes, the number of possible symmetries they may have is limited. In this chapter we discuss crystal symmetry and its relationship to crystal shape.

## SYMMETRY

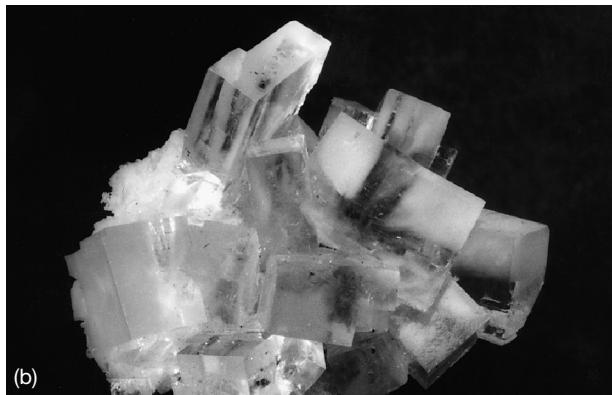
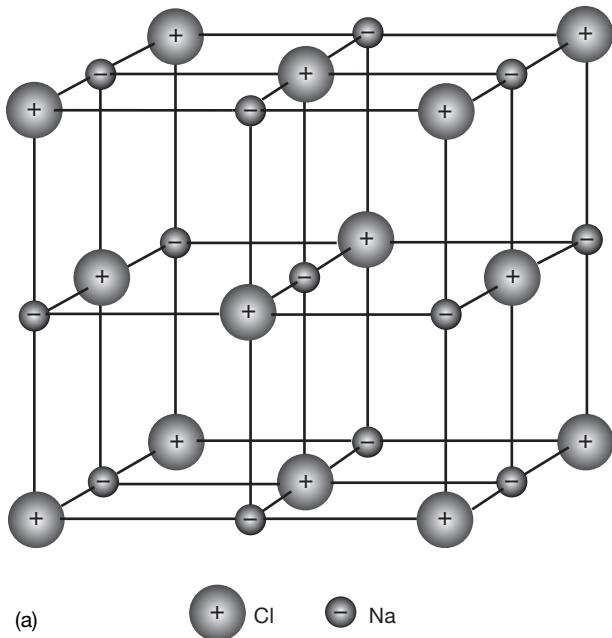
The external shape of a crystal reflects its internal atomic arrangement. Of most importance is a crystal's **symmetry**. As defined by Aristotle, symmetry refers to the relationship between parts of an entity. Zoltai and Stout (1984) give an excellent practical definition of symmetry as it applies to crystals: "Symmetry is the order in arrangement and orientation of atoms in minerals, and the order in the consequent distribution of mineral properties." Figure 1 shows the relationship between halite's atomic structure and its typical crystal shape. A cubic mineral, such as halite, can occur as a cubic crystal with six identical faces because its atoms are arranged in a cubic pattern with identical structure in three perpendicular directions. Although the relationship between atomic structure and crystal shape shown in the figure may seem clear, the relationship is not always so simple. In fact, many cubic halite samples are cleavage fragments from larger crystals with complex shapes.

Looking for symmetry in natural materials can be complicated. Although crystal structures may be

symmetrical, many things control crystal growth, so crystals may not reflect their internal order. Sometimes few or no crystal faces may form. Sometimes several different crystals may become intergrown. Sometimes crystals contain structural imperfections, and other crystals may be too small to see clearly. An experienced eye and an active imagination are often necessary to see the symmetry of a crystal.

## Mirror Planes

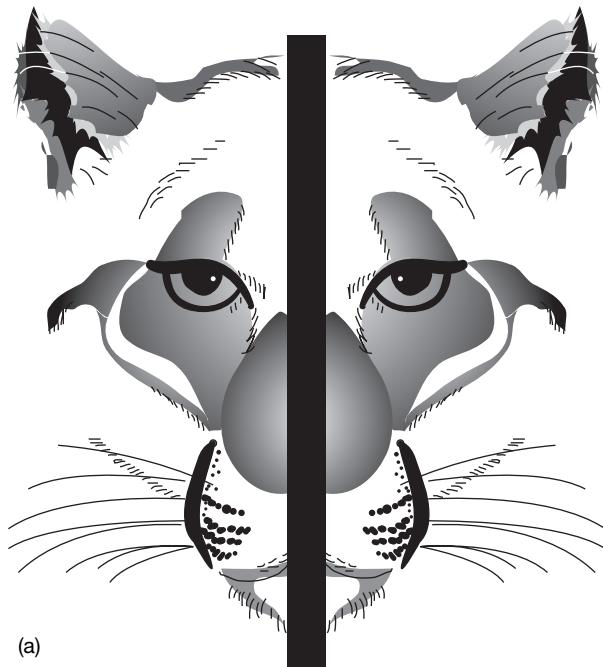
Most animals, including humans, appear symmetrical: an imaginary mirror down their center relates the appearance of their right side to their left side (Figure 2). We call such symmetry **reflection**, and we call the plane of the imaginary mirror the **mirror plane**. In shorthand notation, we use the letter *m* to designate a mirror of symmetry. Reflection is the symmetry **operation**, and the mirror plane is the symmetry **operator**. Reflection often relates identical faces on a crystal. A face, or any object, on one side of a mirror has an equivalent at an equal distance on



**FIGURE 1** (a) The atomic structure of halite showing the cubic arrangement of  $\text{Na}^+$  and  $\text{Cl}^-$  ions. (b) Cubic halite crystals.

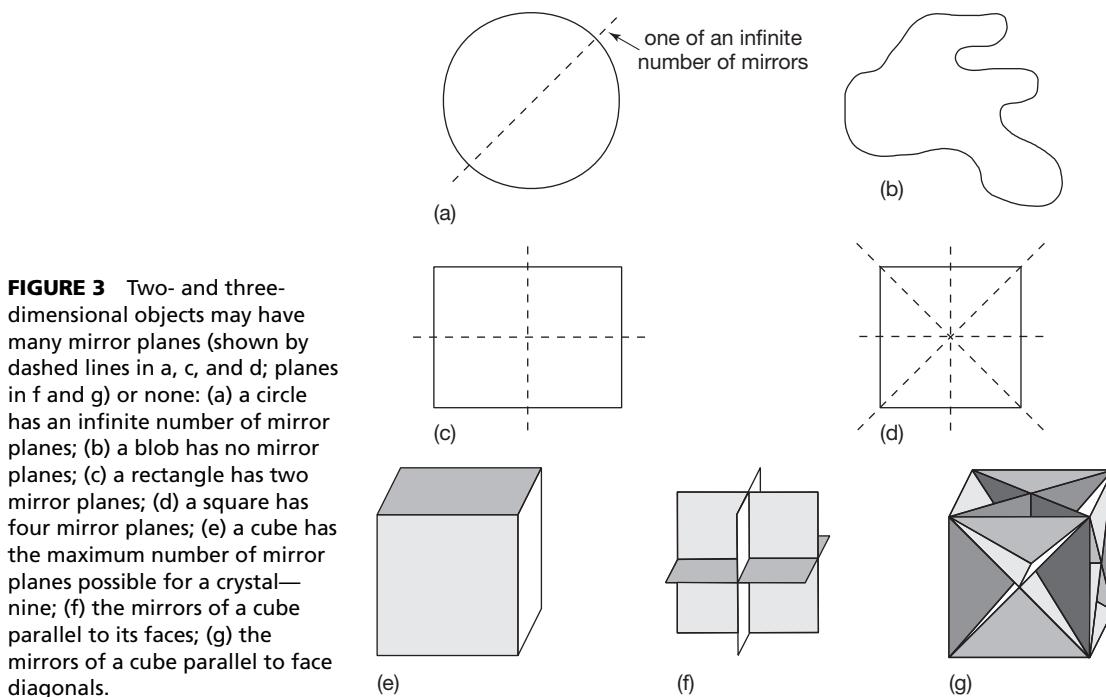
the other side of the mirror. The two faces or objects are the same perpendicular distance from the mirror and have opposite “handedness”; if one points to the right, the other points to the left.

Two-dimensional drawings may have many mirror planes or no mirror planes. Circles, for example, contain an infinite number of mirror planes; any line drawn through the center of the circle is a mirror of symmetry (Figure 3a). Irregular blobs, on the other hand, have no mirror planes (Figure 3b). Rectangles have two mirror planes, while squares have four (Figures 3c and d). Three-dimensional objects, too, may have zero to many mirror planes. A perfect sphere has an infinite number of mirror planes, but, as we will see later, crystals cannot have more mirror planes than a cube. Cubes have nine mirrors (Figures 3e–g). Three are



**FIGURE 2** Animal, including human, faces are often quite symmetrical. (a) Because the right and left sides of the cougar's face are identical, there is a mirror plane running down the center. (b) The visage of country singer Lyle Lovett, on the other hand, appears asymmetrical. His twisted lip, the tilt of his neck and eyes, and other features mean that there is no mirror plane of symmetry down the center of his face.

parallel to pairs of opposite faces (Figure 3f); six intersect opposite faces along their diagonals (Figure 3g). Thus, a cube has more symmetry than a human or a cougar (Figure 2).



**FIGURE 3** Two- and three-dimensional objects may have many mirror planes (shown by dashed lines in a, c, and d; planes in f and g) or none: (a) a circle has an infinite number of mirror planes; (b) a blob has no mirror planes; (c) a rectangle has two mirror planes; (d) a square has four mirror planes; (e) a cube has the maximum number of mirror planes possible for a crystal—nine; (f) the mirrors of a cube parallel to its faces; (g) the mirrors of a cube parallel to face diagonals.

## Rotational Symmetry

Reflection by a mirror is but one of several fundamental types of symmetry operations. A second common type of symmetry in crystals, called **rotational symmetry**, is symmetry with respect to a line called a **rotation axis**. In two dimensions, a lens shape appears unchanged when rotated 180° (symmetry operator 2 in Figure 4). We say it has 2-fold symmetry because two repeats of the rotation operation return it to its original position. Other symmetry operators are shown in Figure 4. Equilateral triangles have 3-fold rotational symmetry (corresponding to rotation of 120°), squares have 4-fold rotational symmetry (rotation of 90°), and hexagons have 6-fold rotational symmetry (rotation of 60°). For reasons we will see later, although we can draw shapes that have 5-fold symmetry, or greater than 6-fold symmetry, minerals never possess such symmetry. Some natural materials, including plants and animals such as a starfish, display apparent symmetries not possible for minerals. All objects have 1-fold rotational symmetry because they remain unchanged after rotation of 360°.

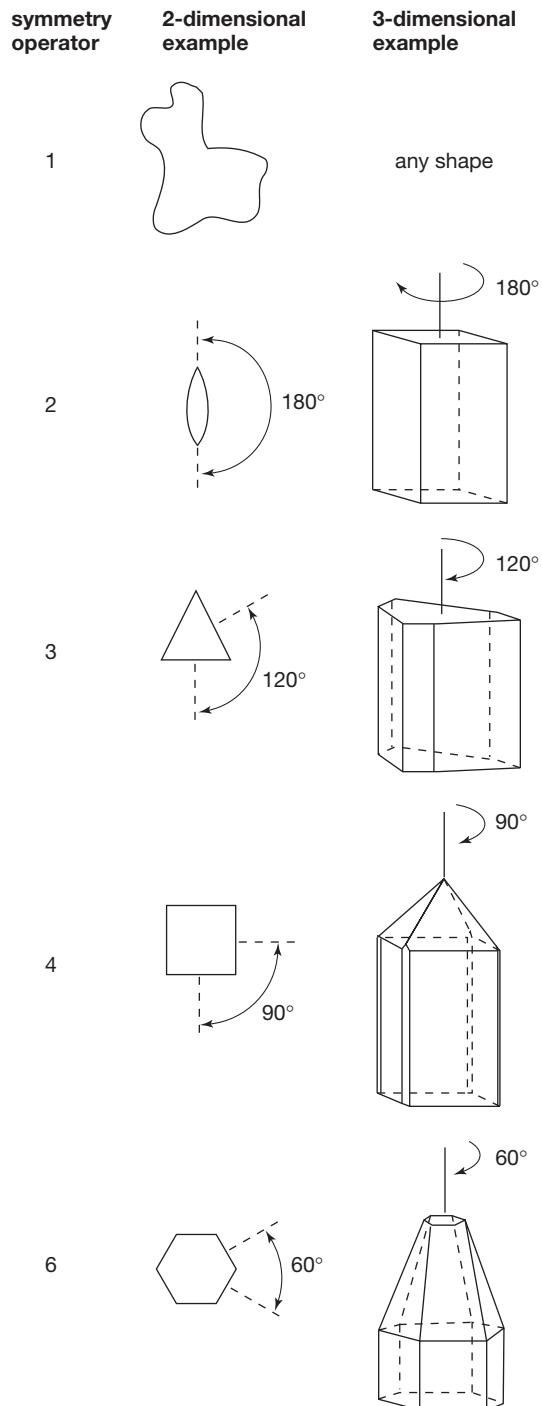
We call all the rotation axes we have just discussed **proper rotation axes**, to contrast them with **rotoinversion axes**, which we will discuss later. In shorthand notation, we symbolize proper rotation axes using the numbers 1, 2, 3, 4, or 6, corresponding to rotations of 360°, 180°, 120°, 90°, and 60°, respectively. Figure 4 shows examples

of both two- and three-dimensional objects with 1-, 2-, 3-, 4-, and 6-fold symmetry.

A cube has 2-fold, 3-fold, and 4-fold rotational symmetry (Figure 5). When rotated 180° about an edge diagonal, it appears unchanged. When rotated 120° about a main diagonal, or when rotated 90° about a line perpendicular to a face, it appears unchanged. Thus, we see that different rotation axes can combine in crystals.

Many minerals grow as **prisms**, crystals having a set of identical faces parallel to one direction. Typically, prismatic crystals are elongated in one direction. Figure 6a shows prismatic crystal of scapolite. Although not clear from the photograph, ideal scapolite crystals have square cross sections and flat ends perpendicular to the prism faces. Quartz, in comparison, forms hexagonal prisms, complicated by sloping **terminating faces** at the ends of the crystals (Figure 6b). Prism faces are, in principle, identical in shape and size, although accidents of growth often lead to minor differences. Some minerals have multiple, non-identical faces, all parallel to a common line. We call the collection of faces a **zone** and the common line the **zone axis**. Zones, present in most crystals, sometimes correspond to axes of symmetry.

Rotational symmetry, even if present, may be hard to see. For example, the 3-fold axes of symmetry in a cube are difficult to see without turning the cube in your hand. Problems may be even more complicated in natural crystals because of growth imperfections in crystal faces, or the presence of many

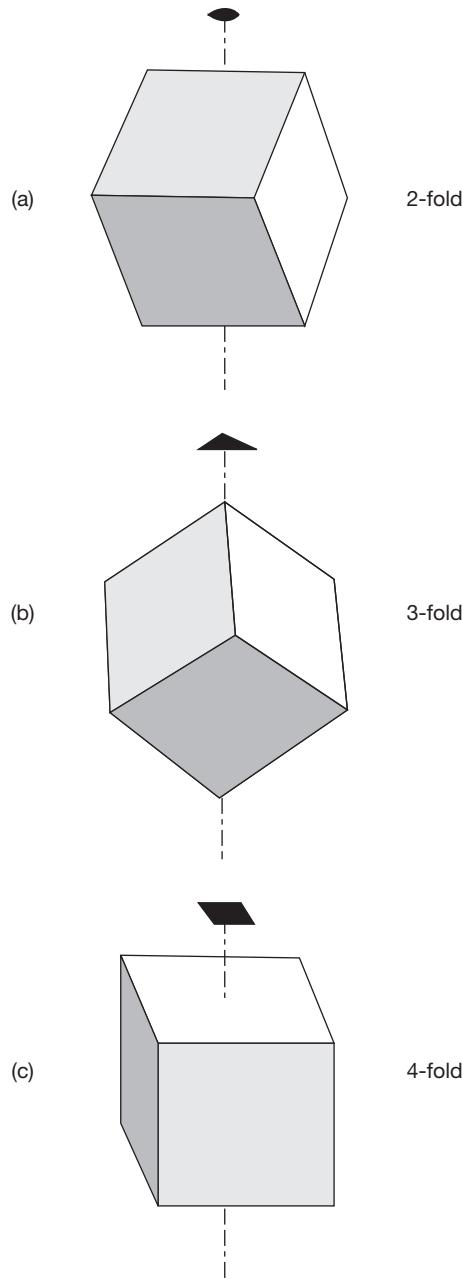


**FIGURE 4** Two- and three-dimensional examples of 1-, 2-, 3-, 4-, and 6-fold axes of symmetry.

differently shaped crystal faces. **Anhedral crystals** exhibit no external symmetry, while **euhedral crystals** may exhibit lots.

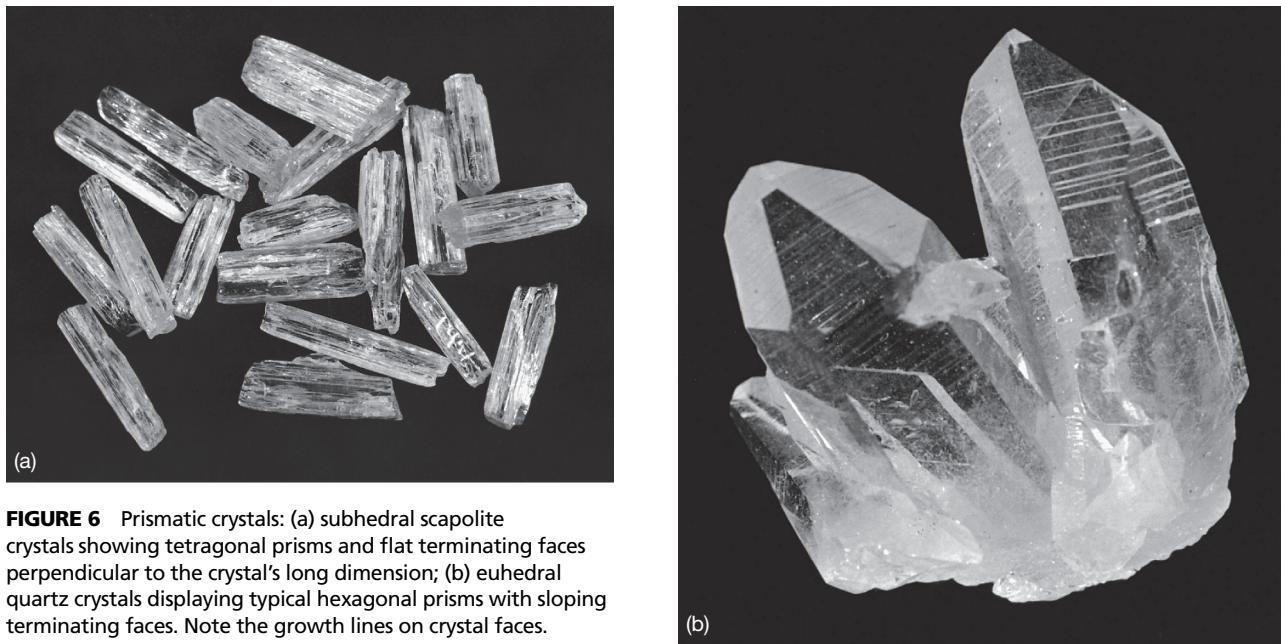
### Inversion Centers

**Inversion**, a third type of symmetry, is symmetry with respect to a point. We call the point the

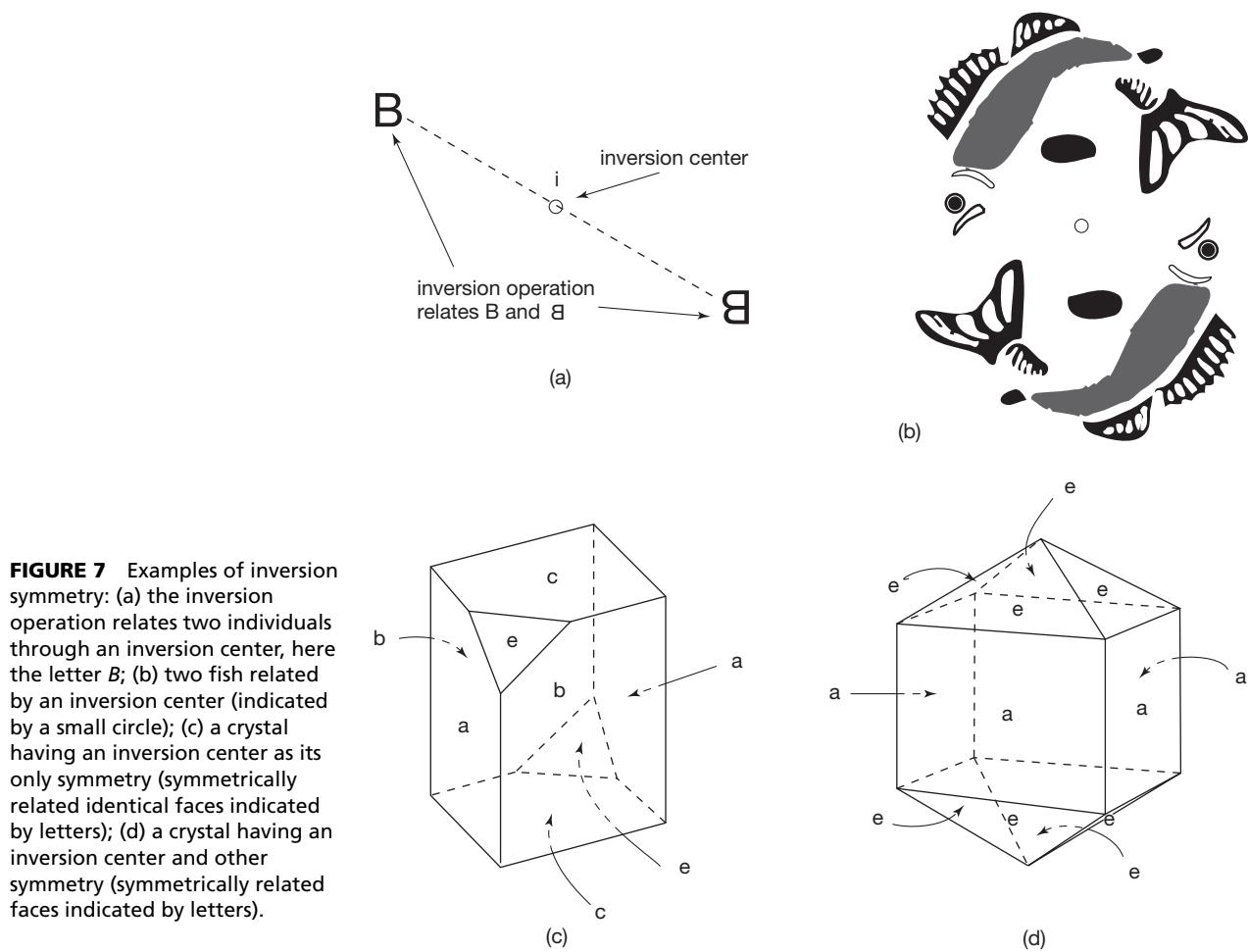


**FIGURE 5** Rotation axes of a cube: (a) the edge diagonals of a cube are 2-fold rotational axes of symmetry; (b) the main diagonals of a cube are 3-fold rotational axes of symmetry; (c) the face perpendiculars of a cube are 4-fold rotational axes of symmetry.

**inversion center** and often designate it with the lowercase letter *i*. As with mirror planes, inversion relates two identical faces on a crystal; but while mirror planes “reflect” faces and change their “handedness,” inversion centers invert them. Inversion produces faces related in the same way that a lens may yield an upside down and backward image (Figure 7). In two dimensions,



**FIGURE 6** Prismatic crystals: (a) subhedral scapolite crystals showing tetragonal prisms and flat terminating faces perpendicular to the crystal's long dimension; (b) euhedral quartz crystals displaying typical hexagonal prisms with sloping terminating faces. Note the growth lines on crystal faces.



**FIGURE 7** Examples of inversion symmetry: (a) the inversion operation relates two individuals through an inversion center, here the letter *B*; (b) two fish related by an inversion center (indicated by a small circle); (c) a crystal having an inversion center as its only symmetry (symmetrically related identical faces indicated by letters); (d) a crystal having an inversion center and other symmetry (symmetrically related faces indicated by letters).

inversion centers give the same results as 2-fold axes of symmetry (Figures 7a and b); in three dimensions, the symmetry is different (Figure 7c and d). Some crystals have combinations of mirror planes, rotation axes, and inversion centers, such as the prismatic crystal with terminating pyramids in Figure 7d. The small letters on the crystal faces in Figures 7c and d indicate faces related by symmetry.

### Symmetry Is a Property

Mineralogists often speak of a crystal's **symmetry elements**—the different kinds of symmetry it has—in quantitative terms. We can count mirror planes, rotation axes, and inversion centers. If objects have only a few symmetry elements, we say they have **low symmetry**. Those that display many have **high symmetry**. In addition, we say that objects with 6-fold rotation axes have higher symmetry than those with 4-fold, 3-fold, or 2-fold axes, and so on. References to high and low symmetry are necessarily vague because symmetry manifests itself in many different ways. **Cubes** have the highest symmetry possible for crystals: three 4-fold axes, four 3-fold axes, six 2-fold axes, nine mirror planes, and an inversion center (Figure 8). Examination of Figures 8a and b should convince you that a regular **octahedron** has this same symmetry, although appearing dissimilar to a cube. The shape of an object depends on its symmetry, the size of its faces, and on the angles between its faces. Cube faces are at 90°

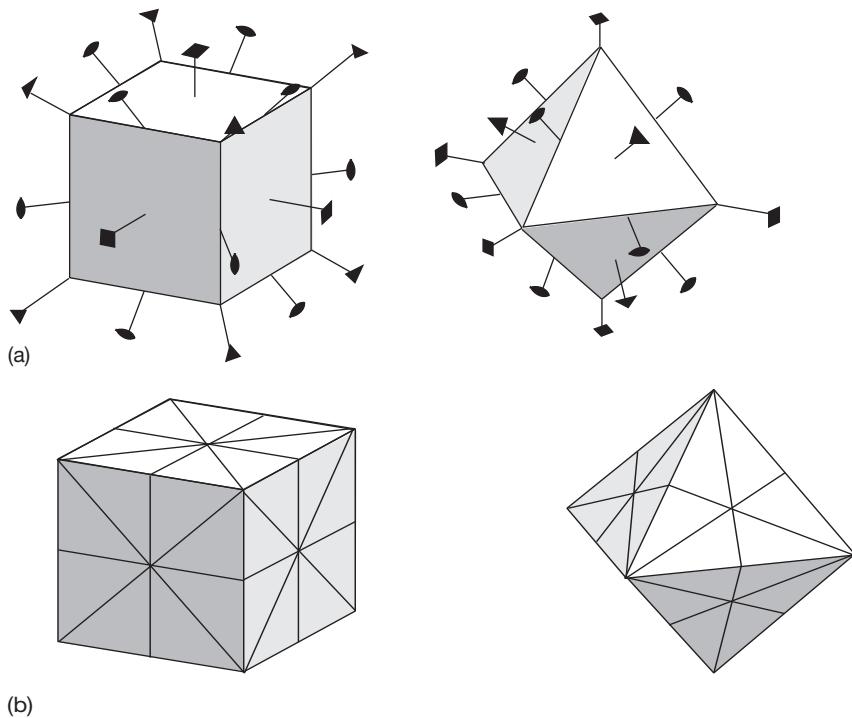
to each other; octahedron faces are at about 55° to each other.

Comparison of the cube and octahedron emphasizes that symmetry is not a physical characteristic. It is a property that objects may possess. With an object in hand, a mineralogist can discuss its symmetry, but a description of an object's symmetry does not unambiguously reveal its appearance. Many objects have mirror planes, yet their overall shapes are quite different. While symmetry does not determine appearance, it does include all aspects of a crystal. For example, if a crystal has six identical faces, it must have six directions of identical atomic structure and, therefore, six directions with the same hardness, reflectivity, and so on. The 6-fold rotation axis present in a hexagonal prism relates six crystal faces, six crystal edges, and six directions with identical atomic structure (Figure 9). Hexagonal crystals are optically uniaxial; they have one unique direction (parallel to the 6-fold rotation axis) that corresponds to the optic axis. Symmetry affects everything in a crystal, including faces, edges, corners, physical properties, optical properties, and atomic arrangement.

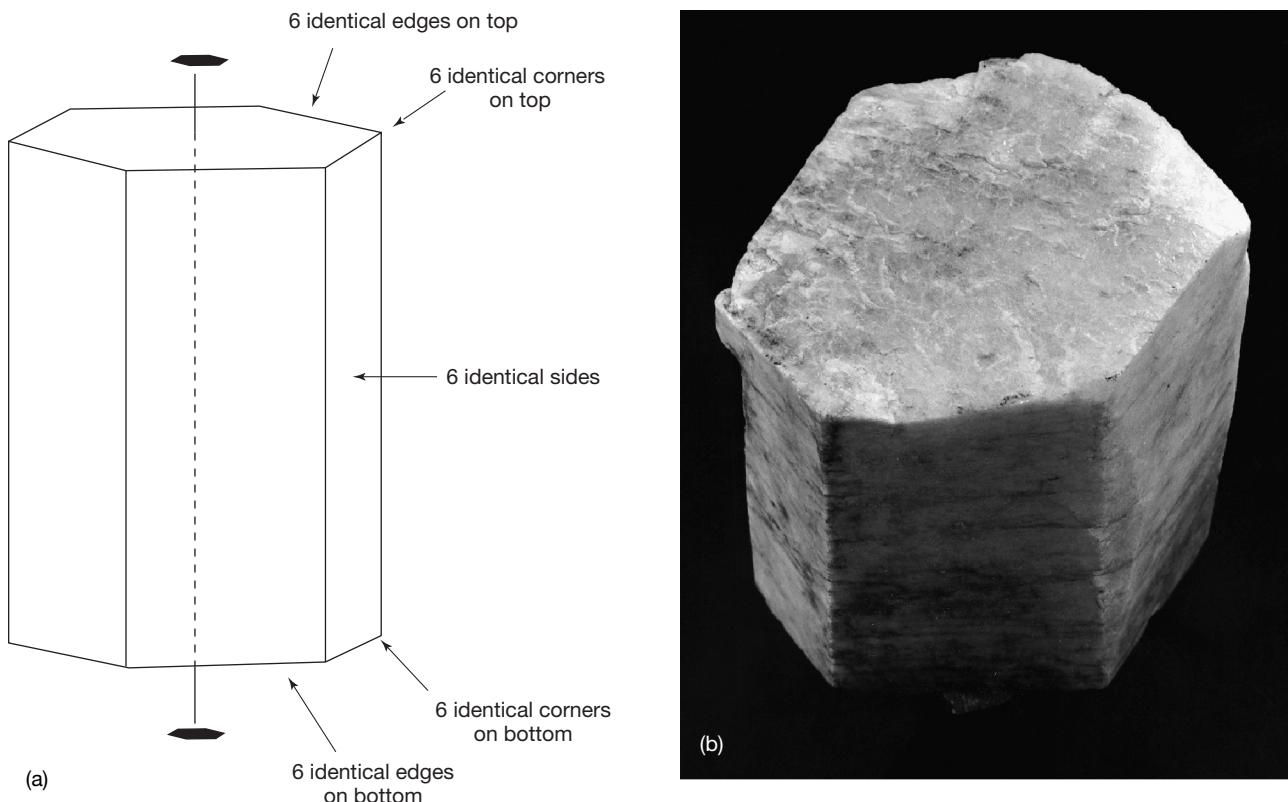
### STEREO DIAGRAMS

#### Symmetry on Stereo Diagrams

A convenient way to look at the symmetry of a crystal is to use a stereographic projection, also called a **stereo diagram**. Although stereo diagrams



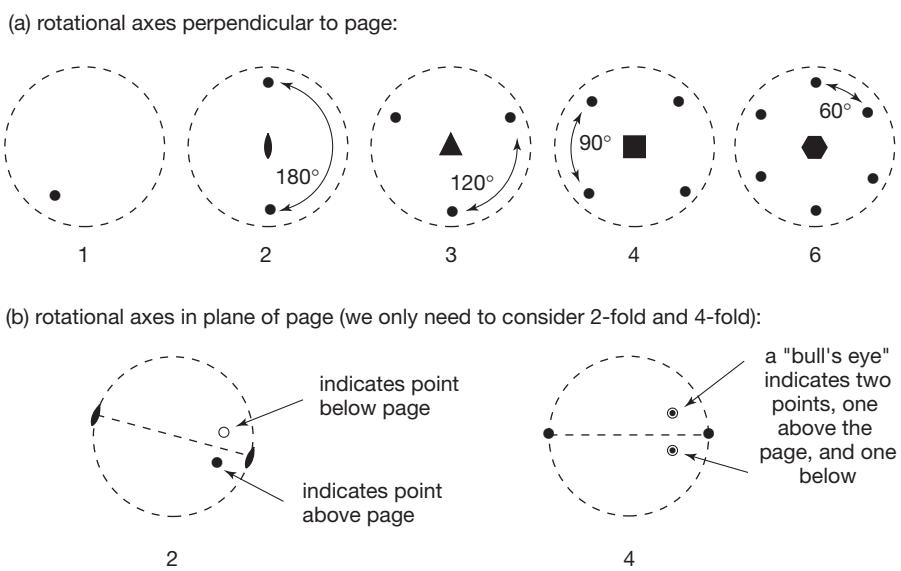
**FIGURE 8** Cube and octahedron: (a) the rotation axis in a cube and an octahedron have identical orientations. Lenses, triangles and squares show 2-fold, 3-fold and 4-fold axes of symmetry; (b) the mirror planes in a cube and octahedron are also oriented identically.



**FIGURE 9** (a) An ideal hexagonal prism; the 6-fold axis relates faces, edges, and corners of the prism; (b) a 20-cm-across hexagonal crystal of beryl that is not as perfectly formed as the drawing.

depict mirror planes, inversion centers, and rotational symmetry, and their relationship to crystal faces, they do not show the exact shape of the faces. Stereo diagrams can be quantitative and very complex. For now, considering their qualitative aspects is sufficient. Figure 10a shows stereographic

projections of 1-, 2-, 3-, 4-, and 6-fold rotation axes perpendicular to the page. The geometric symbols at the center of the diagrams show the kind of rotation axis. In the five drawings the rotation axis has operated on a single black dot, producing 0, 1, 2, 3, or 5 other dots by rotation of  $360^\circ$ ,  $180^\circ$ ,



**FIGURE 10** Rotation axes in stereo diagrams showing equivalent dots: (a) 1-, 2-, 3-, 4-, and 6-fold axes of symmetry perpendicular to the page; (b) 2-fold and 4-fold axes in the plane of the page.

120°, 90°, and 60° around the center of the diagram. Box 1 discusses these operators in detail.

The diagrams in Figure 10a show symmetry, and repetition of points, in the plane of the page quite nicely. However, symmetry operations also work in three dimensions. To accommodate the third dimension, we need a way to show points below and above the page. By convention, solid dots represent points above the plane of the page, and circles represent points below the plane of the page. A point above the page that is directly above one below the page is symbolized by a “bull’s-eye” formed by a small circle around a dot (◎). Points within the plane of the page plot as solid dots on the outside circle of the stereo diagram. Figure 10b shows a 2-fold and 4-fold axis of symmetry lying in the plane of the page. They operate on points above the page to produce points below. For the 4-fold axis, the points below and above the page project on top of each other and are shown as a bull’s-eye. Crystallographers have developed shorthand symbols to describe combinations of mirror planes and rotation axes when the two are perpendicular. We represent them by the symbols  $1/m$ ,  $2/m$ ,  $3/m$ ,  $4/m$ , or  $6/m$ . Box 2 discusses and depicts these combinations of symmetry operators.

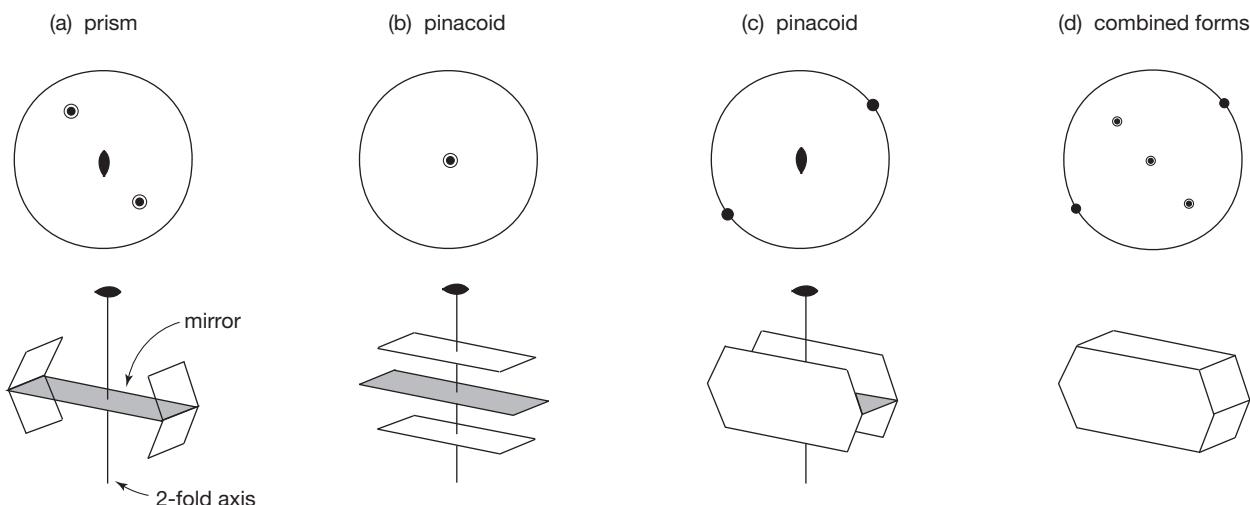
### Special Points and General Points

In the preceding examples of stereo diagrams, we have applied symmetry elements to points to produce other points. The initial points chosen do not lie at the center, on the edges, or at any other **special points** in the diagram. Figure 11 shows four stereo diagrams

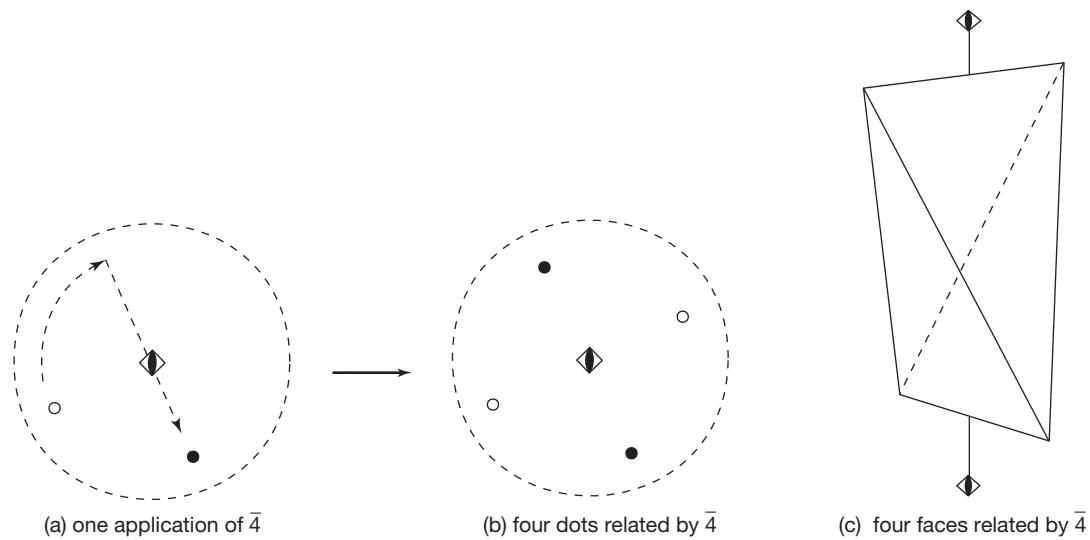
depicting points related by the symmetry  $2/m$ , and drawings showing the same symmetry using crystal faces. A single point was chosen to start, and application of the symmetry operators generated all additional points. In Figure 11a, the **general point** (a point at some nonspecial location) was chosen as a starting point. The result is four points—two above the mirror plane and two below—equivalent to the four faces shown below the stereo diagram. We call a group of identically shaped faces related by symmetry a **form**. We can easily verify that any general point (a point noncoincident with any symmetry elements) will produce a similar pattern. In Figures 11b and 11c, we chose special points on the rotation axis and in the plane of the page. After application of the symmetry operators, only two points result in both cases. The equivalent pairs of faces are shown below the stereo diagrams. Thus, although all three drawings depict the same symmetry, the distribution of points and the equivalent faces are different, depending on whether we start with general points or special points. This observation explains, in part, why crystals of different appearance can have the same symmetry. Different-shaped faces can combine; the combination in Figure 11 produces a monoclinic crystal of eight faces (Figure 11d). The eight faces belong to three forms.

### Rotoinversion

Rotoinversion, a combination of rotation and inversion, is a symmetry operation distinct from the others. The symbols  $\bar{1}$ ,  $\bar{2}$ ,  $\bar{3}$ ,  $\bar{4}$  and  $\bar{6}$  represent rotoinversion axes. They are articulated as “bar-1,” “bar-2,” etc. In a rotoinversion operation, we apply



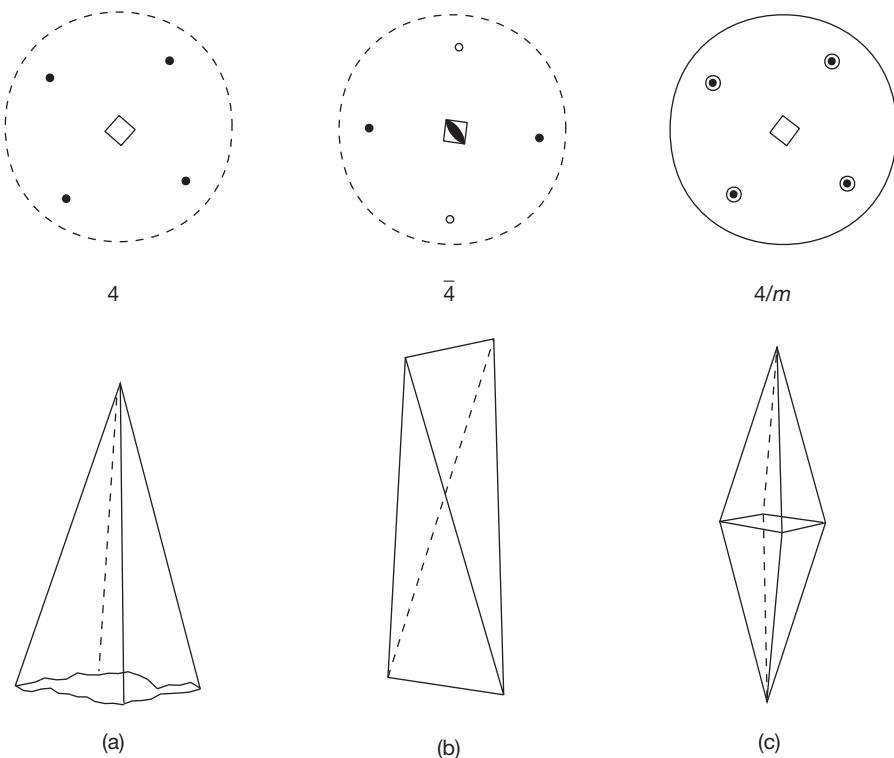
**FIGURE 11** Three examples of stereo diagrams and forms related by  $2/m$  symmetry; the drawings below the stereo diagrams confirm that the forms are consistent with the rotation axis and mirror plane. We call the form depicted in (a) a *prism*; the other two forms (b and c) are both *pinacoids*. In (b), the 2-fold axis symbol has been omitted for clarity. In (d), the three forms have been combined to create a crystal with  $2/m$  symmetry.



**FIGURE 12** (a)  $\bar{4}$  axis operating on a dot; (b) all the dots related by a  $\bar{4}$  axis; (c) crystal faces related by a  $\bar{4}$  axis. We call this form a *disphenoid*.

rotation and inversion simultaneously. For example, in Figure 12a, we apply a  $\bar{4}$  axis to a solid point (above the page) to produce an open point (below the page). The original point is rotated  $90^\circ$  and inverted to produce the second. A  $\bar{4}$  axis relates four points in total (Figure 12b). Figure 12c shows a crystal with  $\bar{4}$  symmetry. The four faces are related by  $90^\circ$  rotation followed by inversion. Box 3 discusses and depicts all possible rotoinversion operators.

Note that  $\bar{4}$  rotoinversion is the only rotoinversion operation distinct from other symmetry operations. A  $\bar{2}$  axis is equivalent to  $m$ ; a  $\bar{3}$  axis is equivalent to a 3-fold axis and an inversion center applied separately; and a  $\bar{6}$  is equivalent to  $3/m$ . The crystal depicted in Figure 12 has a  $\bar{4}$  axis, but it does not have an inversion center, nor does it have a normal 4-fold rotation axis of symmetry. Figure 13 compares a proper 4-fold axis with a



**FIGURE 13** Comparison of a 4-fold axis (a) with a 4-fold rotoinversion axis (b), and with a 4-fold axis combined with an inversion center (c). Stereo diagrams and form drawings are shown for all three.

4-fold rotoinversion axis, with a 4-fold axis and inversion center combined. The operators do not yield the same pattern of points, even when we use the same point as a starting point, nor do they describe the same crystal shapes. The  $\bar{4}$  axis produces four points (or faces) in total, but they are not related by a proper 4-fold axis of rotation. Presence of a  $\bar{4}$  axis does not imply presence of a 4-fold axis. Box 3 discusses all possible rotoinversion axes in more detail. The rotoinversion axes  $\bar{2}$ ,  $\bar{4}$ , and  $\bar{6}$  are not equivalent to rotation and inversion operating separately, nor are they equivalent to proper 2-fold, 4-fold, or 6-fold rotation axes. However, a 3 operation is equivalent to proper 3-fold rotation and inversion operating separately.

Because some of the symmetry operators are redundant, we do not need them all to describe the symmetry of crystals. By convention, crystallographers use the 13 operators in the left-hand column of Table 1. In mathematical terms, these 13 are *sufficient* to describe symmetry in any crystal.

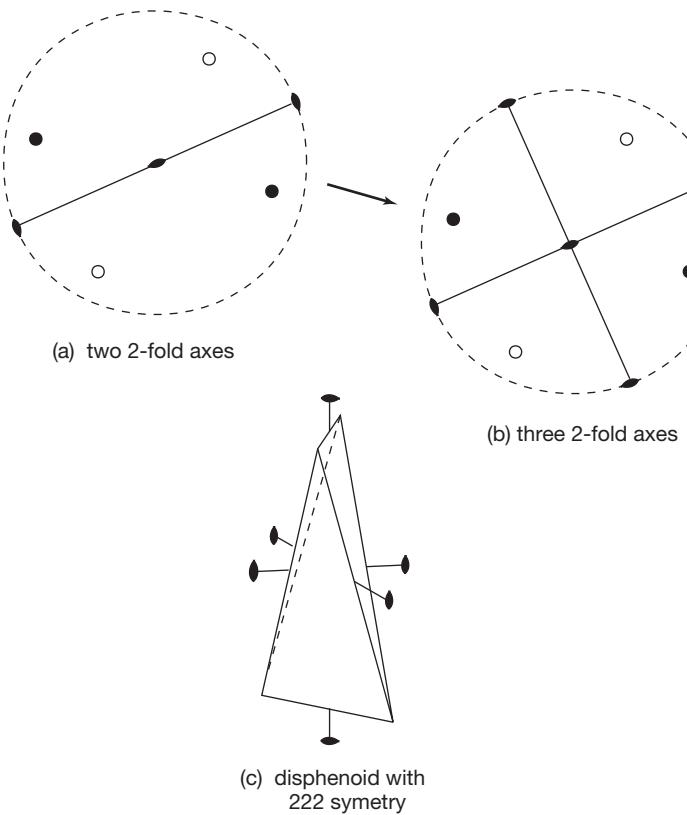
### Combinations of Symmetry Elements: Point Groups

The stereo diagram in Figure 14a contains two 2-fold axes. One is perpendicular to the page and one lies within the page. Starting with one point, application

**TABLE 1** Symmetry Operations

Standard Symmetry Operations	Equivalent Rotoinversion Axes	Equivalent Rotation Axes with Mirror Planes
$i$	$\bar{1}$	
$m$	$\bar{2}$	$1/m$
1		
2		
3		
4		
6		
$\bar{3}$		
$\bar{4}$		
$\bar{6}$		$3/m$
$2/m$		
$4/m$		
$6/m$		

of the two symmetry operators yields three additional points. It also results in a pattern that has a third 2-fold axis perpendicular to the first two (Figure 14b). Thus, we see that all objects that have two perpendicular 2-fold axes of symmetry must have a third 2-fold axis. It does not matter which two 2-fold axes we choose initially; the third must be there. Figure 14



**FIGURE 14** (a) Stereo diagram showing two 2-fold axes at  $90^\circ$  (one perpendicular to the page and one in the plane of the page) and points related by them; (b) stereo diagram showing the same points and the third 2-fold axes that relates them; (c) a disphenoid, a crystal belonging to point group 222, having the symmetry shown in (b).

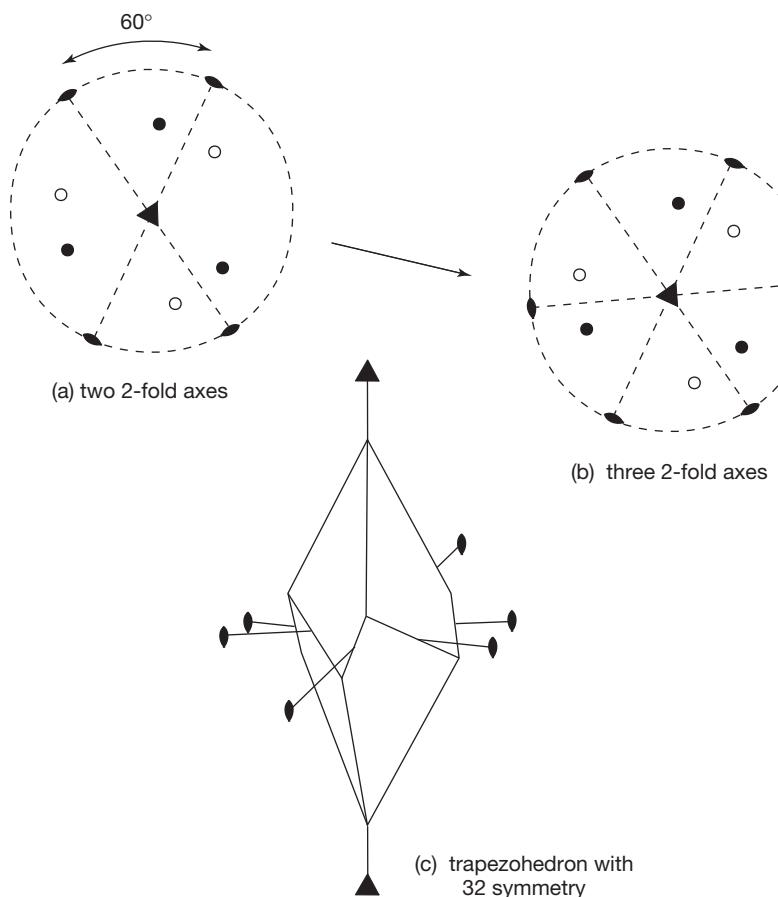
demonstrates a very important principle of symmetry operators: they operate on each other.

The shorthand notation 222 describes the symmetry depicted in Figure 14b, consisting of three mutually perpendicular 2-fold axes. Figure 14c shows one possible crystal with 222 symmetry. The three 2-fold axes pass through the centers of edges of the crystal. We call distinct combinations of symmetry, such as 222, **point groups**; they relate the points in a stereo diagram to each other. The word *group* is used because we may treat the principles of symmetry using mathematical group theory. The terms *operator* and *operation* also derive from group theory. In group theory, the 13 operators in the left-hand column of Table 1 form a **basis**.

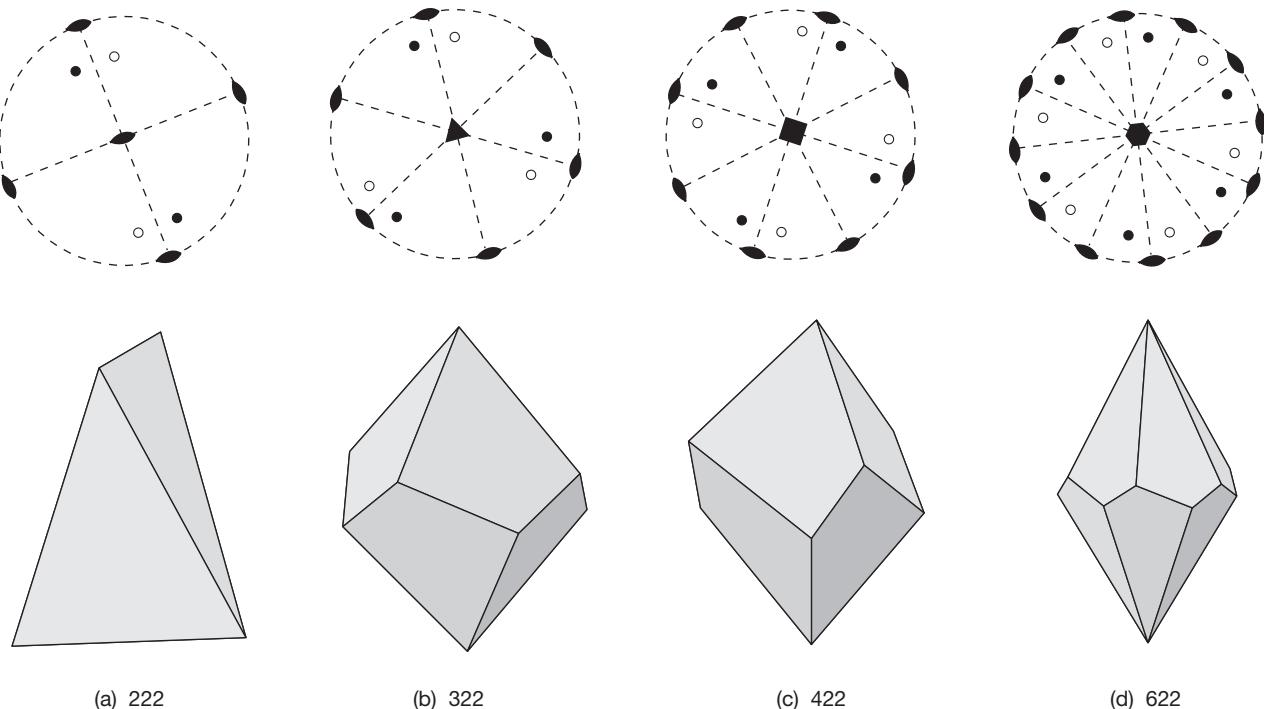
As another example of symmetry operators acting on each other, consider Figure 15a, in which two 2-fold axes intersect at  $60^\circ$ . Starting with one point and applying the symmetry operators, we soon generate five more equivalent points. Examination of the resulting pattern shows that a third 2-fold axis lies at  $60^\circ$  to the first two. A 3-fold axis is perpendicular to the two folds (Figure 15b). Another way of looking at the

symmetry in Figure 15b is to notice that the 3-fold rotation axis acts on the 2-fold axes. It requires that if one 2-fold axis of symmetry is present, two others must be present as well, and that the three are separated by angles of  $120^\circ$ . Consequently, the point group is designated 322 or, more commonly, 32. Figure 15c shows an example of a crystal belonging to point group 32.

In Figure 14 we showed that two perpendicular 2-fold axes required the presence of a third mutually perpendicular one. In Figure 15, we showed that if two 2-fold axes intersect at  $60^\circ$ , another 2-fold and a 3-fold will also be present. Similarly, if we start with a 4-fold axis and one perpendicular 2-fold, we will find other 2-folds perpendicular to the 4-fold and at  $45^\circ$  to each other (Figure 16c). If we start with a 6-fold axis and a perpendicular 2-fold, we will find six 2-fold axes in all (Figure 16d). Figure 16 shows the symmetry of point groups 222, 322, 422, and 622 and drawings of crystals having those symmetries. Note that mirror planes are absent in all four cases. The top and bottom of the crystals do not mirror each other, and the crystal faces do not have mirror planes down their centers (or else an *m* would be included in the



**FIGURE 15** (a) Stereo diagram showing two 2-fold axes at  $60^\circ$  and points related by them; (b) stereo diagram showing the same points and axes, and the additional 2-fold and 3-fold axis that must be present; (c) a crystal belonging to point group 32, having the symmetry shown in (b).



**FIGURE 16** Stereo diagrams and crystal drawings for point groups: (a) 222; (b) 322; (c) 422; (d) 622. Although not shown, the 2-fold axes emerge from the crystals at the center of edges closest to the crystals' equators.

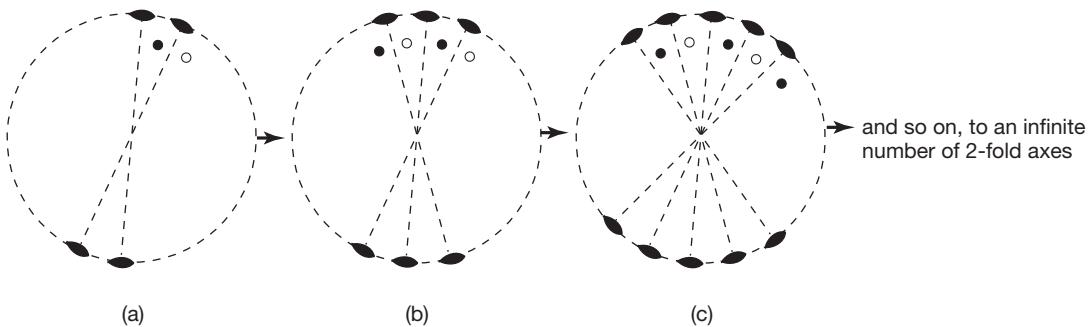
symbol for the point group). The four examples in Figure 16 point out that symmetry operators cannot combine in random ways. The presence of two rotation axes requires a third and perhaps more. We can also show that a combination of a rotation axes and a mirror, at angles other than  $0^\circ$  or  $90^\circ$  to each other, requires other rotation axes to be present. Seeing symmetry on the complicated crystal drawings in Figure 16 is difficult. (That's why we have stereo diagrams!) A better way to examine symmetry of crystals is to study models in the laboratory.

### Special Angles and General Angles

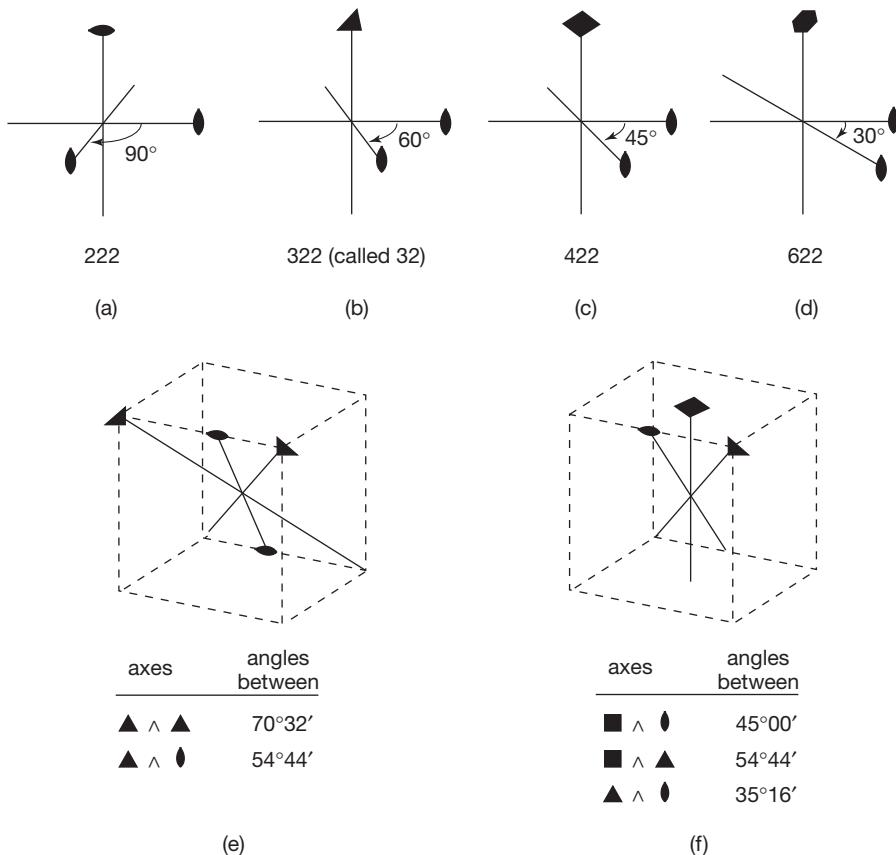
Angles such as  $30^\circ$ ,  $45^\circ$ ,  $60^\circ$ ,  $90^\circ$ , or  $120^\circ$  are called **special angles**. They all divide evenly into  $360^\circ$ .

We call nonspecial angles **general angles**. In the examples in Figure 16, we started with rotation axes that intersected at special angles. Suppose we start with axes that intersect at general angles. What will be the result?

In Figure 17a, we show two 2-fold axes. The angle between them is small and does not divide evenly into  $360^\circ$ . We may apply the 2-fold axes to each other and generate more 2-fold axes. If we continue this operation all the way around the circle, we will not end back where we started. The number of 2-fold axes becomes infinite, and an infinite-fold axis of symmetry must be perpendicular to the plane of the page. This is equivalent to the symmetry of a circle. Since crystal structures consist of a discrete number of atoms, we know that infinite



**FIGURE 17** (a) Two 2-fold axes and two points related by one of them; (b) other points and a 2-fold axis implied by the presence of the first; (c) moving toward an infinite number of 2-fold axes.



symmetry is not possible. We may therefore conclude that if crystals have two 2-fold axes, they must intersect at a special angle so that they are finite in number.

The preceding discussion suggests that rotation axes only combine in a limited number of ways. In fact, only the six combinations depicted in Figure 18 are possible. We have already discussed four of them: 222, 32 (= 322), 422, 622. The other two (Figures 18e and f) are best envisioned by thinking about a cube. The angles between rotation axes are all special angles (to avoid infinite symmetry). In Figures 18e and f, the angles are equal to angles between various diagonals in a cube and perpendiculars to cube faces. If we carried out the exercise, we would find that in crystals with both rotation axes and mirror planes, the angles between the rotation axes and the mirror planes are limited to only a few special angles as well. Otherwise, we have infinite symmetry. In many crystals the angles are 0° (the rotation axis lies within the plane of the mirror) or 90° (the rotation axis is perpendicular to the mirror).

## FORMS AND CRYSTAL MORPHOLOGY

### Forms

As pointed out before, we call a set of identical faces related by symmetry a *form*. Use of this term is unfortunate, because most of us think of *form* as meaning "shape." Further confusion derives from the fact that a single crystal may contain multiple forms, and a single form may have as many as 48 faces. Two crystals with identical forms may look different if the forms are of different sizes. Nonetheless, the term is firmly established in crystallography and unlikely to disappear. Mineralogists use the term *habit* to refer to the common or characteristic shape of a crystal. Habit depends on the symmetry, number, and size of forms that are present and how a crystal grows in relation to other crystals around it. For example, we say pyrite has a *cubic habit* because pyrite crystals frequently grow as cubes or near cubes. Crystals may contain multiple forms, but most minerals have only one common habit.

Nature does not always produce perfectly shaped crystal faces. Accidents of growth and other imperfections lead to differences among

**BOX 1****Proper Rotation Axes and Stereo Diagrams**

Crystallographers use conventional symbols to represent symmetry operators on a stereo diagram (Figures 19 and 20). Figure 19 shows stereo diagrams and crystal drawings for each of the five kinds of rotation axes we have considered. The location of the symbols indicates the orientation of the rotation axis. Small lenses, triangles, squares, and hexagons at the center of the diagram represent 2-, 3-, 4-, and 6-fold axes of rotation perpendicular to the plane of the page (Figure 19):

Symbol	Axis/Mirror
●	2-fold
▲	3-fold
■	4-fold
◆	6-fold
—	mirror

**FIGURE 19** Proper rotation axes in stereo diagrams and equivalent crystal faces: The stereo diagrams depicting the axes contain dots corresponding to crystal faces shown in the drawing in the third column. The fourth column shows more complicated crystals with the same symmetry.

axis	stereo diagram	simple form	crystal with multiple forms
1			
2			
3			
4			
6			

faces of a form, but forms are often quite easily identified. Because the forms present in particular crystals, and the resulting habits, are dependent on atomic structures, they are consistent for a

The third column in Figure 19 shows identical crystal faces related by the rotational symmetry. We call such a set of faces a form. The faces are depicted by dots in the stereo diagrams. In some cases the faces do not make an entire crystal. The fourth column shows more complicated complete crystals (which do not correspond to the stereo diagrams) with the same symmetry.

It is sometimes not possible or desirable to orient rotation axes perpendicular to the page. We indicate axes that lie parallel to the page by straight lines, passing through the center of the diagram—solid if they are parallel to a mirror, dashed if they are not—with the appropriate symbols at each end (Figures 20a and b).

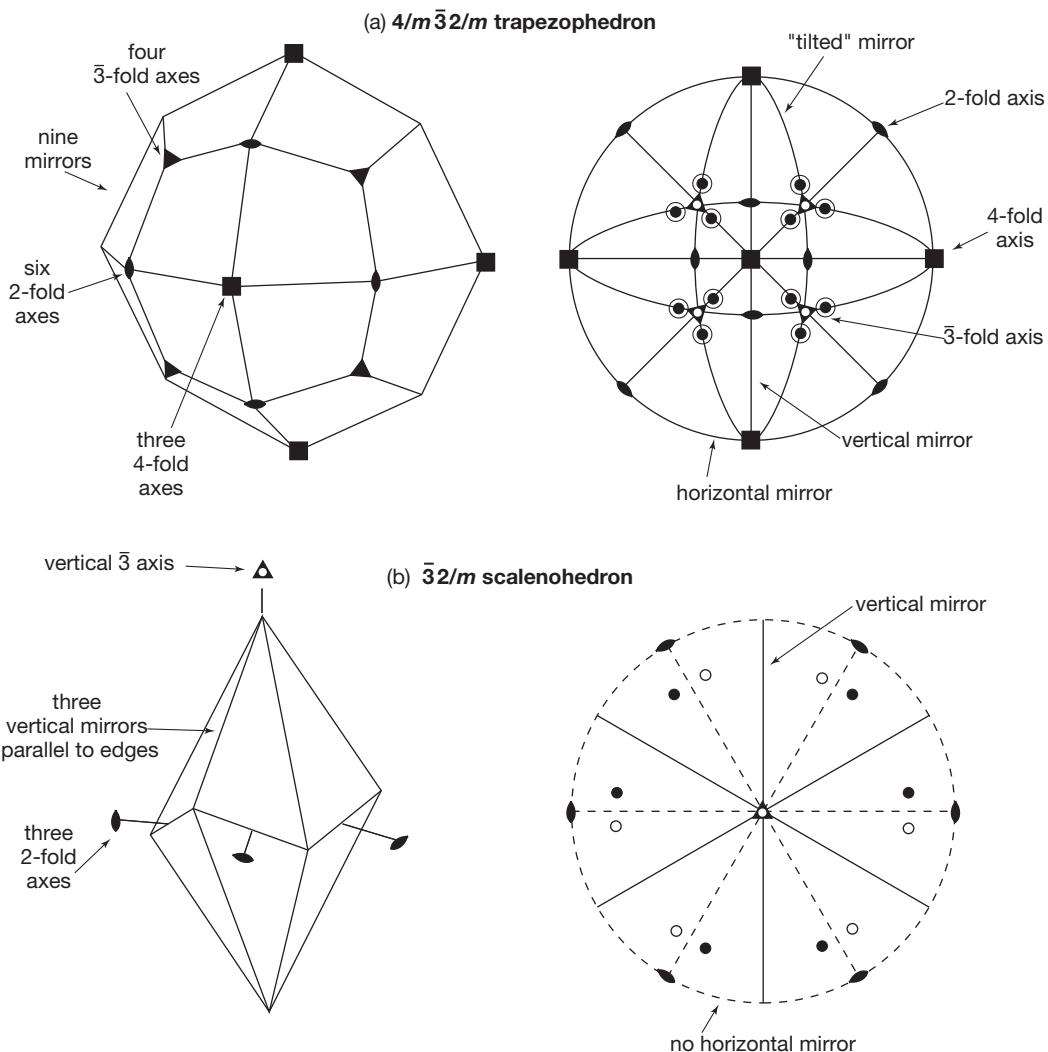
Axes that are neither parallel nor perpendicular to the page plot as symbols between the center and periphery of the stereo diagram (note the 3-fold axes in Figure 20a). The distance from the center to the

given mineral. Uncertainty arises, however, because some structures can have several different forms, and it is not always clear why one may be preferred to another. Kinetic factors, associated

symbol is proportional to the angle between the axis and a line perpendicular to the page. If a crystal has a single axis of symmetry, by convention we usually orient it vertically and place the appropriate symbol at the center of the diagram. However, for crystals that contain only one 2-fold axis of symmetry, the axis is sometimes oriented horizontally, as shown in the second row of Figure 19.

Solid lines show mirror planes. If a crystal has a mirror plane parallel to the page, the circle of the

stereo diagram is solid (Figure 20a); if not, it is dashed (Figure 20b). We indicate mirror planes perpendicular to the page by straight lines passing through the center of the diagram (Figures 20a and b). If a mirror is inclined to the page, we plot it as a great circle whose chord shows the intersection of the mirror with the horizontal equatorial plane (Figure 20a). Note that Figure 20a contains mirror planes in the plane of the page, perpendicular to the page, and inclined to the page.



**FIGURE 20** Trapezohedron and scalenohedron, and their stereo diagrams: (a) a trapezohedron containing 4-fold, 3-fold, and 2-fold axes of symmetry. The 3-fold axes are really  $\bar{3}$  axes and so are indicated by triangles with dots in their centers (see Box 3); (b) a scalenohedron containing a 3-fold axis and three 2-fold axes of symmetry. Both crystals have mirror planes, but in the scalenohedron the mirror planes are all parallel to the long dimension of the crystal (oriented vertically in the stereo diagram).

with the time of crystallization, undoubtedly play a key role.

Some crystals, such as those depicted in Figure 20, have only one form, so all the faces are the

same shape and size. Other crystals, such as the ones in the right-hand columns of Figures 19, 21, and 22, contain more than one form. Figure 23 shows a photograph of a pyrite crystal having more than one form.

## BOX 2

## Rotation Axes with Perpendicular Mirror Planes

In many crystals, rotation axes are perpendicular to mirror planes. When listing symmetry elements, we use the special symbols  $1/m$ ,  $2/m$ ,  $3/m$ ,  $4/m$ , and  $6/m$  to indicate such combinations. Figure 21 shows stereo diagrams for the five combinations. Recall that a solid circle around the outside of the diagram indicates a mirror plane within the page. For  $2/m$ , we have plotted

the 2-fold axis in the plane of the page, so the mirror is perpendicular to the page and shows as a straight solid line instead of a solid circle. The third column in Figure 21 shows identical crystal faces related by the symmetry; the fourth shows more complex crystals, containing faces of different shapes, but still having the same symmetry.

axis	stereo diagram	simple form	crystal with multiple forms
$1/m$ $(=m)$ $(=\bar{2})$			
$2/m$			
$3/m$			
$4/m$			
$6/m$			

**FIGURE 21** Stereo diagrams and drawings of faces and crystals having rotation axes with perpendicular mirror planes. Crystal faces are plotted in the same manner as in Figure 19.

We call the forms shown in Figure 16 *closed forms* because they enclose space without other forms being present. In contrast, we call the forms in Figure 24 *open forms* because they do not completely enclose space. Some forms in Figures 19, 21, and 22 are open forms, too. Because crystals cannot be open sided, additional crystal faces must terminate open forms. For example, in

Figure 4, pyramids (with four or six faces) and pedions (single faces) terminate prisms (open forms). Prisms, pyramids, and pedions are all open forms that, when combined, produce a closed shape. Crystals with only one form must, of necessity, have a closed form.

The number of possible forms is limited. On the basis of the relative positions of their faces,

## BOX 3

## Rotoinversion

Besides proper rotation axes (1, 2, 3, 4, and 6), many crystals contain a rotoinversion axis, symbolized by  $\bar{1}$ ,  $\bar{2}$ ,  $\bar{3}$ ,  $\bar{4}$ , and  $\bar{6}$ . Rotoinversion involves a combination of rotation and inversion in one operation:

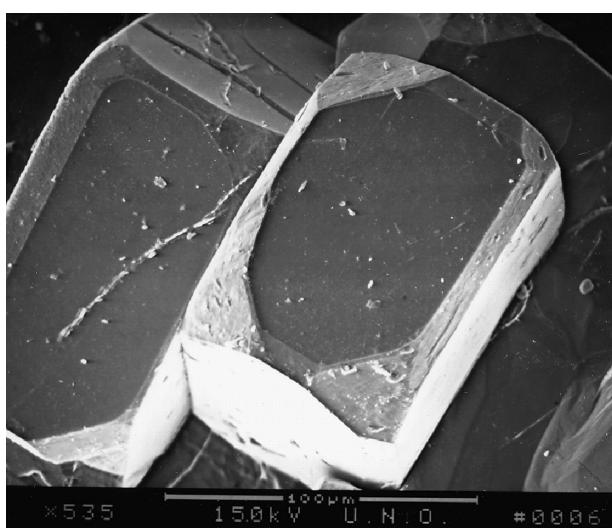
Symbol	Axis	Rotation Angle
	$\bar{1}$	360°
$\Delta$	$\bar{2}$	180°
$\diamond$	$\bar{3}$	120°
	$\bar{4}$	90°
	$\bar{6}$	60°

A 1-fold rotoinversion axis involves rotating 360° and then inverting. Because a 360° rotation is equivalent to no rotation at all, a 1-axis is identical to an inversion center. A 2-fold rotoinversion axis involves rotation of 180° followed by inversion. This has the same result as a mirror plane perpendicular to the 2-fold axis. Similarly, a 6-fold axis is equivalent to  $3/m$ . We normally don't talk about  $\bar{1}$ ,  $\bar{2}$ , or  $\bar{6}$  axes.

It is important to emphasize that rotoinversion is a combined operation. Rotation and inversion are applied together to produce an equivalent point or crystal face. It makes no difference whether we think of rotation followed by inversion, or vice versa; the results come out the same. Figure 22 shows the five rotoinversion axes in stereo diagrams and forms related by them. The last column shows a complete crystal with equivalent symmetry. It is sometimes difficult to see rotoinversion symmetry in crystals.

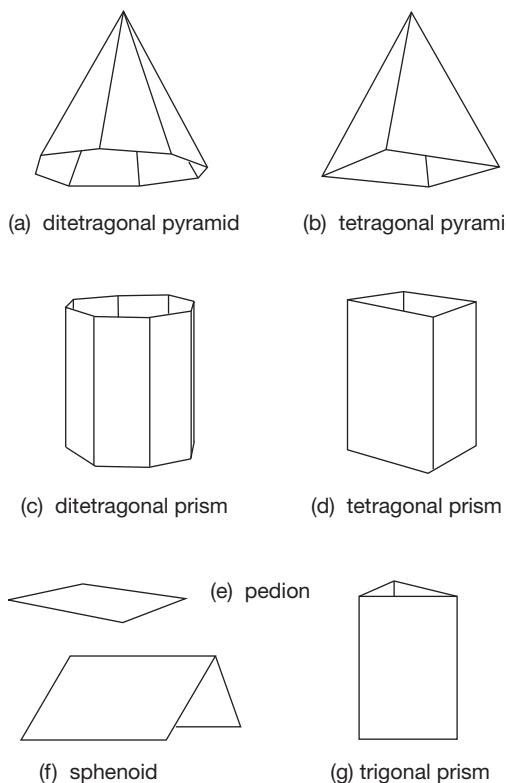
axis	stereo diagram	simple form	crystal with multiple forms
$\bar{1}$ (=i)			
$\bar{2}$ (=m)			
$\bar{3}$			
$\bar{4}$			
$\bar{6}$ (=3/m)			

**FIGURE 22** Stereo diagrams and drawings of faces and crystals having rotoinversion symmetry. Crystal faces are plotted in the same manner as in Figures 19 and 21.



**FIGURE 23** Scanning electron microscope photo of small pyrite crystals (about 0.1 mm across) with multiple forms.

only 48 can be distinguished (Figure 25). Crystallographers use various schemes to name them, but A. F. Rogers's scheme, published in 1935, is commonly used in the United States (Box 4). Table 2 gives basic names that we can expand to the entire 48 using modifiers. Some modifiers have obvious meanings. For example, a hexagonal pyramid has six sides, while a tetragonal pyramid has only four. Figure 26 in Box 4 gives examples of forms and names. We should emphasize that although only 48 possible forms exist, they can have an infinite number of sizes and shapes. A **disphenoid**, a form consisting of four faces, may be tall and skinny or short and wide. Nevertheless, it is still a disphenoid (Figures 27a and b). It is also a disphenoid even if another form truncates the faces (Figure 27c).



**FIGURE 24** Examples of open forms: (a) ditetragonal pyramid; (b) tetragonal pyramid; (c) ditetragonal prism; (d) tetragonal prism; (e) pedion; (f) sphenoid; (g) trigonal prism.

### Combinations of Forms

Most natural crystals contain more than one form, leading to a large but limited number of possible combinations. The number is limited because the shape and symmetry of crystal faces depend on the atomic arrangement in a crystal. If the atoms within a crystal are not arranged in hexagonal patterns, forms may not have hexagonal symmetry. Similarly, a crystal may not develop a cubic form unless atoms are in a cubic arrangement. Thus, certain forms never coexist in crystals, while others are often found together. Figure 28 shows some idealized crystals with various combinations of forms.

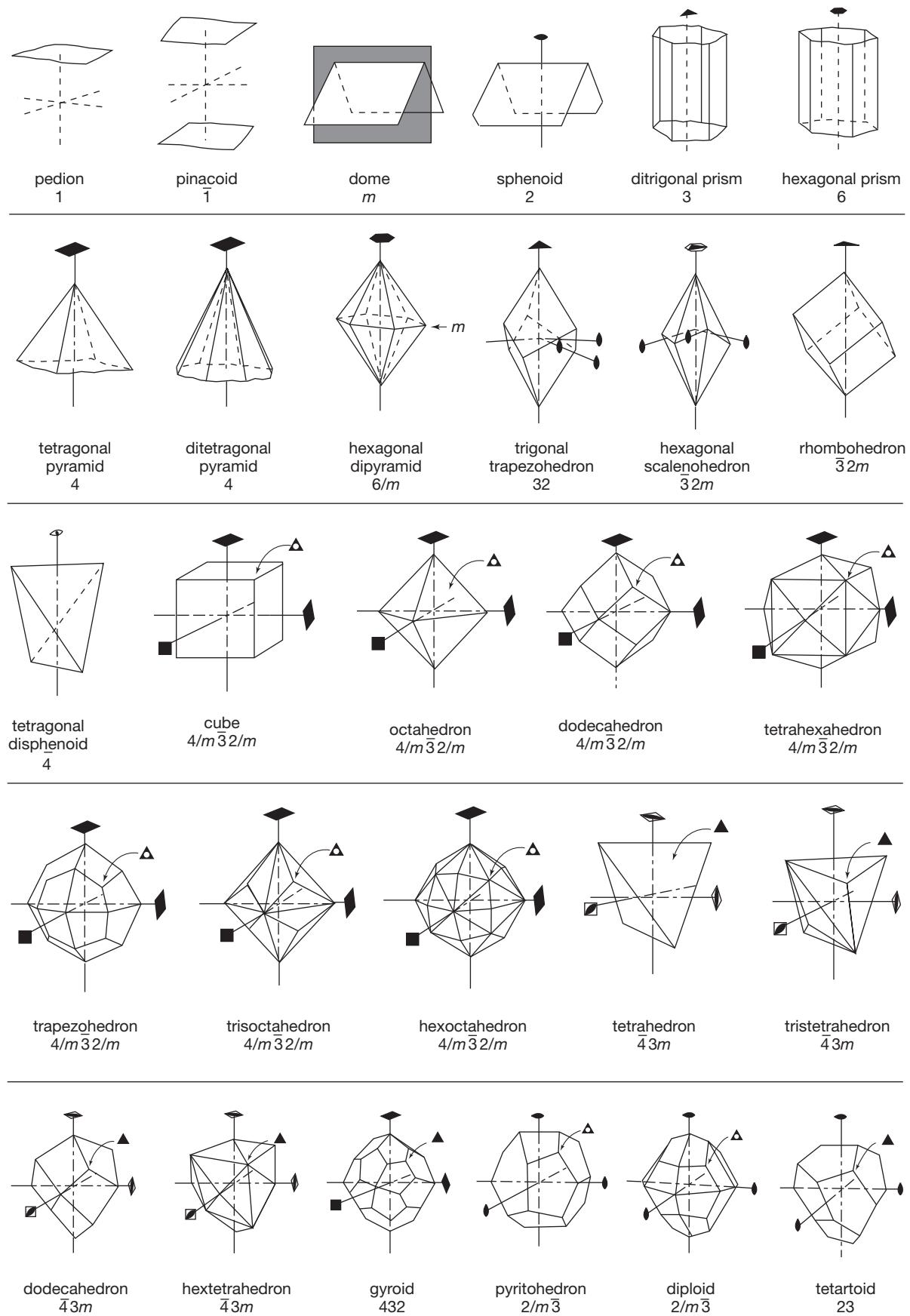
### PLOTTING CRYSTAL FACES ON A STEREO DIAGRAM

Until now, we have used stereo diagrams to discuss symmetry in a qualitative way, and we have compared the symmetry of stereo diagrams with the symmetry of ideal crystals. When studying the symmetry of a real crystal, being able to plot

**TABLE 2 Basic Names of Forms**

<b>Open Forms</b>	
pedions	single face
pinacoids	2 parallel faces
prisms	3, 4, 6, 8, or 12 faces, all parallel to a common line
pyramids	3, 4, 6, 8, or 12 nonparallel that intersect at a common point
domes	2 nonparallel faces related by a mirror
sphenoids	2 nonparallel faces related by a 2-fold axis
<b>Closed Forms</b>	
scalenohedrons	8 or 12 scalene triangle-shaped faces
trapezohedrons	6, 8, or 12 trapezoid-shaped faces
disphenoids	4 nonequilateral triangular faces
dipyramids	two 3-, 4-, 6-, 8-, or 12-sided pyramids related by a mirror
rhombohedrons	6 rhomb-shaped faces
tetrahedrons	4 equilateral triangular faces
cubes (hexahedrons)	6 square faces
octahedrons	8 equilateral triangle-shaped faces
dodecahedrons	12 rhomb-shaped faces
pyritohedrons and tetartoids	12 five-sided faces
diploids and gyroids	24 five-sided faces

symmetry elements and crystal faces on stereo diagrams is often useful. Since three-dimensional crystals are to be shown on a flat piece of paper, such plots must involve projections. Although there are alternatives, the standard procedure used is reasonably straightforward, discussed in Box 5 and shown in Figure 29. Dwelling on the procedure is not necessary, but the implications

**FIGURE 25** Some of the 48 possible forms.

**BOX 4****Names of the Most Important Forms\***

Forms have names based on geometric shapes (for example, prism or pyramid) with Greek words used as modifiers. Most of them can be translated into English with just a small Greek vocabulary.

**Suffixes:**

- gonal (angle)
- hedron (face)

**Prefixes:**

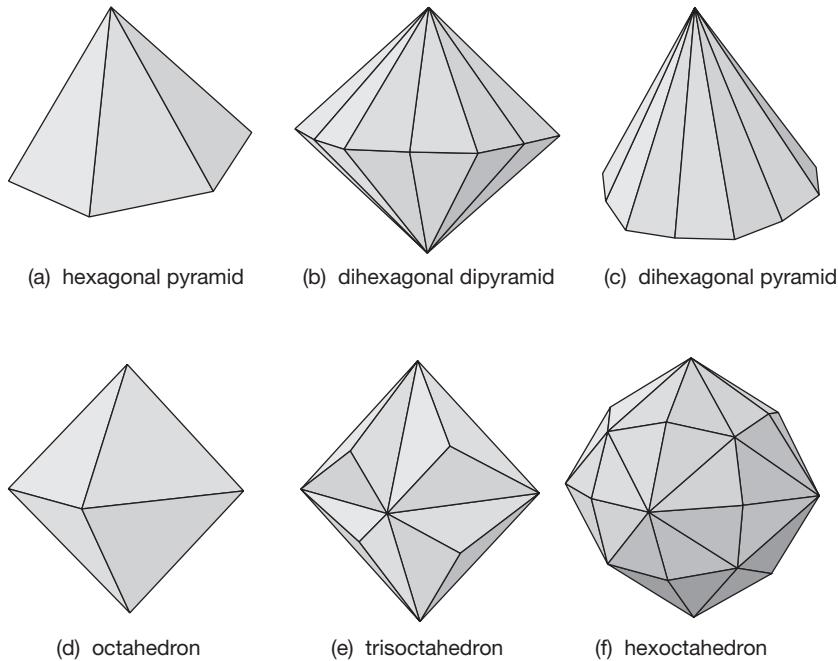
- scaleno- (scalene triangle)
- rhombo- (rhomb shaped)
- trapezo- (trapezoid shaped)

**Numerical Prefixes:**

- di- (two)
- tris- (three)
- tetra- (four)
- penta- (five)
- hexa- (six)
- octa- (eight)
- dodeca- (twelve)

In crystal drawings, forms are indicated by lower-case letters, often the first letter of the form name (for example, *o* is used to indicate octahedron faces). Some form names are single words (for example, *tetrahedron*, a four-sided closed form). Others consist of two words, the first describing the shape of the cross section of the ideal form (for example, *hexagonal pyramid*, a pyramid with a hexagonal base). The prefixes *di-*, *tris-*, *tetra-*, and *hex-* are used to indicate a doubling, tripling, and so on, of faces. If each of the six sides on a hexagonal pyramid (Figure 26a) is split down the middle to produce two faces (Figure 26c), the result is a dihexagonal pyramid. Similarly, if each of the faces on an octahedron (Figure 26d) is replaced by three faces, the result is a trisoctahedron (Figure 26e). If each of the faces on an octahedron is replaced by six faces, the result is a hexoctahedron (Figure 26f). A further modifying prefix can be applied to the word *pyramids*. The prefix *di-* indicates that there are two equivalent pyramids related by a mirror plane. Figure 26b shows a dihexagonal dipyratid.

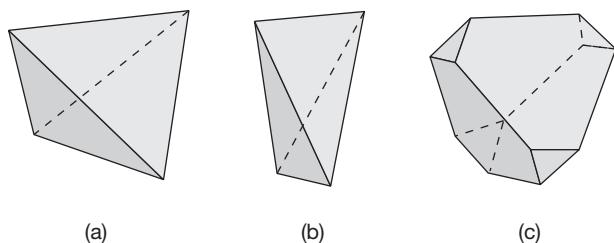
\*Adapted from Rogers, 1935.



**FIGURE 26** Examples of forms and form names: (a) hexagonal pyramid; (b) dihexagonal dipyratid; (c) dihexagonal pyramid; (d) octahedron; (e) trisoctahedron; (f) hexoctahedron.

of stereo diagrams are important. Figure 30 shows a hexagonal prism terminated by flat faces (pinacoids) at either end, and a corresponding stereo diagram. To show the orientations of a crystal

face on a stereo diagram, we plot the orientations of a line perpendicular to the face. We call such a line a *pole*. The stereo diagram in Figure 30 contains eight points, corresponding to the eight face poles



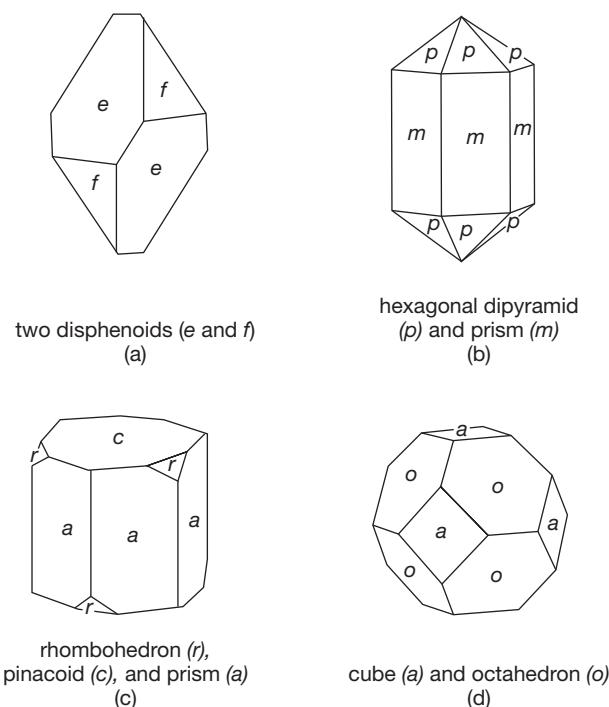
**FIGURE 27** (a) and (b) are different-shaped disphenoids; (c) two disphenoids together.

of the crystal. Because the six prism faces are vertical, their poles are horizontal and plot as points on the circle of the stereo diagram. In stereo projections, all points that plot on the circle represent vertical faces. Similarly, the top and bottom faces (pinacoid) of the crystal plot as points at the center of the stereo projection. A small, open circle represents the face below the equator, while a dot represents the one on top. Plotted on top of each other, the two symbols resemble a bull's-eye. All points at the center of a stereo diagram represent horizontal faces; the faces may be either on the top or on the bottom of the crystal. The angular relationships between the prismatic faces are well shown on the stereo diagram; the dots

representing those faces are  $60^\circ$  from each other. The angle between the pinacoid and prism faces is  $90^\circ$  since the end faces plot in the center of the diagram and the prism faces on the outside. For clarity, we have plotted the crystal faces on Figure 30b and the crystal symmetry on Figure 30c, but crystallographers usually combine the two kinds of diagrams.

If faces are neither horizontal nor vertical, they plot within, but not at the center of, the circle. Inclined faces plot at various distances from the center, depending on their slopes. If nearly horizontal, they are near the center of the diagram; if nearly vertical, they are near the perimeter. Figure 31 shows a hexagonal pyramid with a flat base (pedion) projected onto a stereo diagram. The six pyramidal faces result in solid dots, located between the center and edge of the circle. They are solid because they represent faces above the equator. The pedion plots as an open circle at the center of the diagram since it is a horizontal face below the equator.

As a final example of a stereo diagram, consider a complicated tetragonal crystal (vesuvianite) shown in Figure 33a. The drawing is based on an imperfectly formed natural sample. Figure 33b, a stereo diagram, shows the symmetry of the crystal. Figure 33c shows the orientation of faces. The prism forms (labeled *m* and *a*) yield points on the circumference of the stereo diagram since they are vertical. The pyramidal faces (*e*) yield bull's-eye patterns representing four faces above and four faces below the equatorial plane. The pinacoid (*c*) yields a bull's-eye pattern at the center of the diagram. Note that although seeing all symmetry elements in the crystal is difficult, they are more easily seen on the stereo diagram. With the aid of a diagram, we see that vesuvianite belongs to point group  $4/m2/m2/m$ . Its symmetry consists of five rotation axes: four 2-fold axes and a 4-fold perpendicular to them. Each rotation axis is perpendicular to a mirror.



**FIGURE 28** Combined forms in ideal crystals and letters used to indicate various forms: (a) two disphenoids (*e* and *f*); (b) hexagonal dipyramid (*p*) and prism (*m*); (c) rhombohedron (*r*), pinacoid (*c*), and prism (*a*); (d) cube (*a*) and octahedron (*o*).

## POINT GROUPS AND CRYSTAL SYSTEMS

Table 1 contains 13 distinct symmetry operators. If we made a complete analysis, we would find that the number of possible ways they can combine is surprisingly small. Only 32 combinations are possible; they represent the only combinations of symmetry elements that crystals, or arrangements of atoms, can have. This leads to the division of crystals into 32 distinct point groups, also sometimes called *crystal classes*, each having their own distinct symmetry. Although the expression

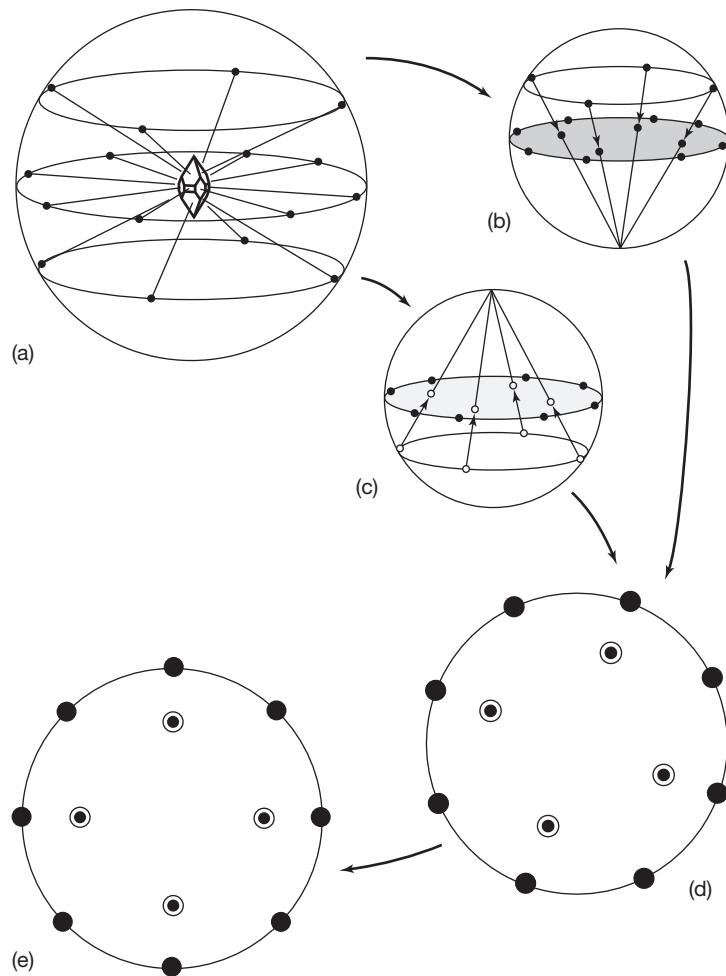
## BOX 5

## Plotting Crystal Faces on a Stereo Diagram

The process of plotting crystal faces on a stereo diagram is depicted in Figure 29. The crystal is imagined to lie at the center of a sphere. Perpendiculars (called **poles**) to each face on the crystal are extended until they intersect the sphere (Figure 29a). To create a two-dimensional drawing, we project the points on the surface of the sphere onto the sphere's equatorial plane, which intersects the sphere in a circle. To do this, we draw lines connecting each point in the northern hemisphere with the south pole of the sphere (Figure 29b), and each point in the southern hemisphere with the north pole of the sphere (Figure 29c). Where the lines will pass through the equatorial plane, we place an open circle to represent faces "below

the equator" and solid dots to represent faces "above the equator." Each face on the crystal is thus represented by a point on the equatorial plane and located within the circle that represents the equator. The circle and points within it are the stereo projection (Figure 29d). The stereo projection shows the same symmetry as the original crystal; in Figure 29 the symmetry includes a 4-fold axis, several mirrors, and 2-fold axes.

Normally, we orient stereo projections so that lines of symmetry are north-south or east-west if possible (Figure 29e). However, we have not done that in some of the diagrams in this chapter to emphasize that orientation is only a matter of convention.

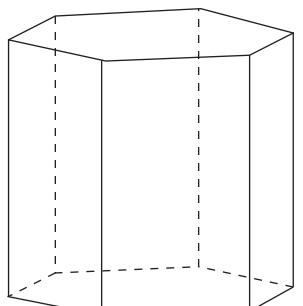


**FIGURE 29** Constructing a stereo diagram: (a) normals are drawn to crystal faces to project them onto a sphere; in (b) and (c) the points on the sphere are projected onto the equatorial plane; (d) the result is the stereo diagram. Solid dots are points projected from on or above the equator; open circles are points projected from below the equator; a "bull's eye" indicates both; (e) usually we rotate the diagram so lines of symmetry are north-south or east-west, if possible.

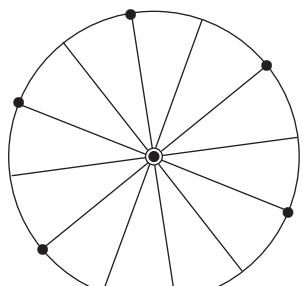
*point group* refers only to symmetry, and *crystal class* refers specifically to the symmetry of a crystal, the semantic difference is subtle and the two phrases are often used interchangeably by mineralogists. We can make drawings of crystal shapes

with all 32 possible symmetries (Figure 34), but some of them are not represented by any known minerals.

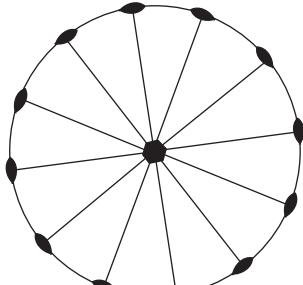
Mineralogists group the 32 classes into six crystal systems based on common symmetry



(a)



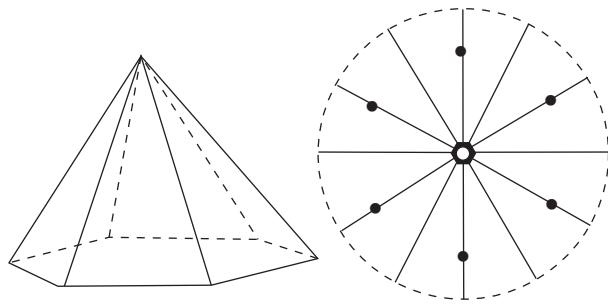
(b)



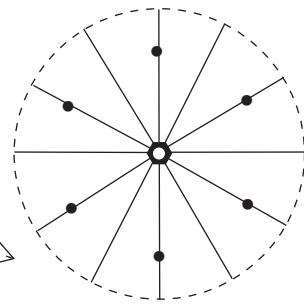
(c)

**FIGURE 30** Hexagonal prism with terminating pinacoid:  
(a) crystal drawing; (b) stereo diagram showing orientation of faces and mirror planes; (c) stereo diagram showing the total symmetry of the crystal. Note the pinacoid plots as a "bull's eye" at the center of the diagram.

elements: cubic, hexagonal, orthorhombic, tetragonal, monoclinic, and triclinic. Figure 35 shows some representative drawings for common minerals that belong to each system. Box 6 contains a flow chart that can be used to determine the crystal system and point group of many well-formed crystals. Sometimes determining the class and system of a crystal, especially for imperfect crystals, is quite difficult or impossible. Yet, crystals that belong to a given system share some common characteristics, so it is may be possible to identify



(a)



(b)

**FIGURE 31** Hexagonal pyramid and pedion:  
(a) crystal drawing; (b) stereo projection showing orientation of faces and crystal symmetry. Note the pedion plots as an open circle at the center of the diagram.

the crystal system quite quickly, especially for crystals with lots of symmetry:

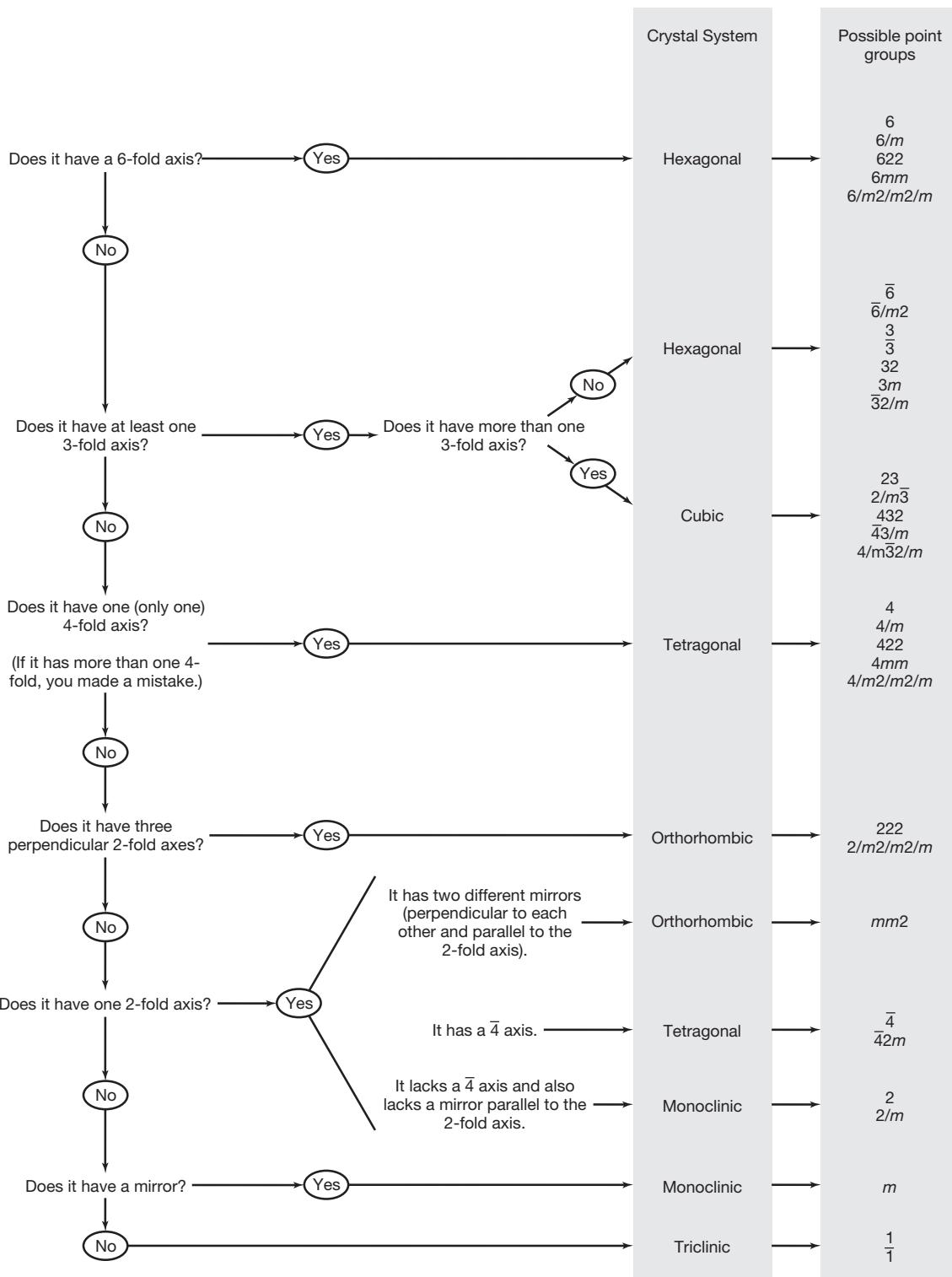
**Cubic System:** This system is also called the *isometric system*. Crystals have high symmetry, all having four 3-fold or  $\bar{3}$  axes. Some have three 4-fold axes as well, and some have 2-fold axes or mirror planes. Cubes and octahedra are examples of forms belonging to the cubic system, but other forms belong to the cubic system, too (including the last 16 entries in Figure 25). We call the general form (the form with the most faces), having 48 faces, a hexoctahedron (see the last entry in Figure 34). Many complex shapes are possible, but all tend to be **equant**, meaning they are approximately equidimensional. Often the crystals contain only one or two forms. Minerals of the cubic system are optically isotropic; they have the same optical properties in all directions.

**Hexagonal System:** Crystals have a single 3-fold,  $\bar{3}$  or 6-fold axis. Crystals with more than one 3-fold or  $\bar{3}$  axis belong to the cubic system. Hexagonal crystals may also have 2-fold axes and mirror planes. Because they have one direction that is different from others, hexagonal crystals are often prisms of three or six sides terminated by pyramids or pinacoids. Other forms, including the scalenohedron and rhombohedron, are also possible. Minerals of the hexagonal system are optically uniaxial; the single optic axis is parallel to the 3-fold,  $\bar{3}$  or 6-fold axis of symmetry.

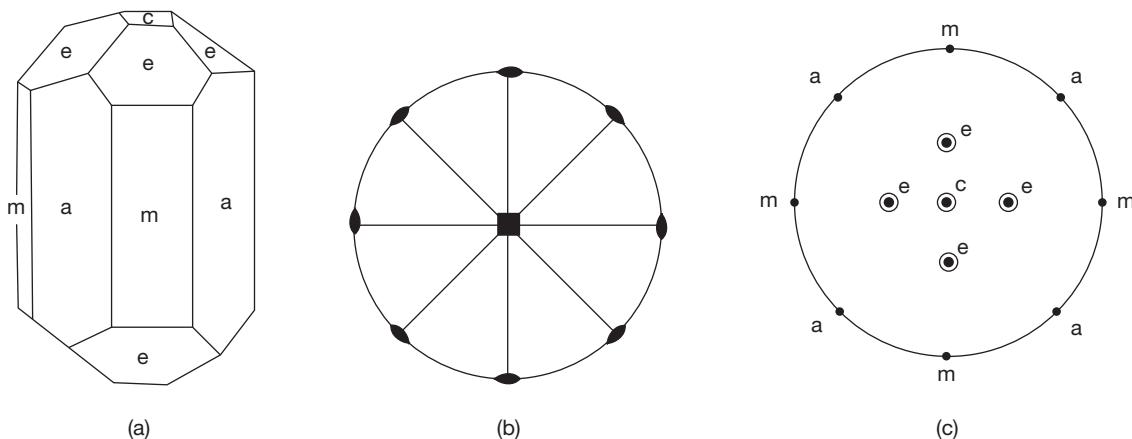
**Tetragonal System:** One 4-fold or  $\bar{4}$  axis of symmetry characterizes all tetragonal crystals; crystals that have more than one 4-fold axis must belong to the cubic system. Tetragonal crystals

**BOX 6****Determining Crystal System and Point Group**

The flow chart shown below can be used to determine a crystal's system and point group. The procedure is relatively straightforward for most well-formed crystals. However, for subhedral or anhedral crystals it is often impossible.



**FIGURE 32** Flow chart for determining crystal system and crystal class.



**FIGURE 33** Vesuvianite crystal: (a) idealized crystal drawing; (b) stereo diagram showing symmetry of crystal; (c) stereo diagram showing orientation of crystal faces.

may also have 2-folds and mirror planes. As with the crystals in the hexagonal system, tetragonal crystals are often combinations of prismatic and other forms. Minerals of the tetragonal system are optically uniaxial; the single optic axis is parallel to the 4-fold, or  $\frac{1}{4}$  axis, of symmetry.

**Orthorhombic System:** Crystals have three perpendicular 2-fold axes, two perpendicular mirror planes paralleling a 2-fold axis, or three perpendicular  $2/m$  axes. A shoebox shape is an excellent example, but many shapes and forms are possible. The disphenoids in Figure 27 have point group symmetry 222 and belong to the orthorhombic system. Sometimes orthorhombic crystals may be rather equant but they are often quite tabular. Minerals belonging to the orthorhombic system are optically biaxial.

**Monoclinic System:** Crystals are characterized by a single 2-fold axis or mirror, or by a 2-fold axis perpendicular to a mirror. In the simplest case, they may appear as shoeboxes squashed in one direction so that one angle at some corners is not  $90^\circ$ . The symmetry may be hard to see because monoclinic crystals often comprise many different forms. Minerals belonging to the monoclinic system are optically biaxial.

**Triclinic System:** Crystals have no symmetry greater than a 1-fold axis or an inversion center. Minerals belonging to the triclinic system are optically biaxial.

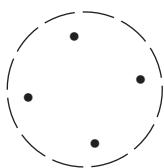
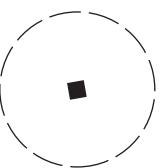
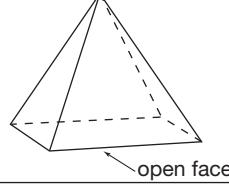
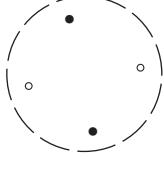
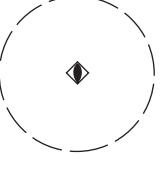
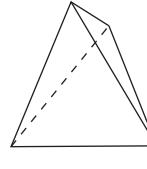
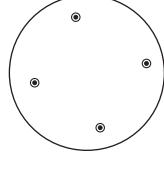
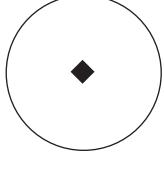
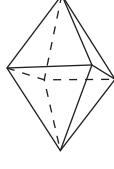
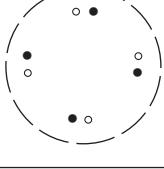
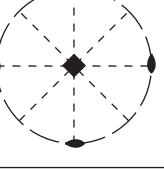
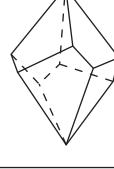
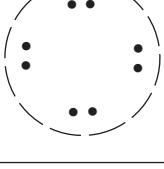
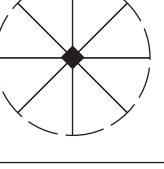
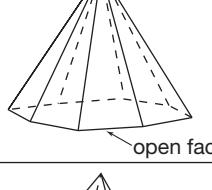
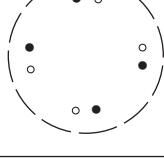
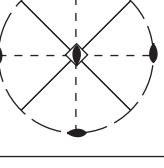
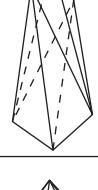
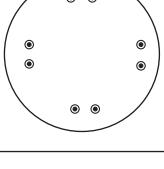
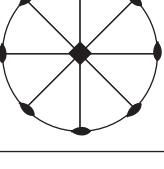
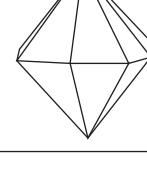
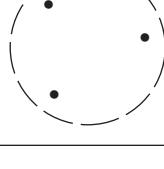
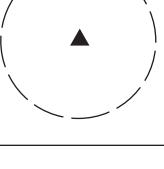
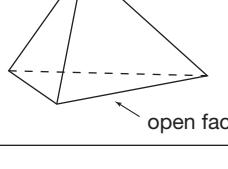
All six crystal systems are represented by common minerals. For common minerals, 8% are cubic, 9% are tetragonal, 9% are triclinic, 17% are hexagonal, 27% are orthorhombic, and 30% are monoclinic. Within each system, different point groups have different amounts of symmetry. Most

natural crystals fall into the point group with the highest symmetry in each system. Few belong to the point groups of lowest symmetry. Figure 34 depicts stereo diagrams for all the 32 possible point groups and shows crystal drawings of their general forms. The point groups are designated using a conventional notation called *Hermann-Mauguin symbols* (Box 7).

We call the crystal shapes shown in Figure 34 *general forms* because they are equivalent to general points in a stereo diagram. The faces are at nonspecial angles to mirror planes and rotation axes, and the number of faces is the maximum for a single form within the point group. The 32 groups also contain special forms. Figure 25 shows some of them. Faces of special forms are parallel or perpendicular to symmetry elements, or at other special angles to the symmetry operators. All special forms comprise fewer faces than general forms of the same class, and sometimes only one face. The names of the general forms in Figure 34 are sometimes used as names for the point groups. For example, we call the class  $6/m2/m2/m$  the *dibexagonal dipyramidal class*. More commonly, however, we simply refer to the classes by their symmetry using Hermann-Mauguin symbols. Table 3 gives a complete list of all the forms possible in each crystal system and the number of faces comprising the form. Some forms exist in all crystal systems, some in a few, and some, like the octahedron, in only one. Table 3 is convenient when identifying forms because the possibilities in each crystal system are limited. For example, if we note four equivalent faces on a tetragonal crystal, they must represent a prism, pyramid, or disphenoid. We can decide which by noting the relative orientations of the four faces. Prism faces are parallel, pyramid faces converge in one direction (and intersect at a point unless another face terminates them), and disphenoid faces converge in pairs (Figure 27).

point group	general form on stereo diagram	complete symmetry	general form	general form name
1				pedion
$\bar{1}$				pinacoid
2				sphenoid
$m$				dome
$2/m$				monoclinic prism
222				rhombic disphenoid
$mm2$				rhombic pyramid
$2/m2/m2/m$				rhombic dipyramid

**FIGURE 34** The 32 point groups: their symmetries and general forms.

point group	general form on stereo diagram	complete symmetry	general form	general form name
4				tetragonal pyramid
$\bar{4}$				tetragonal disphenoid
$4/m$				tetragonal dipyramid
$422$				tetragonal trapezohedron
$4mm$				ditetragonal pyramid
$\bar{4}2m$				tetragonal scalenohedron
$4/m2/m2/m$				ditetragonal dipyramid
3				trigonal pyramid

**FIGURE 34** (continued)

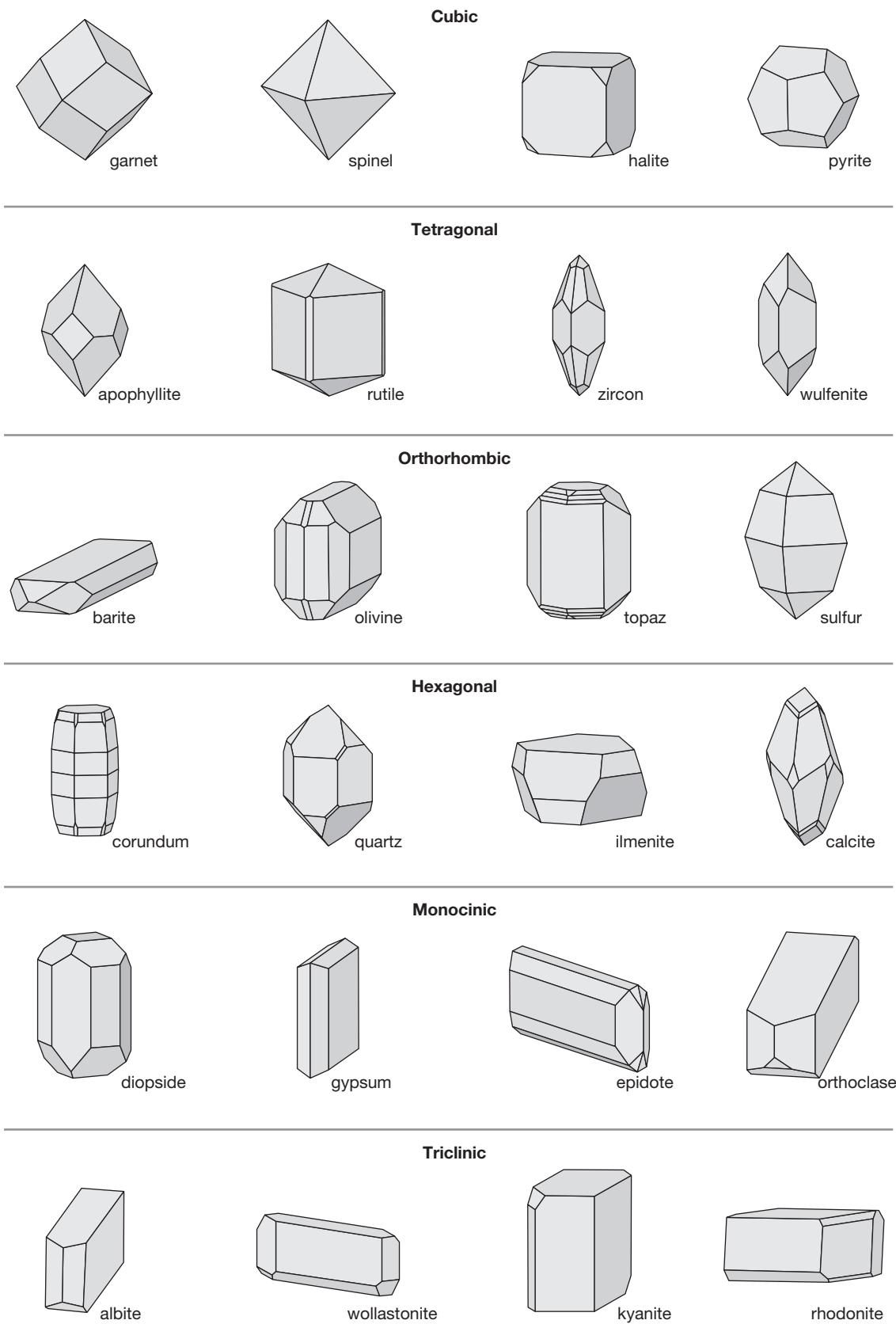
point group	general form on stereo diagram	complete symmetry	general form	general form name
$\bar{3}$				rhombohedron
32				trigonal trapezohedron
$3m$				ditrigonal pyramid open face on bottom
$\bar{3}2m$				hexagonal scalenohedron
6				hexagonal pyramid open face on bottom
$\bar{6}$				trigonal dipyramidal
$6/m$				hexagonal dipyramidal
622				hexagonal trapezohedron

**FIGURE 34** (continued)

point group	general form on stereo diagram	complete symmetry	general form	general form name
$6mm$				dihexagonal pyramid open face on bottom
$\bar{6}m2$				ditrigonal dipyramid
$6/m2/m2/m$				dihexagonal dipyramid
$23$				tetartoid
$2/m\bar{3}$				diploid
$432$				gyroid
$\bar{4}3m$				hextetrahedron
$4/m\bar{3}2/m$				hexoctahedron

**FIGURE 34** (continued)

## Crystal Morphology and Symmetry



**FIGURE 35** Examples of mineral crystals belonging to the six different crystal systems. Crystals belonging to the same system often share characteristics. Cubic crystals are all equant (equidimensional) and contain few forms. Most tetragonal crystals show one 4-fold axis of symmetry, and hexagonal crystals always have a single 6- or 3-fold axis of symmetry. Monoclinic and triclinic crystals are more difficult to distinguish, but crystals of both systems are often tabular (thin in one dimension).

**BOX 7****Hermann-Mauguin Symbols**

The symbols used in this text are based on notations developed by C. H. Hermann and C. V. Mauguin in the early 1900s. They have been used by most crystallographers since about 1930. Numbers refer to rotation axes of symmetry; a bar over a number indicates a rotoinversion axis. Mirrors, designated by  $m$ , are perpendicular to an axis if they appear as a denominator (for example,  $4/m$ ), and parallel to an axis otherwise. When articulating the symbols, they are pronounced just as if they were typographical characters.  $4/m\bar{3}2/m$ , for example, is read "four over m, bar three, two over m."

One, two, or three symbols describe a point group; they combine in different ways for different systems (Figure 34):

For cubic point groups, the first symbol describes three mutually perpendicular principal symmetry axes, oriented perpendicular to cubic faces (if cubic faces are present). The second describes four axes oriented at angles of  $54^\circ 44'$  to the principal axes. They correspond to the "body diagonals" of a cube, a diagonal from a corner through the center to the opposite corner. The third symbol, if present, describes six 2-fold axes or mirror planes oriented at angles of  $45^\circ$  to the principal axes. They correspond to "edge diagonals" of a cube, diagonals from the center of edges through the center of the cube to the opposite edge.

For hexagonal point groups, the first symbol describes the single principal axis. The second, if present, describes three secondary rotation axes oriented at  $120^\circ$  to each other and perpendicular to the principal axis, or three mirror planes oriented at  $120^\circ$  to each other and parallel to the principal axis. The third symbol, if present, represents mirror planes or 2-fold axes oriented between the secondary axes.

For tetragonal point groups, the first symbol represents the principal axis. The second, if present, represents two secondary axes perpendicular to each other and to the principal axis, or two mirror planes oriented at  $90^\circ$  to each other and parallel to the principal axis. The third represents axes or mirror planes between the secondary axes.

Only three orthorhombic point groups are possible. Point group 222 has three mutually perpendicular 2-fold axes. Point group  $mm2$  has one 2-fold axis with two mutually perpendicular mirror planes parallel to it. Point group  $2/m2/m2/m$  has three perpendicular 2-fold axes with mirror planes perpendicular to each.

For monoclinic point groups, only one symmetry element is included in the Hermann-Mauguin symbols because the only possible symmetries are a 2-fold axis, a mirror, or a 2-fold axis with a mirror perpendicular to it. Similarly, for triclinic crystals, the only possible point groups are 1 and  $\bar{1}$ .

Crystal System	Possible First Symbol	Possible Second Symbol	Possible Third Symbol
cubic	$4, 4/m, \bar{4}, 2, 2/m$	$3, \bar{3},$	$2, 2/m, m$
hexagonal	$6, 6/m, \bar{6}, 3, \bar{3}$	$2, 2/m, m$	$2, 2/m, m$
tetragonal	$4, 4/m, \bar{4}$	$2, 2/m, m$	$2, 2/m, m$
orthorhombic	$2, 2/m, m$	$2, 2/m, m$	$2/m, m$
monoclinic	$2, 2/m, m$		
triclinic	$1, \bar{1}$		

**TABLE 3** The Possible Forms of Each Point Group

Triclinic-Monoclinic-Orthorhombic Systems

Form	Class							
	1	$\bar{1}$	2	$m$	$\frac{2}{m}$	222	2mm	$\frac{2}{m} \frac{2}{m} \frac{2}{m}$
1 pedion	X		X	X			X	
2 pinacoid		X	X	X	X	X	X	X
2 dome			X	X			X	
2 sphenoid			X	X				
4 prism					X	X	X	X
4 disphenoid						X		
4 pyramid							X	
8 dipyramid								X

(continued)

**TABLE 3 (continued)****Tetragonal System**

Number of Faces	Form	Class						
		4	$\bar{4}$	$\frac{4}{m}$	422	4mm	$\bar{4}2m$	$\frac{4}{m}\frac{2}{m}\frac{2}{m}$
1	pedion	X				X		
2	pinacoid		X	X	X		X	X
4	tetragonal prism	X	X	X	X	X	X	X
4	tetragonal pyramid	X				X		
4	tetragonal disphenoid		X				X	
8	ditetragonal prism				X	X	X	X
8	tetragonal dipyramid			X	X	X	X	X
8	tetragonal trapezohedron				X			
8	tetragonal scalenohedron						X	
8	ditetragonal pyramid					X		
10	ditetragonal dipyramid							X

**Hexagonal System**

Number of Faces	Form	Class										
		3	$\bar{3}$	32	$3m$	$\frac{3}{m}\frac{2}{m}$	6	$\frac{3}{m}$	$\frac{6}{m}$	622	6mm	$\bar{6}m2$
1	pedion	X			X		X			X		
2	pinacoid		X	X		X		X	X		X	X
3	trigonal prism	X		X	X			X				
3	trigonal pyramid	X			X							
6	ditrigonal prism			X	X						X	
6	hexagonal prism	X	X	X	X	X		X	X	X	X	
6	trigonal dipyramid			X			X				X	
6	rhombohedron	X	X		X							
6	trigonal trapezohedron	X										
6	ditrigonal pyramid			X								
6	hexagonal pyramid		X		X				X			
12	hexagonal dipyramid			X			X			X	X	
12	hexagonal scalenohedron			X								
12	dihexagonal prism								X	X	X	
12	ditrigonal bipyramid									X		
12	hexagonal trapezohedron								X			
12	dihexagonal pyramid									X		
24	dihexagonal dipyramid										X	

**Cubic System**

Number of Faces	Form	Class					
		23	432	$\frac{2}{m}\frac{3}{m}$	$\bar{4}3m$	$\frac{4}{m}\frac{3}{m}\frac{2}{m}$	
4	tetrahedron	X				X	
6	cube (hexahedron)	X	X	X		X	X
8	octahedron		X	X			X
12	dodecahedron	X	X	X	X		X
12	pyritohedron	X		X			
12	tristetrahedron	X					
12	deltohedron	X				X	
12	tetartoid	X					
24	tetrahexahedron		X			X	X
24	trapezohedron	X		X			X
24	trisoctahedron		X	X			X
24	hextetrahedron					X	
24	diploid			X			
24	gyroid		X				
48	hexoctahedron						X

**Questions for Thought**

Some of the following questions have no specific correct answers; they are intended to promote thought and discussion.

- When we think of symmetry, we usually think of some sort of repetitive motif such as a pattern on wallpaper or of a physical object such as a crystal. However, symmetry applies to other things. Give

several examples of symmetry that do not involve repetition of a physical pattern or the shape of an object.

- We can describe the symmetry of crystals using 13 different operators (Table 1). Why do we need 13? Why not fewer or more?

3. How can two different crystals with identical symmetry have different forms and shapes?
4. If you examine a crystal and see lots of symmetry, what can you infer about the crystal's atomic structure? On the other hand, if you examine a crystal and see no symmetry, what can you infer about the crystal's atomic structure?
5. When we list Hermann-Mauguin symbols for point groups, we never include *i*. Some point groups, however, do have inversion centers of symmetry. Why do we omit the *i* from the symbols?
6. Why can crystals have no more than three 4-fold axes of symmetry?
7. A crystal may have one 2-fold axis of symmetry. It may also have more, but no crystals have two 2-fold axes of symmetry. Why can't crystals have two 2-fold axes of symmetry? What is the maximum number of 2-fold axes of symmetry they can have?
8. Why are there only 32 point groups?
9. Although there are only 32 point groups, crystals can have many possible forms, and some forms belong to more than one point group. Why are there so many possible forms? How can they belong to more than one point group?
10. Some crystals have only one form. Others have many. What controls or limits the possible combinations of forms in crystals?
11. Can a crystal consist of only open forms?
12. To what point groups do each of the four crystals depicted in Figure 28 belong?

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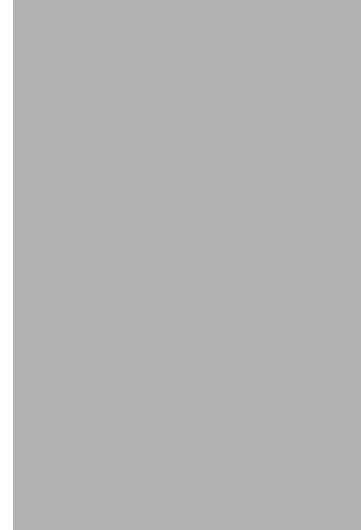
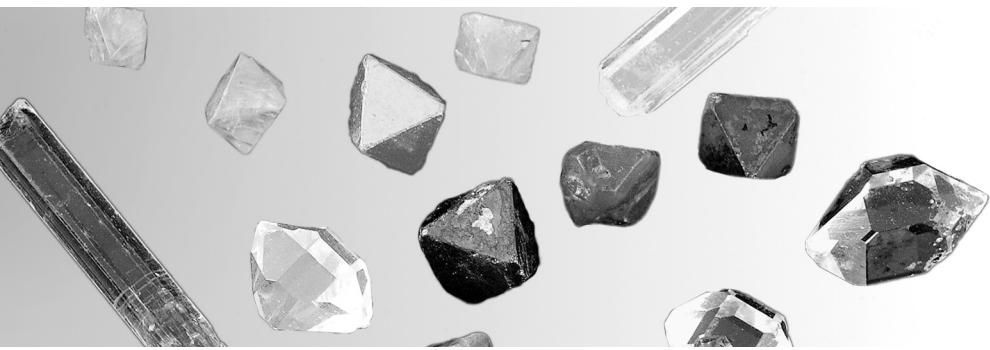
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# Crystallography



# Crystallography

In this chapter, we look at the implications of that symmetry. We find that all crystals are made of basic building blocks called *unit cells*, and that the unit cells fit together in a pattern described by a Bravais lattice. There are six possible unit cell shapes, and each defines a different crystal system. There are 14 possible Bravais lattices. We can often make inferences about unit cells and Bravais lattices on the basis of crystal habit and symmetry. The overall symmetry of an atomic structure depends on more than just unit cell and lattice; it also depends on the locations of atoms in the unit cell. There are 230 possible structure symmetries, called *space groups*. Identifying space group symmetry requires the use of X-ray techniques.

## OBSERVATIONS IN THE SEVENTEENTH AND EIGHTEENTH CENTURIES

In 1669 Nicolaus Steno studied many quartz crystals and found angles between adjacent prism faces, termed **interfacial angles**, to be  $120^\circ$  no matter how the crystals had formed (Figure 1). Steno could not make precise measurements, and some of his contemporaries argued that he was overlooking subtle differences. A century later, in 1780, more accurate measurements became possible when Carangeot invented the **goniometer**, a protractor-like device used to measure interfacial angles on crystals. Carangeot's measurements confirmed Steno's earlier observations. Shortly after, Romé de l'Isle (1782) stated the first law of symmetry, a law called the "constancy of interfacial angles," which we commonly call **Steno's law**. This law states that *angles between equivalent faces of crystals of the same mineral are always the same*. The law acknowledges that the size and shape of the crystals may vary.

In 1784 René Haüy studied calcite crystals and found that they had the same shape, no matter what

their size. Haüy hypothesized the existence of basic building blocks called **integral molecules** and argued that large crystals formed when many integral molecules bonded together. Haüy erroneously concluded that integral molecules formed basic units that could not be broken down further. At the same time, Berzelius and others established that the composition of a mineral does not depend on sample size. Additionally, Joseph Proust and John Dalton proved that elements combined in proportions of small rational numbers. Scientists soon combined these crystallographic and chemical observations and came to several conclusions:

- Crystals are made of small basic building blocks.
- The blocks stack together in a regular way, creating the whole crystal.
- Each block contains a small number of atoms.
- All building blocks have the same atomic composition.
- The building block has shape and symmetry that relate to the shape and symmetry of the entire crystal.



**FIGURE 1** Quartz crystals. Nicolaus Steno studied quartz crystals and found that the angles between prism faces were always 120°

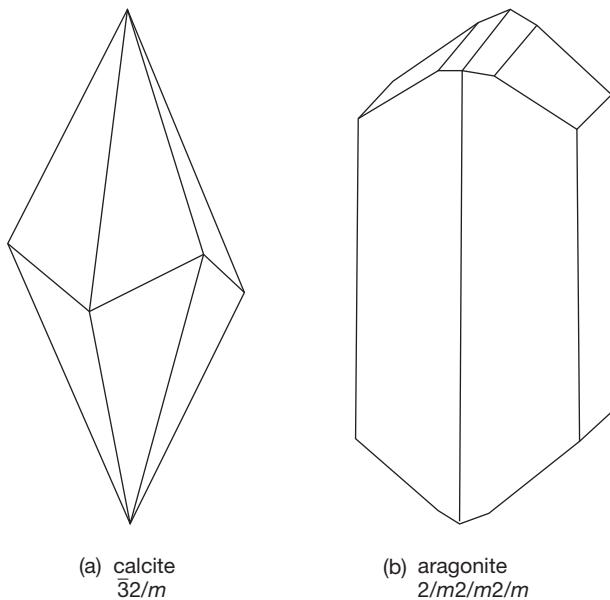
Early in the 1800s, several researchers found that crystals of similar, but not identical, chemical composition could have identical shapes. W. H. Wollaston (c. 1809) showed that calcite ( $\text{CaCO}_3$ ), magnesite ( $\text{MgCO}_3$ ), and siderite ( $\text{FeCO}_3$ ) all formed the same distinctive rhombohedral crystals (Figure 2). Those who studied sulfate compounds also found that crystals of different compositions had the same crystal shape. The rhombohedral carbonates, and the sulfates, are examples of **isomorphous series**. Wollaston and others concluded that when crystal shapes in such series are truly identical, the distribution of atoms within the crystals must be identical as well, even if the compositions are not. Minerals with identical atomic distributions are termed **isostructural**.

Sometimes isostructural minerals form solid solutions because they can mix to form intermediate compositions. Fayalite ( $\text{Fe}_2\text{SiO}_4$ ) and forsterite ( $\text{Mg}_2\text{SiO}_4$ ) are isostructural and form a complete solid solution; olivines can have any intermediate composition. In contrast, halite ( $\text{NaCl}$ ) and periclase ( $\text{MgO}$ ) are isostructural but do not form solid solutions. Calcite and siderite are isostructural but their mutual solubility is limited, and they form only limited (or partial) solid solutions.

In 1821 Eilhard Mitscherlich, a student of Berzelius's, discovered that the same elements may combine in different atomic structures. For instance, calcite and aragonite both have composition  $\text{CaCO}_3$ , but they have different crystal shapes and physical properties. We call such minerals



**FIGURE 2** Rhombohedral carbonates. Because calcite (left), rhodochrosite (crystals in top sample), and siderite (dark mineral in the bottom right sample) all have the same atomic arrangement, they all form the same shaped (rhombohedral) crystals.



**FIGURE 3** Typical calcite and aragonite crystals: (a) calcite ( $\bar{3}2/m$ ) and (b) aragonite ( $2/m2/m2/m$ ) have the same composition, but their atomic arrangements, crystal shapes, and symmetries are different.

**polymorphs** because, although identical in composition, they have different crystal morphologies. Mineralogists have now studied several other  $\text{CaCO}_3$  polymorphs, but none except vaterite occur naturally. In calcite and vaterite the basic building blocks are rhombohedral, while in aragonite they are orthorhombic (Figure 3). It soon became clear that no direct correlation exists between the shapes of building blocks and crystal composition, as Haüy had originally thought.

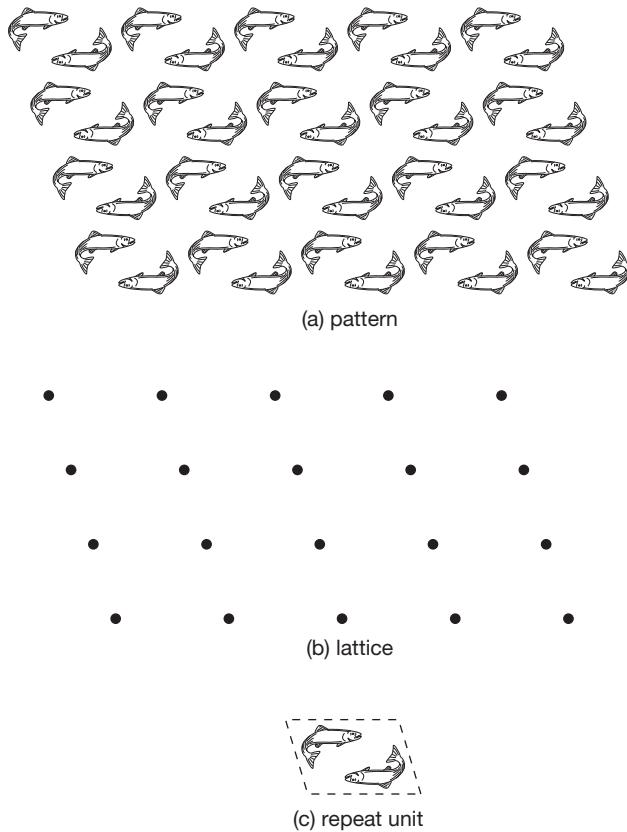
Despite flaws in some of his ideas, however, we must credit René Haüy as one of the founders of crystallography. In later years, he pioneered the application of mathematical concepts to crystallography and established the basis for modern crystallography. Crystallographers still use much of his work today. We now accept that:

- All crystals have basic building blocks called **unit cells**.
- The unit cells are arranged in a pattern described by points in a **lattice**.
- The relative proportions of elements in a unit cell are given by the chemical formula of a mineral.
- Crystals belong to one of six crystal systems. Unit cells of distinct shape and symmetry characterize each crystal system.
- Total crystal symmetry depends on both unit cell symmetry and lattice symmetry.

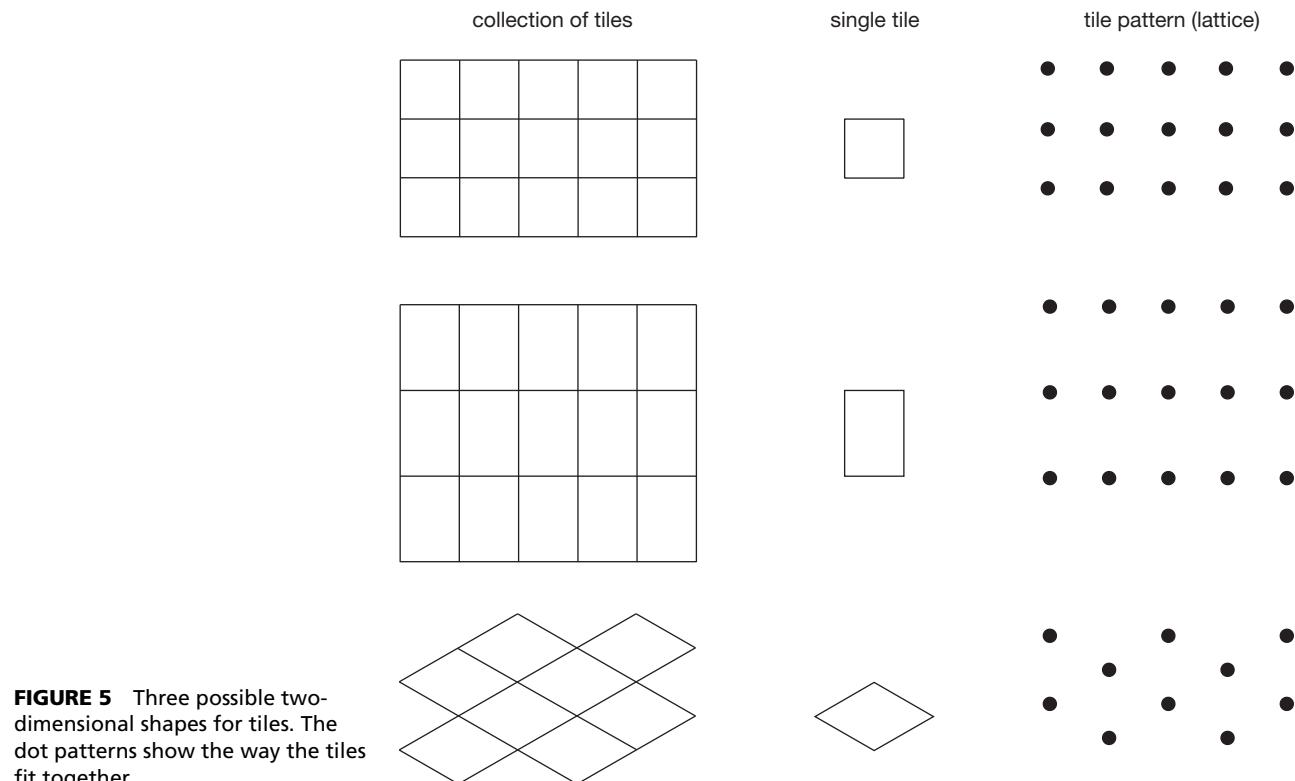
Symmetry due to rotation, reflection, and inversion are all types of **point symmetry**. The orderly

repetition of patterns due to **translation** is another form of symmetry, called **space symmetry**. Space symmetry differs from point symmetry. Space symmetry repeats something an infinite number of times to fill space, while point symmetry repeats something a discrete number of times and only describes symmetry localized about a central point. Point symmetry operators return a dot or a crystal face to its original position and orientation after 1, 2, 3, 4, or 6 repeats of the operation, but space symmetry operators do not.

We often envision translational symmetry by thinking about a lattice. Figure 4a shows a pair of fish repeated by translation in two directions. If a dot replaces each pair, the resulting pattern is the lattice, a pattern of dots that repeats indefinitely (Figure 4b). The distances between lattice points are the translations that define the lattice. Each dot represents one repeat unit—a pair of fish and some space around them (Figure 4c). The lattice describes how the repeat units fit together to produce the whole pattern.



**FIGURE 4** Crystal structures must have units that repeat in an orderly way, just like the trout in this figure: (a) pairs of trout (related by a 2-fold axis) repeating in two dimensions; (b) the lattice that describes the repetition; (c) a repeat unit containing two trout related by a 2-fold axis. This unit repeats according to the lattice in (b), yielding the entire pattern.



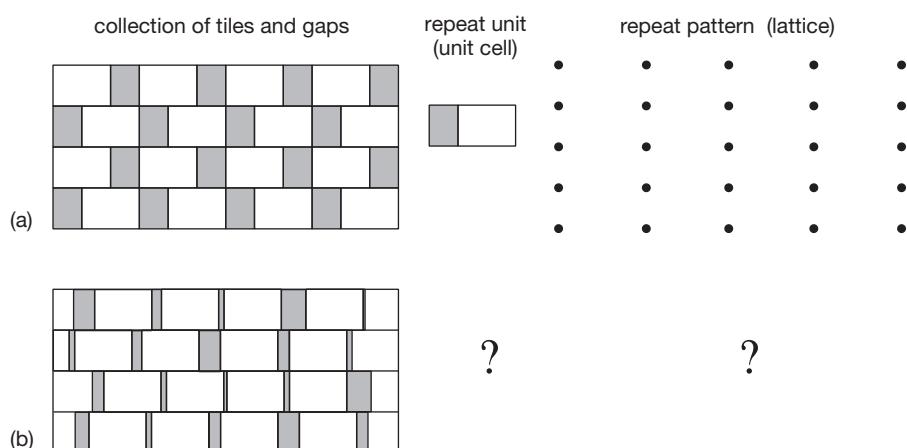
**FIGURE 5** Three possible two-dimensional shapes for tiles. The dot patterns show the way the tiles fit together.

## UNIT CELLS AND LATTICES IN TWO DIMENSIONS

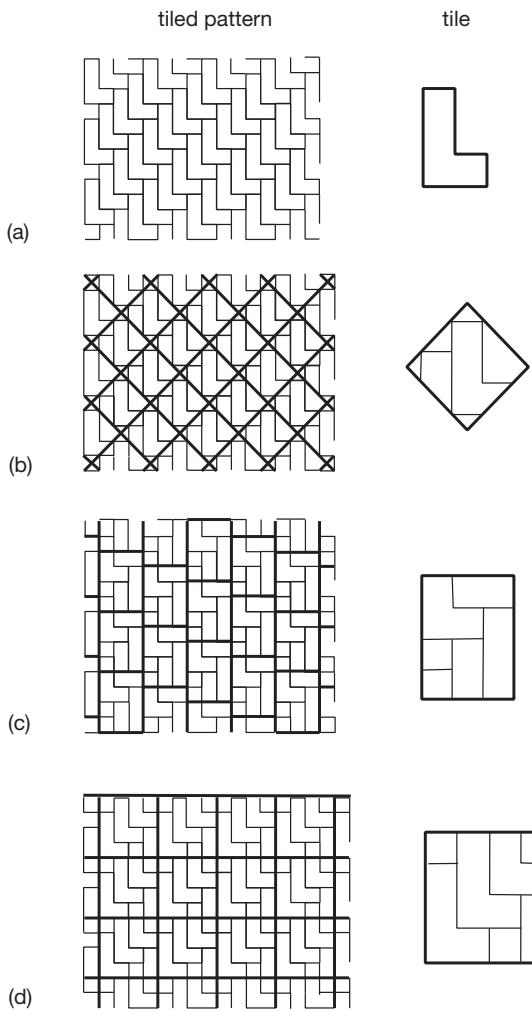
### Shapes of Unit Cells in Two Dimensions

What possible shapes can unit cells have? Mineralogists begin answering this by considering only two dimensions. This is much like imagining what shapes we can use to tile a floor. Figure 5 shows some possible tile shapes. In the right-hand column of Figure 5, a single dot has replaced each tile to show how the tiles repeat.

What happens when gaps occur between unit cells? Figure 6 shows the two possibilities: The gaps may be either regularly (Figure 6a) or randomly (Figure 6b) distributed. If regularly, we can simply redefine the unit cells to include the gap. If randomly, the entire structure is not composed of identical building blocks that fit together in a regular way. It is not repetitive and we cannot describe it with a regular pattern. It does not, therefore, represent a crystal structure, so we need not consider unit cell shapes that do not fit together without gaps between them.

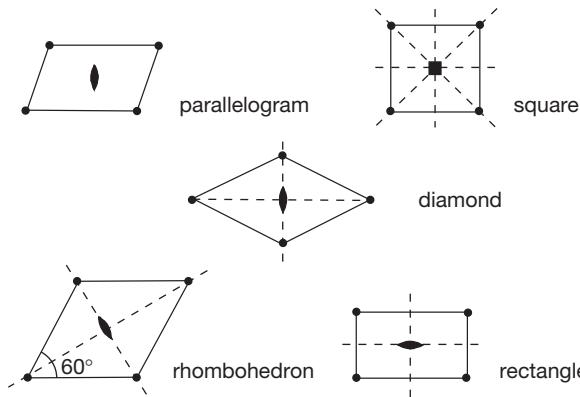


**FIGURE 6** What happens if there are gaps in a pattern? (a) We can redefine the unit cell to include the gaps, provided the gaps are distributed in a regular manner. (b) If the gaps are randomly distributed, then there is no unit cell, or lattice, that adequately describes the pattern.



**FIGURE 7** A floor pattern made of L-shaped polygons: (a) the overall pattern; (b) a square tile can be used to create the pattern; (c) a rectangular tile can be used to create the pattern; (d) a larger square tile can be used to create the pattern.

Various complex patterns can appear on tiled floors, but the tiles are usually simple shapes such as squares or rectangles. For example, to tile a floor in the L-shaped pattern shown in Figure 7a, we could use L-shaped tiles. However, square or rectangular tiles would do the job just as well; Figures 7b, c, and d show some examples. In fact, we can make any repetitive two-dimensional pattern, no matter how complicated, with tiles of one of four fundamental shapes: parallelogram, rhomb, rectangle, and square. For reasons we will see later, we usually distinguish two types of rhombs: those with **nonspecial angles** and those with  $60^\circ$  and  $120^\circ$  angles. For the rest of this chapter, we will refer to the general type of rhomb as a *diamond*, and *rhomb* will be reserved for shapes with only  $60^\circ$  and  $120^\circ$  angles. Figure 8



**FIGURE 8** The five basic two-dimensional shapes and their symmetry. Dashed lines indicate mirror planes. Lenses and squares show 2-fold and 4-fold rotation axes.

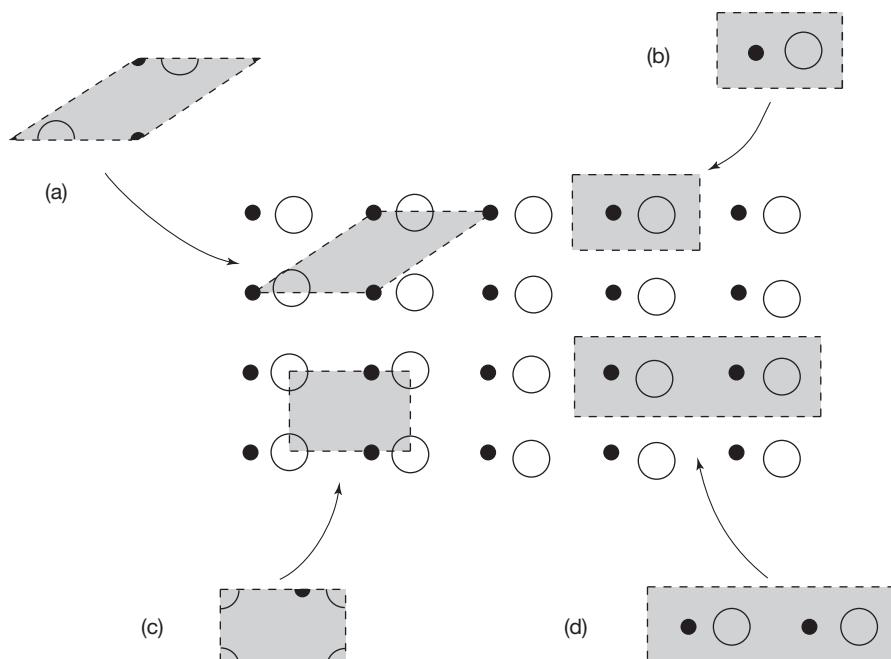
shows the five basic shapes, the only ones needed to discuss two-dimensional unit cells, and their symmetries.

### Motifs and Lattices

We call designs that repeat, such as those on wallpaper, *motifs*. The term *motif* is used in an analogous way in music to refer to a sequence of notes that repeat. Interior decorators or clothing designers use the term to describe a common theme or element in their work. We can think of patterns as starting with one motif. The motif is then reproduced by translating (moving) it a certain distance and reprinting it. The distance of the translation is the distance between lattice points. If a dot replaces each motif, we get the lattice.

Figure 4 shows a motif (two fish) repeated according to an inclined lattice. When combined with surrounding empty space, motifs form unit cells. The unit cells, which are all parallelograms, stack together to form the entire pattern. Unit cells may have any of the shapes in Figure 8.

Figure 9 shows a pattern made of two atoms, symbolized by solid and open circles. The entire pattern consists of motifs composed of one of each. The figure shows several possible choices of unit cells. By convention, however, we usually choose the smallest unit cell that contains the same symmetry as the entire pattern or structure. Unit cells a, b, and c contain only one motif in total (one solid circle and one open circle). We call them *primitive* because they are the smallest choices possible. All primitive unit cells contain exactly one motif in total. We term unit cell d in Figure 9 *doubly primitive* because it contains two motifs. Unit cell b in Figure 9 would be the choice of most crystallographers because it is



**FIGURE 9** Pattern based on a motif containing two atoms, shown by solid and open circles; a, b, c, and d are possible choices for a unit cell. Cells a, b, and c contain one motif (a total of one white circle and one black dot); d contains two circles and two dots. The entire pattern, and unit cells b, c, and d, show a mirror plane. Unit cell a, however, does not, and so is an inappropriate choice for a unit cell because it does not reflect the symmetry of the entire pattern.

simple, primitive, and contains the same symmetry as the entire structure (Box 1). Note that unit cell a, while also being primitive, does not have a mirror plane of symmetry; the other choices do.

Well-known Dutch artist M. C. Escher used repetitive patterns to create many complicated drawings. Figure 11 shows a pattern in Escher's style. A basic motif, composed of five American icons, repeats to make the entire pattern. For this pattern, we may choose a unit cell that includes one of each of the five figures and white space around them; it may have any of an infinite number of possible shapes. However, for any repetitive pattern, we can find a unit cell with one of the five shapes in Figure 8. For Figure 11, we get such a cell by drawing lines connecting four equivalent points; for example, the center of W. C. Fields's nose. Depending on the noses we choose, it is a parallelogram or has a diamond shape. If we choose four near-neighbor noses, we get a primitive unit cell; it includes one of each of the figures in total, but some figures are fragmented because they overlap the unit cell edges.

For any structure or lattice, we can always choose a primitive unit cell. Figure 12 shows a motif—here two smiley faces—arranged in a diamond pattern. A primitive diamond-shaped unit cell can be chosen (Figures 12b and c). However, a nonprimitive rectangular unit cell, containing four faces, can also be chosen (Figures 12d and e). The rectangular unit cell emphasizes 90° angular relationships, so most crystallographers would choose a nonprimitive rectangular unit cell. The two rectangular

unit cells shown have the same symmetry (a 2-fold rotation axis with two perpendicular mirror planes), but the one in Figure 12d, perhaps, shows the pattern more clearly and is a better choice. Cells with an extra lattice point (motif) in the middle, such as the rectangular one in Figure 12d with the extra pair of faces, are termed *centered*.

Unit cells and lattices are not real objects; they are concepts used by humans to help understand the repetitive nature of crystal structures. As emphasized in Figure 12, the exact outline of a unit cell is arbitrary. It is chosen for convenience, often to help visualization. Although we may think of lattice points as representing corners of unit cells, they actually do not represent corners or any other specific points within unit cells. Unit cells and lattices are just concepts that provide a convenient way to think about and discuss the repetition of structures and symmetry. Although crystallographers follow standard conventions, they are often forced to make choices. If they choose primitive unit cells, each lattice point corresponds to one unit cell and one motif. If they choose nonprimitive unit cells, lattices represent the way motifs repeat, but not the way unit cells repeat, because there is more than one lattice point per unit cell.

Figure 13 shows the five possible two-dimensional lattices, called the five **plane lattices** (corresponding to the five basic unit cell shapes) and their symmetries. Crystallographers call these lattices the *clinonet*, *diamond net*, *hexanet*, *orthonet*, and *square net*. Each corresponds to one of the possible unit cell shapes in Figure 8. To emphasize that the

## BOX 1

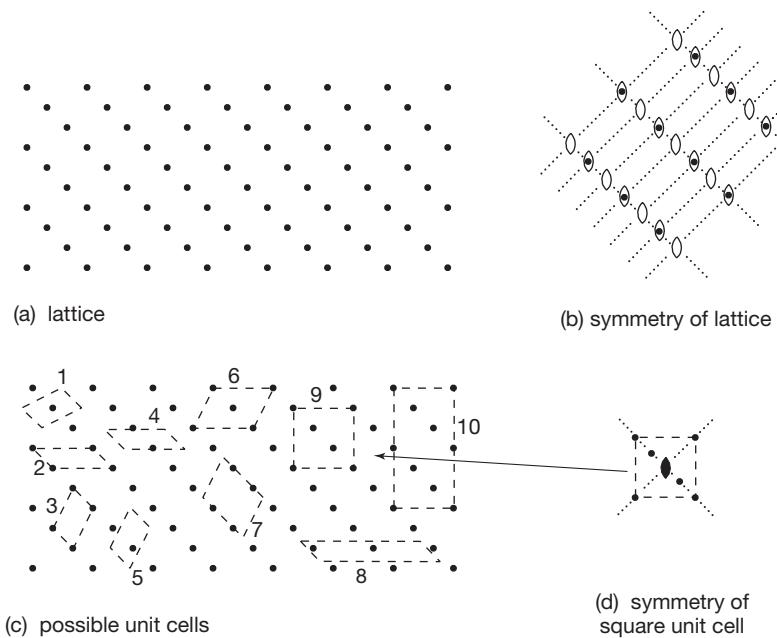
## Choices of a Unit Cell

In two dimensions, unit cells are parallelograms, including rectangles and squares, that can be fit together to produce an entire pattern. They may be chosen in many ways, although mineralogists follow some standard conventions (see text). Consider the lattice below (Figure 10a). Its symmetry is shown in Figure 10b: 2-fold axes (perpendicular to the page) located at each lattice point and between lattice points, and two sets of mirror planes at  $90^\circ$  to each other.

Figure 10c shows some possible choices of unit cells. Let's count the number of lattice points in the cells. If points are completely inside the cell, they count as one. If points are on a corner, they are a quarter in the unit cell because they are shared between four cells; if they are on a side, they are half in the cell. Some of the unit cells (cells 1 through 5) are **primitive**, containing only one lattice point in total. Cells 6, 7, and 8 are **doubly primitive**, containing two points. Cell 9 contains three points and cell 10 contains six.

The area of a cell depends only on the number of lattice points within it. All the primitive cells, for example, have the same area despite differences in shape and lattice point location. In addition, the doubly primitive unit cells all have exactly twice the area of the primitive unit cells. Two of the unit cells (9 and 10) are **orthogonal**, meaning that the angles at the corners are  $90^\circ$ . Only cell 9 is square.

Unit cells are chosen for convenience. Sometimes crystallographers choose primitive unit cells because they are simple. In this example, however, cell 9, although not primitive, is probably the choice that some crystallographers would make. Because it is square, it is easier to see. Of more importance, it contains the same symmetry elements (2-fold axis and mirror planes at  $90^\circ$  to each other) that the original structure does (Figures 10b and 10d).



**FIGURE 10** A lattice, its symmetry, and some choices for a unit cell: (a) the open circles show the lattice; (b) the symmetry of the lattice includes mirror planes (dashed lines) and 2-fold axes (lens shape); (c) some possible unit cell shapes; (d) the symmetry of cell 9, a square unit cell.

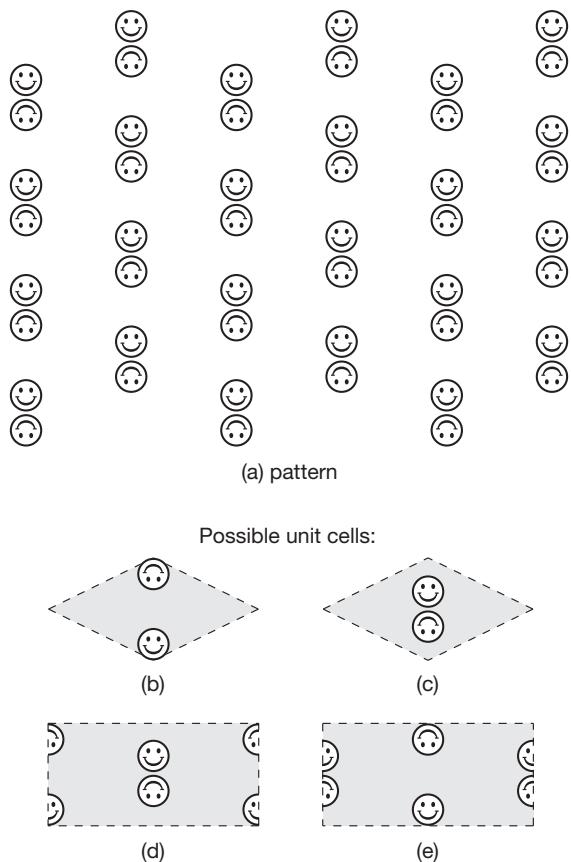
choice of a unit cell is arbitrary, note again that a centered rectangular unit cell (doubly primitive) can be chosen instead of a primitive diamond-shaped unit cell (Figure 14a), and a six-sided nonprimitive hexagonal unit cell can be chosen to replace a rhomb to emphasize the 6-fold symmetry (Figure 14b).

We can describe translational symmetry and lattices using vectors, and we can explain many

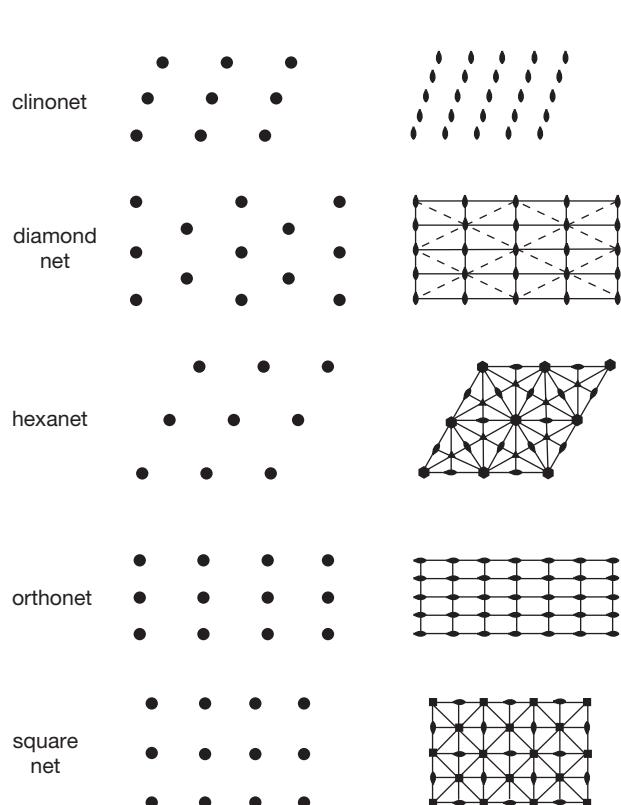
fundamental properties of lattices using vector properties (Box 2). The vectors that describe the translations relating one lattice point to its near neighbors have magnitudes and orientations equivalent to edges of primitive unit cells. The five basic unit cell shapes represent all possible combinations of two vectors if the absolute magnitude of the vectors is ignored.



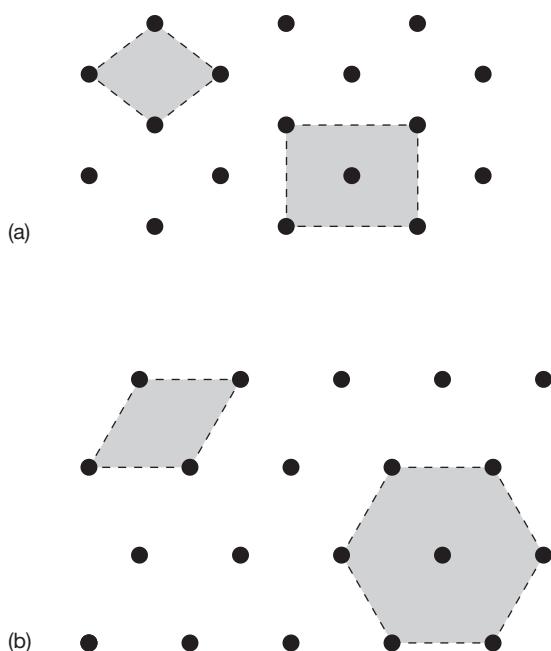
**FIGURE 11** Five American icons arranged in a repetitive two-dimensional pattern. See text for explanation.



**FIGURE 12** (a) A smiley-face motif repeating in a diamond pattern. Figures (b) and (c) are possible choices for diamond shaped unit cells; d and e are possible choices for rectangular unit cells.



**FIGURE 13** The five plane lattices (nets) and their symmetries. Rotation axes are shown using the standard lens, diamond, square, and hexagonal symbols; mirrors are shown as solid lines. For the diamond net, the dashed lines show a diamond-shaped unit cell, but a rectangular centered unit cell may also be chosen.



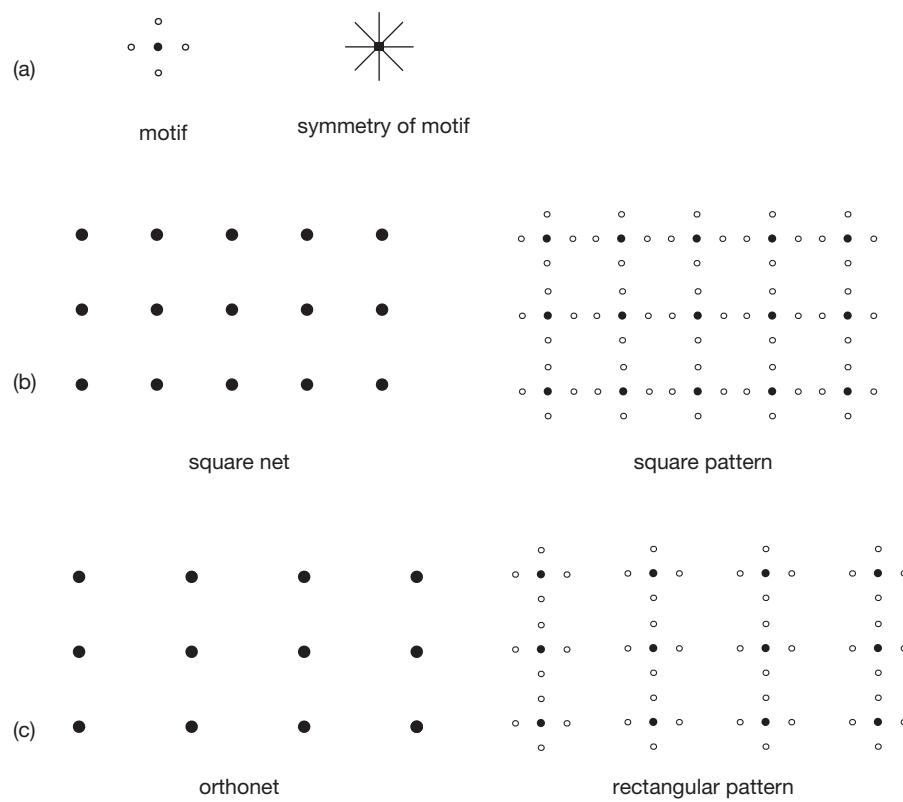
**FIGURE 14** (a) Diamond-shaped and rectangular unit cells can both produce the same pattern but the rectangular cell is not primitive. (b) Both rhombohedral and hexagonal unit cells can create a hexanet but the hexagonal cell is not primitive.

### Symmetry of the Motif and the Lattice

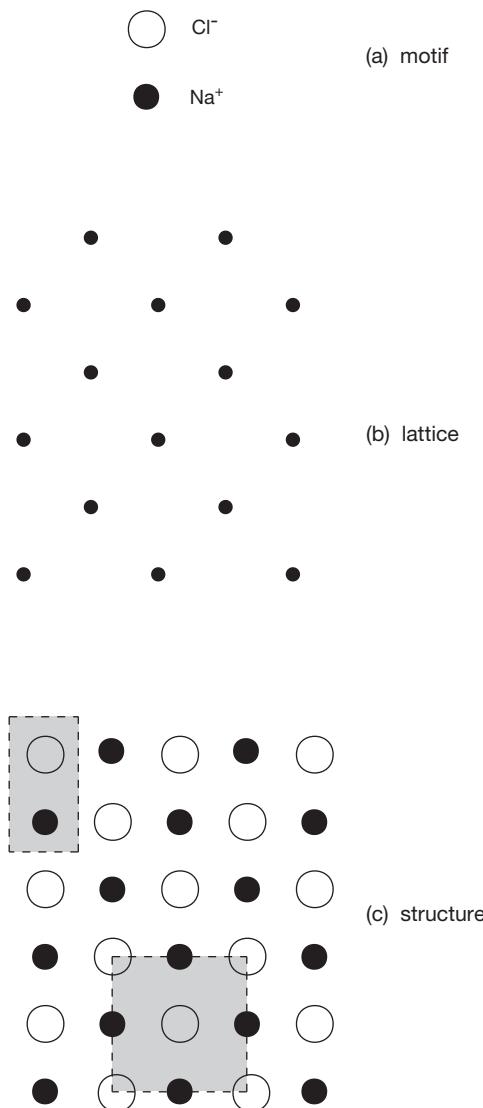
Let's consider the motif in Figure 15a, in which the solid and open circles represent different atoms. The motif has a 4-fold axis of symmetry and four mirror

planes at 45° to each other. In Figure 15b, the motif repeats according to a square net; in Figure 15c it repeats following an orthonet. The overall pattern formed with the square net still has 4-fold axes of symmetry and mirror planes just as the original motif does, while the pattern formed with the orthonet does not. A combination of a 4-fold rotation axis with an orthonet is an impossible combination for atomic structures. We assumed that the four open circles were identical atoms with identical bonds around them (or else 4-fold symmetry would not be present). In our final structure, therefore, all open circles must have identical surroundings. They do not with the orthonet. If the open circles all represent absolutely identical atoms, how can they pack closer together in one direction than in the other? The answer is that they cannot.

The preceding discussion points out a second important law of crystallography: *If a motif has certain symmetry, the lattice must have at least that much symmetry.* A motif with the 4-fold axis of symmetry requires a square plane lattice because it is the only plane lattice with a 4-fold axis. A motif may have less symmetry than a lattice. If a motif has a 2-fold axis of symmetry, it may be repeated according to any of the five plane lattices because they all have 2-fold axes of symmetry. Halite, NaCl, is an excellent example of a mineral in which the basic motif has less symmetry than the lattice (Figure 16). In two dimensions the lattice has square symmetry, but the motif, consisting of one Na and one Cl atom, does not. Notice, however,



**FIGURE 15** Symmetry of lattices, motifs, and patterns: (a) a motif of five atoms and its symmetry (4-fold axis and four mirrors); (b) the motif repeated according to a square net to produce a square pattern; (c) the motif repeating according to an orthonet to produce a rectangular pattern.



**FIGURE 16** Halite: (a) The basic motif contains one  $\text{Cl}^-$  and one  $\text{Na}^+$  atom. (b) The motif repeats according to a square net (tilted here). (c) The structure has the same symmetry as the lattice, which is more than the symmetry of the motif. A primitive unit cell does not show this symmetry, but a doubly primitive square unit cell does.

that we can choose a nonprimitive unit cell containing two motifs that does have square symmetry.

Figure 17 shows some patterns based on the flags of Canadian provinces. They all have translational symmetry. The two on the right have rotational symmetry, and the lower right drawing contains mirror planes. Possible unit cells are shown on each pattern. Note that in each of the four patterns, the symmetry of the motif is less than that of the unit cell shape and lattice. Above, we pointed out that if a motif has symmetry, the lattice must have at least that much symmetry. Here we see that the opposite is not true: *A lattice may have more symmetry than the motif it repeats.* Note also that the same translations that relate one unit cell to its

neighbors also relate the symmetry elements. Rotation axes and mirror planes operate on each other; now we see that *translational symmetry also affects rotation axes and mirror planes.*

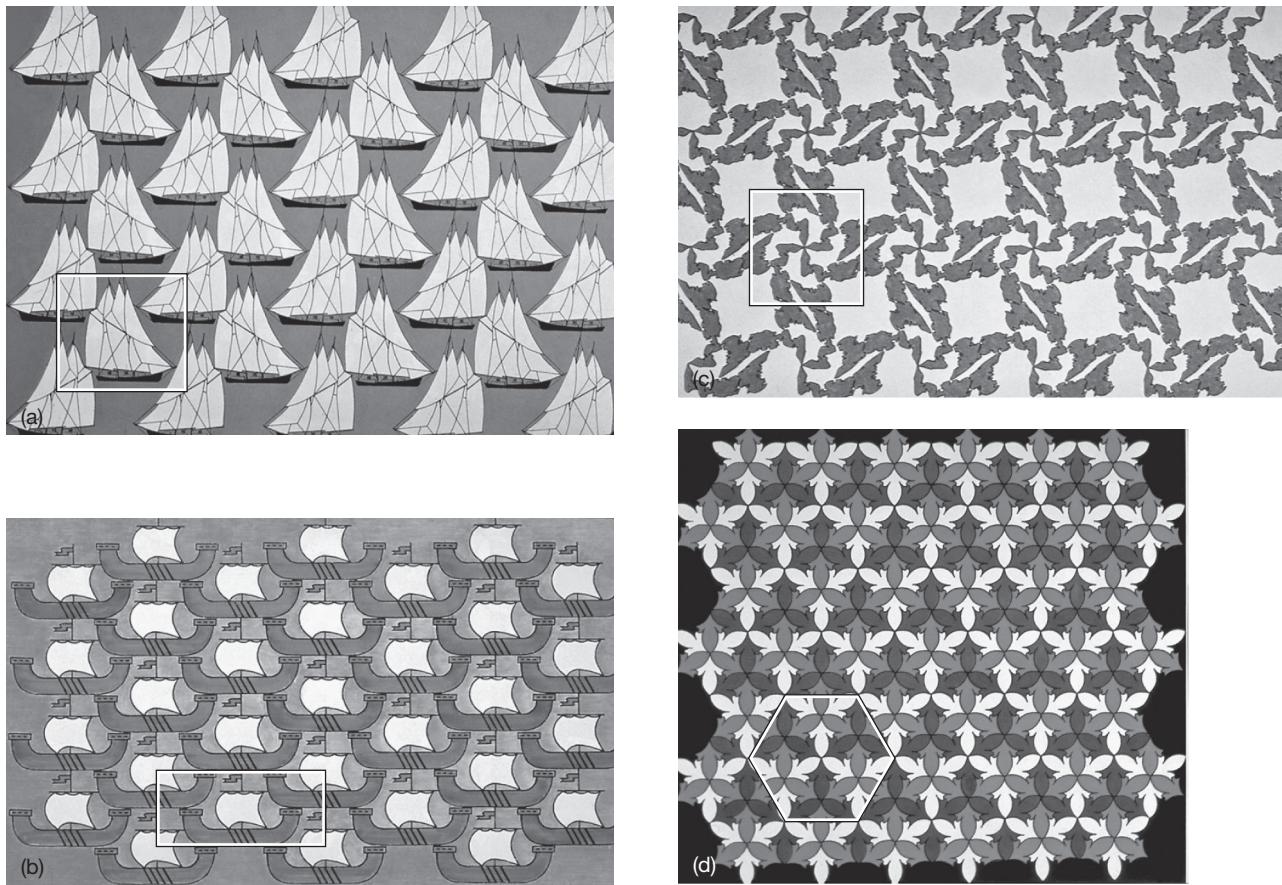
## UNIT CELLS AND LATTICES IN THREE DIMENSIONS

### What Shapes Are Possible?

In the preceding discussion, we established that two-dimensional unit cells must have one of five shapes. What shapes are possible in *three* dimensions? We can answer this question by considering the shapes of bricks that we can stack together without leaving gaps. To begin with, the bottoms of the bricks will have one of the five two-dimensional shapes in Figure 8. Let's consider possible brick shapes with a square bottom (Figure 18). The first two, a cubic unit cell and a tetragonal unit cell, are orthogonal shapes: All angles are  $90^\circ$ , and all faces are either squares or rectangles. The symmetries of these two shapes correspond to two of the 32 point groups:  $4/m\bar{3}2/m$  and  $4/m2/m2/m$ , respectively. The next shape has two faces that are not square or rectangular (Figure 18c). At each corner, three edges come together and form three angles. Two of the angles are  $90^\circ$ ; one is not. This unit cell is monoclinic and has  $2/m$  symmetry.

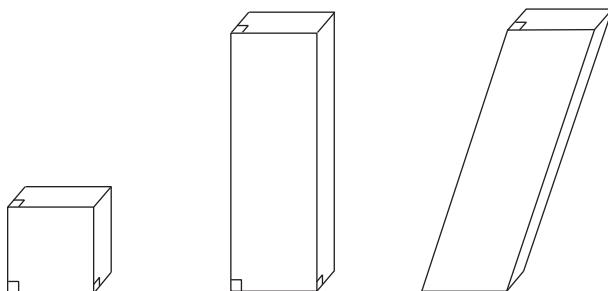
Instead of imagining a brick with a square base, we could imagine other shapes. Figure 20 shows some unit cells with rectangular bases. Two are simply repeats of those we derived using the square base. An important new one is the orthorhombic unit cell (Figure 20b), shaped like an orthorhombic prism (shoebox shape), which has symmetry  $2/m2/m2/m$ . Figure 21a shows a rhombic prism, a brick having a rhomb-shaped base. Three rhombic prisms placed together create a hexagonal unit cell, which has symmetry  $6/m2/m2/m$  (Figure 21b). Finally, Figure 22 shows a triclinic unit cell, which is based on a parallelogram and has no edges of equal length and no angles of  $90^\circ$ .

Although we could use other shapes as bricks, they are equivalent to the ones just mentioned, singly or in combination. There are only six distinct possibilities, having six distinct symmetries (Figure 23). Each corresponds to one of the six crystal systems listed in Table 1. This brings us to a third important law of crystallography: *The symmetries of the unit cells are the same as the point groups of greatest symmetry in each of the crystal systems.* To describe the shape of a unit cell, we give dimensions and angles. The lengths of unit cell edges and the



**FIGURE 17** Drawings based on the flags of four Canadian provinces. In all four of the drawings, the unit cell shape (outlined by black and white lines) and lattice have greater symmetry than the overall pattern because the motifs have less symmetry than the shape of the unit cell. The two drawings on the left have square unit cells, as shown. Only the bottom left pattern, however, has a 4-fold access of symmetry. The drawing in the upper right has a centered orthorhombic unit cell (equivalent to a diamond-shaped unit cell) but the pattern has no rotation axes or mirrors of symmetry. The drawing in the lower right has a hexagonal unit cell, but the overall pattern does not have 6-fold symmetry. It does, however contain 3-fold axes and mirrors. These drawings were modified from F. Brisse, La symétrie bidimensionnelle et le Canada, *Canadian Mineralogist*, 19 (1981). Used by permission.

angles between them, together called the *unit cell parameters*, are usually designated as  $a$ ,  $b$ ,  $c$ ,  $\alpha$ ,  $\beta$ , and  $\gamma$  (Figure 22). For primitive unit cells,  $a$ ,  $b$ , and  $c$  are the magnitudes of the vectors relating lattice points, and  $\alpha$ ,  $\beta$ , and  $\gamma$ , and are the angles between vectors.



**FIGURE 18** Bricks with square bottoms include: (a) cube; (b) tetragonal prism; (c) monoclinic prism.

In two dimensions, we observed that a plane lattice describes the way floor tiles or unit cells pack. In three dimensions, a space lattice describes the way bricks or unit cells can be packed together. We can envision space lattices as identical points that repeat indefinitely in three-dimensional space. The possible space lattices are named after the possible unit cell shapes: cubic, hexagonal, tetragonal, orthorhombic, monoclinic, and triclinic. Each has unique symmetry that is equivalent to the symmetry of the unit cell. Any crystal may be characterized by one of the six lattices.

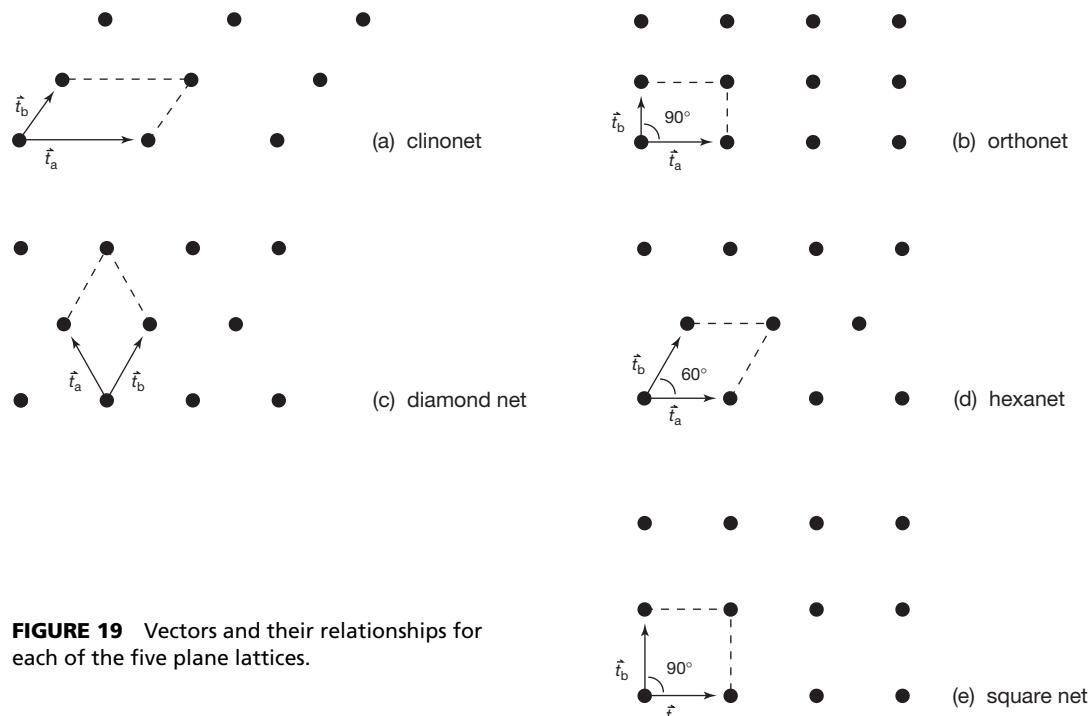
Figure 24, patterned after an Escher print, contains a motif (an egg) repeating in three directions. A primitive unit cell might include one egg and some space around it. An easier way to envisage a primitive unit cell is to consider a rectangular solid with an egg at each corner and none inside. Each egg is then shared between eight unit cells. The four largest eggs form the front face of such a solid. If we

## BOX 2

## Lattices and Vectors in Two Dimensions

The points in a lattice can be generated by starting with one point and defining two translations, described by vectors  $\vec{t}_a$  and  $\vec{t}_b$  which translate any point in a lattice to a new location. The relationship between  $\vec{t}_a$  and  $\vec{t}_b$  determines the kind of lattice (Figure 19a–e).

Magnitude of $\vec{t}_a$ and $\vec{t}_b$	Angle Between $\vec{t}_a$ and $\vec{t}_b$	Unit Cell Shape	Plane Lattice
$t_a \neq t_b$	general	parallelogram	clinonet
$t_a \neq t_b$	90°	rectangle	orthonet
$t_a = t_b$	general	diamond	diamond net
$t_a = t_b$	60°	rhomb	hexanet
$t_a = t_b$	90°	square	square net

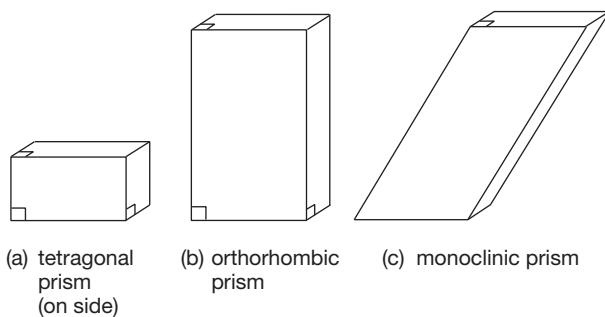


**FIGURE 19** Vectors and their relationships for each of the five plane lattices.

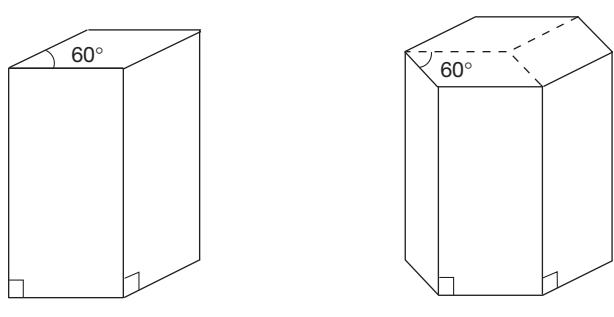
replace each egg with a dot, we get a space lattice; it shows the way unit cells repeat to give the entire three-dimensional pattern. Notice that we can think of the space lattice as plane lattices stacked on top

of each other. The distance between adjacent planes is constant.

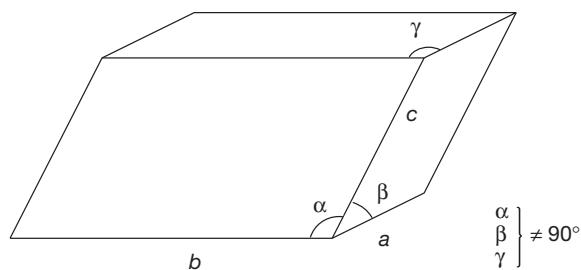
We based the preceding discussion mostly on geometry; we can also use vectors and vector



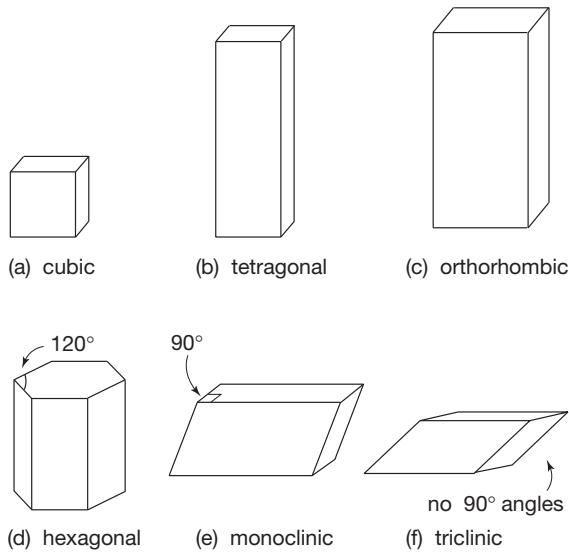
**FIGURE 20** Bricks with rectangular bottoms: (a) tetragonal prism (on its side); (b) orthorhombic prism; (c) monoclinic prism.



**FIGURE 21** Bricks having a rhomb-shaped base: (a) rhombic prism; (b) hexagonal prism.

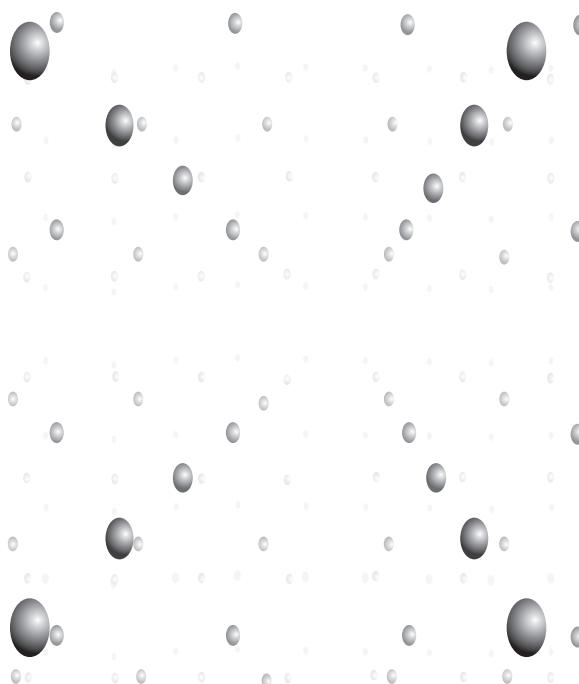


**FIGURE 22** A triclinic unit cell with edge lengths and angles  $a$ ,  $b$ ,  $c$ ,  $\alpha$ ,  $\beta$ , and  $\gamma$ . All faces and edges intersect at non- $90^\circ$  angles.



**FIGURE 23** The six basic three-dimensional unit cell shapes. The hexagonal unit cell (d) is equivalent to three rhombic prisms, see Figure 21.

properties to derive three-dimensional unit cells (Box 3). We need three vectors to describe the way lattice points repeat. Essentially, the first two vectors describe the way lattice points repeat to make plane lattices, while the third describes how plane lattices stack one above another to produce a space lattice.



**FIGURE 24** A motif (here an egg) repeating in space. If each egg is replaced with a point, we get a space lattice.

### Cells with Extra Lattice Points

As pointed out earlier, we can think of three-dimensional lattices (space lattices) as layers of two-dimensional lattices (plane lattices) stacked on top of each other in a regular and evenly spaced way. Figure 13 shows the symmetry elements of each of the plane lattices. When we stack plane lattices, unless we take care, symmetry elements in one layer will not correspond with those in another. The resulting space lattice will have no rotation axes or mirror planes of symmetry.

Stacking square plane lattices to produce space lattices can be done in many ways. If one plane lattice is placed randomly above another, we may preserve no symmetry. Alternatively, we may stack the layers exactly one above another to preserve maximum symmetry. If the distance between layers is the same as the distance between points in a layer the three-dimensional lattice has a cubic arrangement of lattice points (Figure 26a). Each cubic unit cell contains one  $8 \times \frac{1}{8}$  lattice point in total. We designate unit cells containing only one lattice point with the letter  $P$  standing for primitive.

Figure 26b shows another possible way of stacking square plane lattices to create a cubic unit cell. The distance between adjacent layers is half the distance between points in each individual layer. Each layer is offset from the ones above and below it. Lattice points in the first, third, fifth, and so on layers are directly above each other, and

**TABLE 1** Crystal Systems and Unit Cell Symmetry

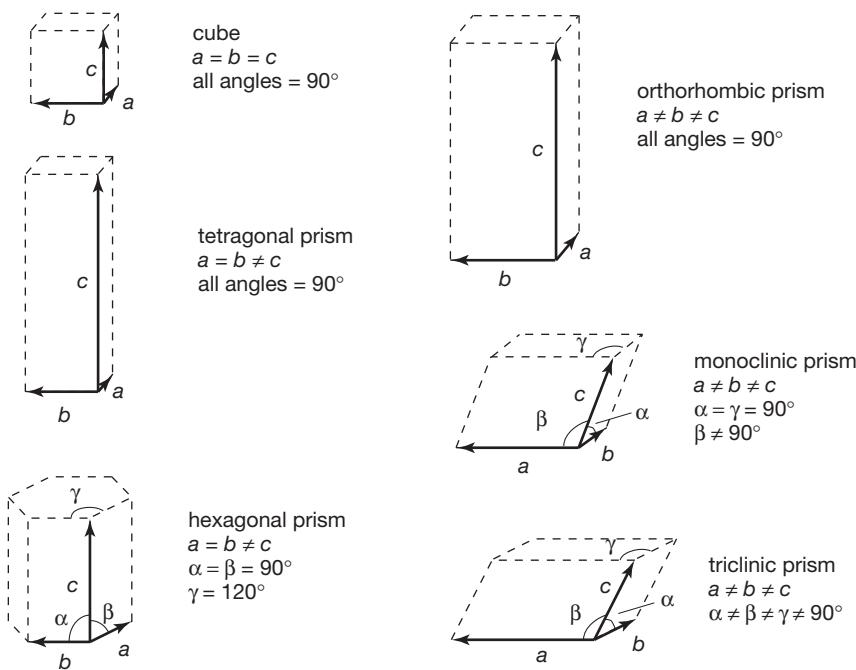
Unit Cell Shape	Crystal System	Unit Cell Symmetry
cubic	cubic	$4/m\bar{3}2/m$
tetragonal	tetragonal	$4/m2/m2/m$
hexagonal	hexagonal	$6/m2/m2/m$
orthorhombic	orthorhombic	$2/m2/m2/m$
monoclinic	monoclinic	$2/m$
triclinic	triclinic	$\bar{1}$

## BOX 3

## Vectors and Space Lattices

We can generate the six possible space lattices using vectors in the same way we generated the plane lattices. Consider three vectors,  $\vec{t}_a$ ,  $\vec{t}_b$  and  $\vec{t}_c$  which cause a lattice point to translate and repeat in space. The relationships between  $\vec{t}_a$ ,  $\vec{t}_b$  and  $\vec{t}_c$  determine the type of lattice. The three vectors may be equal or different in magnitude, and the angles between them may be general or special. The possible combinations are summarized in the table below. Figure 25 depicts unit cells and vector relationships for each.

Magnitudes of $\vec{t}_a$ , $\vec{t}_b$ and $\vec{t}_c$	Angles Between $\vec{t}_a$ , $\vec{t}_b$ and $\vec{t}_c$	Unit Cell Shape	Lattice
$\vec{t}_a \neq \vec{t}_b \neq \vec{t}_c$	All angles general	triclinic	triclinic
$\vec{t}_a \neq \vec{t}_b \neq \vec{t}_c$	One angle general, the others $90^\circ$	monoclinic	monoclinic
$\vec{t}_a = \vec{t}_b \neq \vec{t}_c$	$\vec{t}_a \wedge \vec{t}_b = 120^\circ$ $\vec{t}_a \wedge \vec{t}_c = 90^\circ$ $\vec{t}_b \wedge \vec{t}_c = 90^\circ$	hexagonal prism	hexagonal
$\vec{t}_a \neq \vec{t}_b \neq \vec{t}_c$	All angles $90^\circ$	orthorhombic prism	orthorhombic
$\vec{t}_a = \vec{t}_b \neq \vec{t}_c$	All angles $90^\circ$	tetragonal prism	tetragonal
$\vec{t}_a = \vec{t}_b = \vec{t}_c$	All angles $90^\circ$	cube	cubic



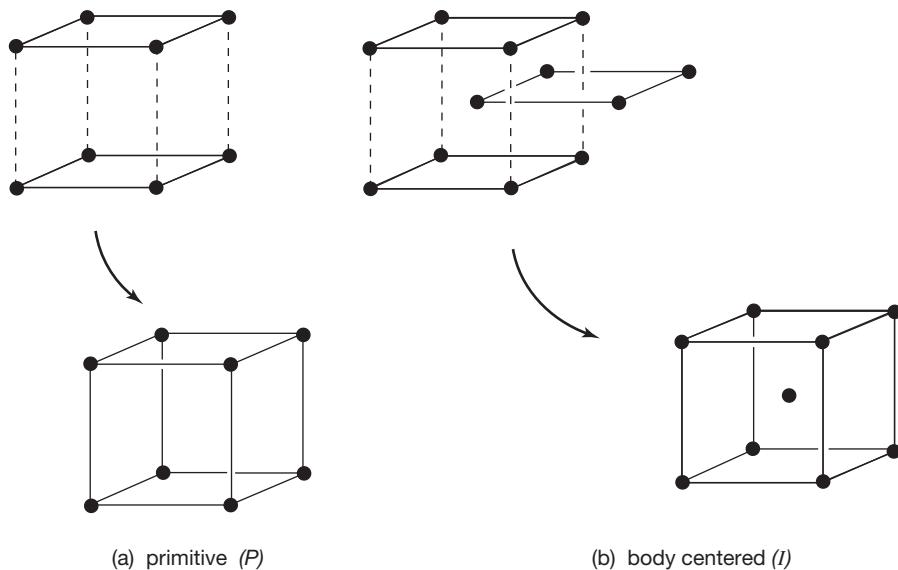
**FIGURE 25** The six unit cell shapes corresponding to the six space lattices, with vector relationships shown:  $a$ ,  $b$ , and  $c$  are magnitudes of vectors relating lattice points at the unit cell corners;  $\alpha$ ,  $\beta$ , and  $\gamma$  are the angles between the vectors.

create a cubic arrangement of lattice points; lattice points in the second, fourth, sixth and so on layers lie exactly in the center of the cubes. We can think of the cubes as nonprimitive unit cells. They are doubly primitive, having an extra lattice point at their center. We call them *body-centered* and designate them with the letter  $I$ .

We can stack diamond lattices to produce an orthorhombic unit cell (all angles  $90^\circ$ , but sides of different lengths) with extra lattice points in two opposite faces (Figure 27a). The resulting cells are

called *end-centered* and designated by the letter  $A$ ,  $B$ , or  $C$ , depending on the locations of the extra lattice points compared with the crystallographic axes. Alternatively, we may stack the diamond lattices to produce a unit cell with extra lattice points in the center of each face (Figure 27b). We call such unit cells *face-centered*, and designate them by the letter  $F$ .

Stacking hexagonal plane lattices is more complicated than stacking other lattices because



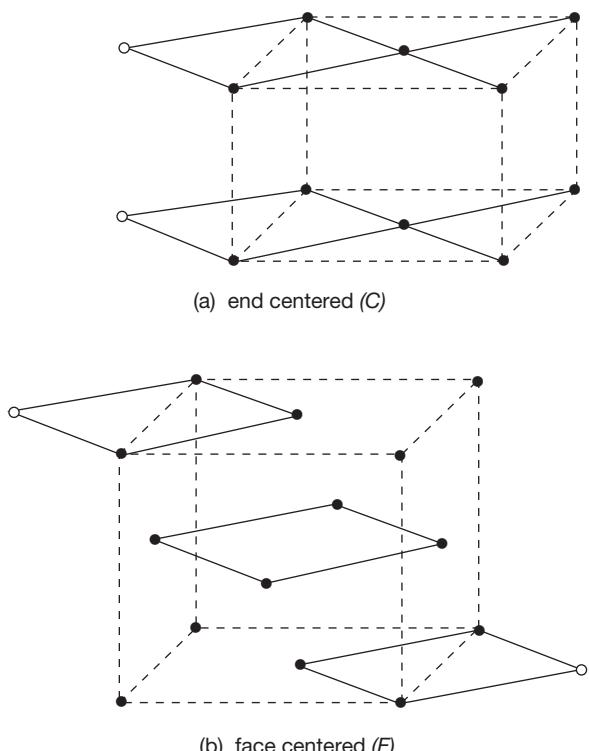
**FIGURE 26** Stacking square plane lattices to produce three-dimensional lattices: (a) primitive cubic lattice ( $P$ ); (b) body-centered cubic lattice ( $I$ ).

hexagonal plane lattices have more symmetry. Figure 28a shows the symmetry of a hexagonal plane lattice. If we stack plane lattices so that 6-fold axes in all the layers coincide, we produce a simple hexagonal space lattice. The three-dimensional

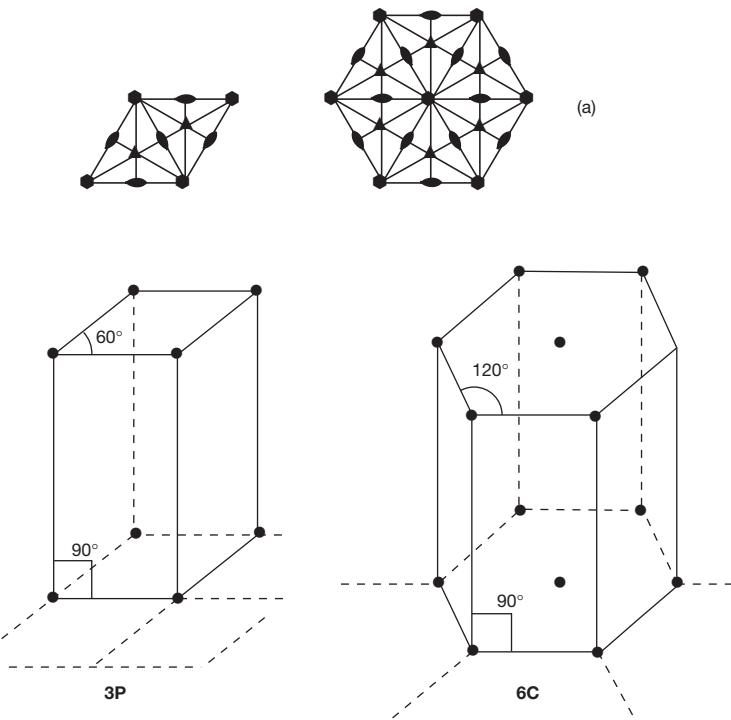
result is a unit cell shaped like a rhombic prism (Figure 28b) or an equivalent hexagonal unit cell (Figure 28c).

We may also stack hexagonal plane lattices so they do not preserve the 6-fold axes of symmetry but do preserve the 3-fold axes. Figure 29a shows how we do this. The second layer is placed above the first so that its lattice points lie above the center of equilateral triangles in the first layer (Figure 29b). The third layer is similarly placed above the second, and the fourth layer lies directly above the first. We give this arrangement of lattice points the symbol  $R$ , for rhombohedral. We can connect lattice points to make a nonprimitive unit cell, shaped like a rhombic prism, with its base in the first layer and its top in the fourth layer (Figure 29c). Lattice points are at the corners and two extra lattice points are inside the prism. Another way of choosing a unit cell is to isolate eight lattice points from several adjacent rhombohedral prisms and connect them as shown in Figures 29d and e. One point is from the first layer, three from the second, three from the third, and one from the fourth. The result is a primitive rhombohedral unit cell. It has 12 equal-length edges, and eight identically shaped faces. Lattice points are only at the corners of this unit cell.

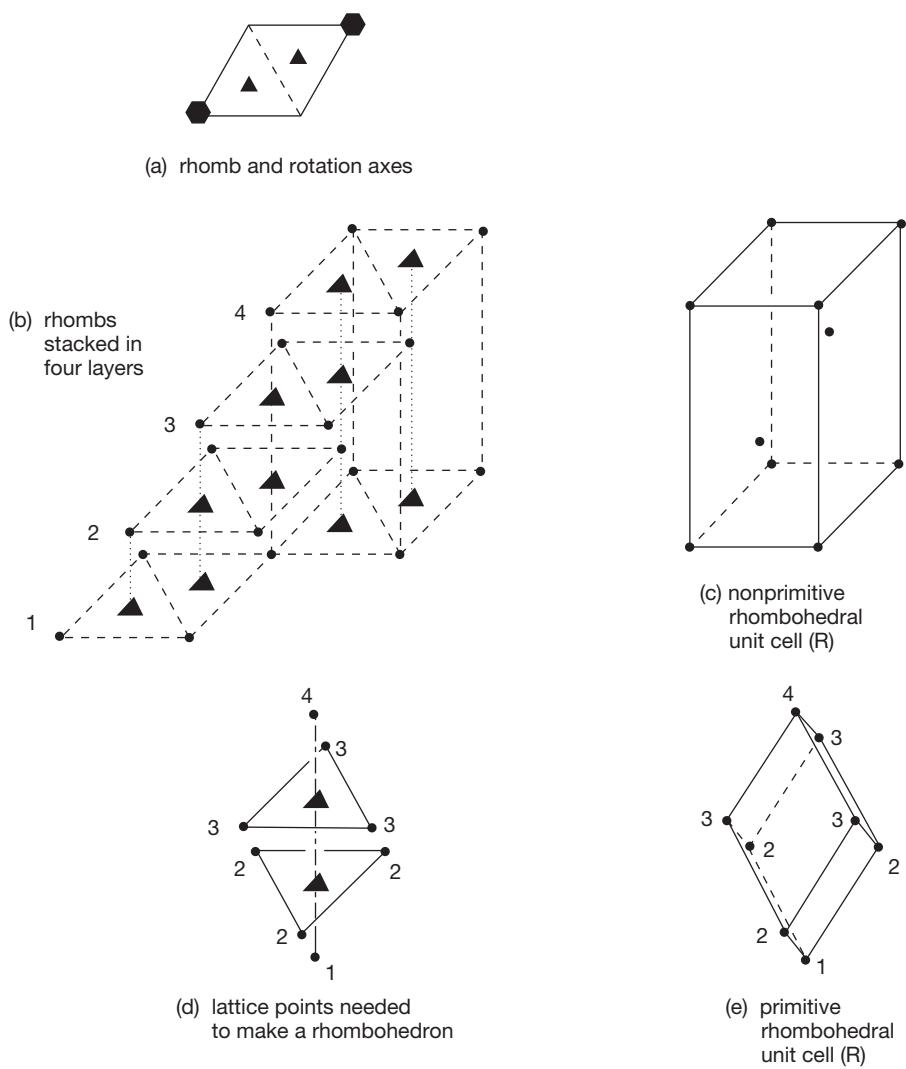
Figure 30 shows several possible choices for the unit cell of calcite. If we replace each  $\text{CaCO}_3$  unit (equivalent to a motif) with a point, we get a rhombohedral lattice. We can choose a unit cell in several different ways. The unit cell in Figure 30a is doubly primitive. We could also choose a hexagonal prism as a unit cell (Figure 30b). A third possibility is a face-centered rhomb (Figure 30c). Lattice points are



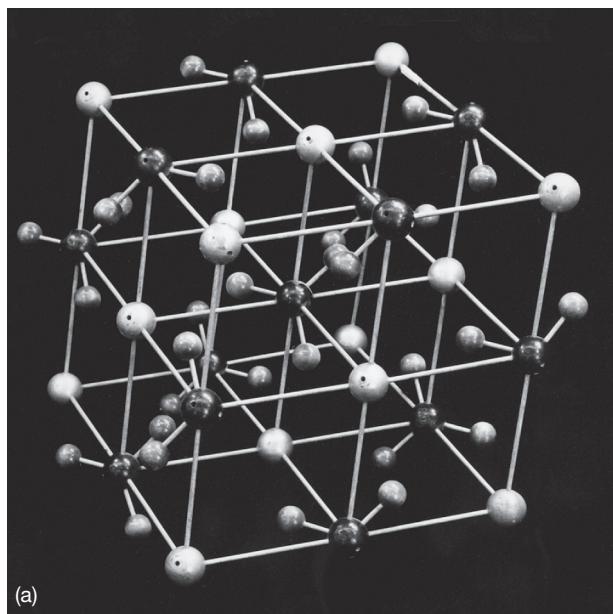
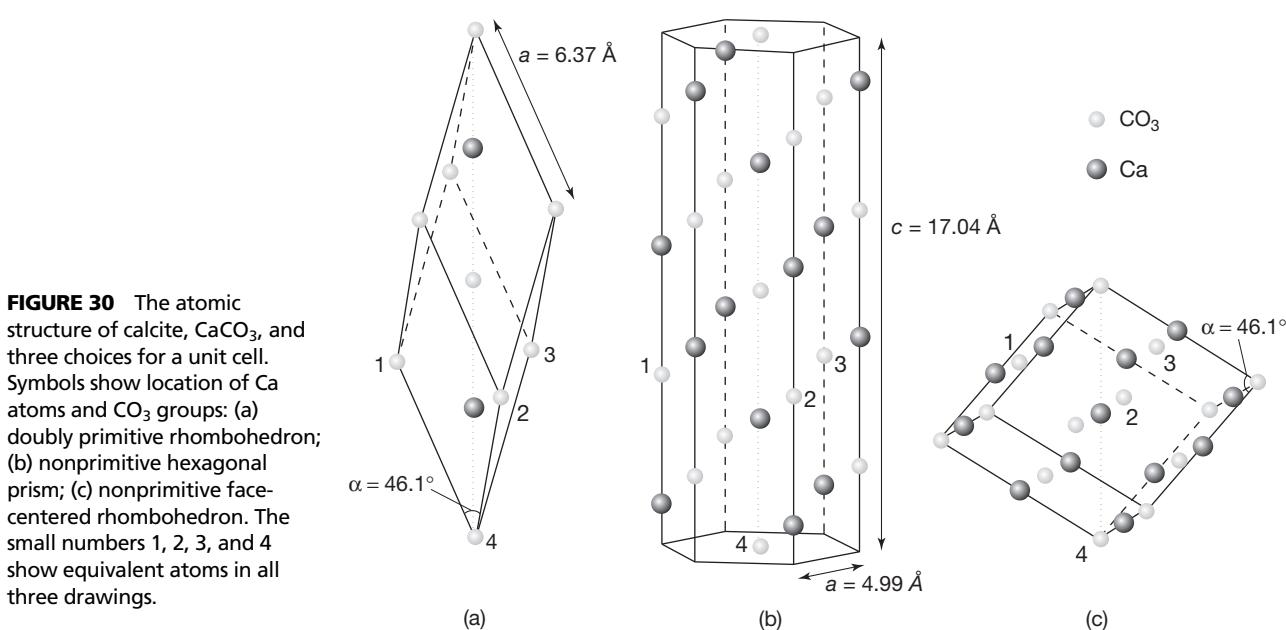
**FIGURE 27** Stacking diamond plane lattices to produce three-dimensional orthorhombic unit cells. (a) If the three-dimensional cell has extra points in two opposite faces, we designate it by *A*, *B*, or *C* (see text). (b) If the three-dimensional cell has extra points in the center of each face, we designate it *F*.



**FIGURE 28** Stacking hexagonal plane lattices: (a) the symmetry of a rhomb and hexagon in the plane lattice; lattice points coincide with 6-fold rotation axes; (b) a primitive unit cell, shaped like a rhombohedral prism, that describes a hexagonal space lattice; (c) a nonprimitive unit cell, shaped like a hexagonal prism, that describes a hexagonal space lattice.



**FIGURE 29** An alternative way to stack hexagonal plane lattices: (a) rhomb showing locations of some 3-fold and 6-fold axes; (b) stacking rhombs to preserve 3-fold symmetry, but not 6-fold symmetry (different layers in the stack are indicated with numbers); (c) the resulting nonprimitive three-dimensional cell has two extra lattice points within it; (d) eight points that can be used to define an alternative three-dimensional unit cell (numbers indicate layers); (e) the result is a primitive rhombohedral unit cell (R).



**FIGURE 31** Ball-and-stick model of calcite: (a) model does not depict the standard unit cell for calcite (see text), but does show the atomic arrangement that leads to calcite's excellent rhombohedral cleavage; (b) calcite cleavage rhombs.

at the center of each face and at the corners. Although the three possible unit cells look different, they all give the atomic structure of calcite when many unit cells are stacked together. One of the first two is the choice of most mineralogists. The third one is equivalent in shape to the standard cleavage rhombohedron that forms when calcite crystals break. Figure 31a shows a ball-and-stick model equivalent to the cleavage rhombohedron (shown in a photo in Figure 31b).



## BRAVAIS LATTICES

When all possibilities have been examined, we can show that only 14 distinctly different space lattices exist. We call them the 14 **Bravais lattices**, named after Auguste Bravais, a French scientist who was the first to show that there were only 14 possibilities. The 14 Bravais lattices correspond to 14 different unit cells that may have any of six different symmetries, depending on the crystal system. Six of the possible unit cells are primitive, one in each system (as was shown in Figure 25). For convenience, we may think of them as having lattice points only at the corners, but it is important to remember that the choice of unit cells and lattice points is arbitrary. Eight unit cells share each of the eight lattice points at the corners of a primitive unit cell, so the total number of lattice points per cell is one. The other eight Bravais lattices involve nonprimitive unit

cells containing two, three, or four lattice points. Body-centered unit cells, for example, contain one extra lattice point at their center (see Figure 26b). Face-centered unit cells have lattice points in the centers of six faces (see Figure 27b). Each of the six points is half in the unit cell and half in an adjacent cell. The total number of lattice points is therefore 1 (at the corners)+3 (in the faces) = 4. Table 2 lists the different types of space lattices and their symbols. Note that all types do not exist in all systems. For example, end-centered unit cells only exist in the orthorhombic system; they cannot exist in the other systems because of symmetry constraints.

As pointed out in the discussion of two-dimensional lattices, we sometimes make arbitrary decisions when choosing unit cells. The 14 Bravais lattices, in fact, do not represent the only 14 that we could list. For example, in the monoclinic system, the body-centered ( $2I$ ) unit cell is equivalent to a face-centered one ( $2F$ ), with different dimensions. Most crystallographers consider only the body-centered cell because that is the way it has been done since the time of Bravais. The important thing to realize is that no matter what unit cells and lattices we consider, only 14 are distinct. Furthermore, the 14 in Table 2 are the simplest and the ones used by most crystallographers.

**TABLE 2** Space Lattices

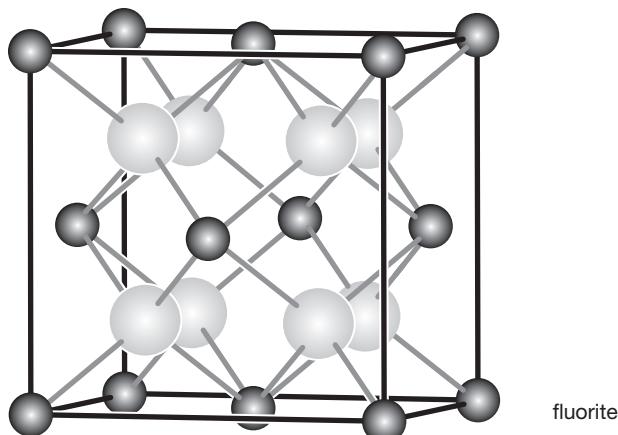
Name	Symbol	Crystal Systems	Number of Lattice Points per Cell	Unit Cell and Lattice Points
primitive	$23P$	cubic	1	
	$4P$	tetragonal	1	
	$222P$	orthorhombic	1	
	$6P$ or $6C$	hexagonal	1 or 3	
	$2P$	monoclinic	1	
	$1P$	triclinic	1	
body-centered	$23I$	cubic	2	
	$4I$	tetragonal	2	
	$222I$	orthorhombic	2	
	$2I$	monoclinic	2	
face-centered	$23F$	cubic	4	
	$222F$	orthorhombic	4	
end-centered	$222A$ $222B$ , $222C$ ,	orthorhombic	2	
rhombohedral	$3R$	hexagonal	1	

## UNIT CELL SYMMETRY AND CRYSTAL SYMMETRY

Consider fluorite ( $\text{CaF}_2$ ), spinel ( $\text{MgAl}_2\text{O}_4$ ), the garnet almandine ( $\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ ), and the rare mineral tetrahedrite ( $\text{Cu}_{12}\text{As}_4\text{S}_{13}$ ). Tetrahedrite has a primitive cubic unit cell; fluorite and spinel have face-centered cubic unit cells; almandine has a body-centered cubic unit cell. In fluorite,  $\text{Ca}^{2+}$  is found at the corners of the unit cell and at the center of each face, while  $\text{F}^-$  occupies sites completely within the unit cell (Figure 32). Spinel, almandine, and tetrahedrite have more complex structures, in part because they contain more than one cation.

When many unit cells stack together, we get a crystal that may or may not have the same symmetry as a single unit cell. In fluorite, spinel, and almandine crystals, the unit cells stack together so that all symmetry elements (rotation axes and mirror planes) are preserved. However, fluorite crystals are typically cubes, spinel crystals are typically octahedra, and almandine crystals are typically dodecahedra (Figures 33a–c). Other forms are possible for these minerals, especially for almandine. Tetrahedrite crystals (Figure 33d), in contrast with the other three, do not have the same symmetry as their unit cell. Although made of cubic unit cells, the crystals lack 4-fold rotation axes.

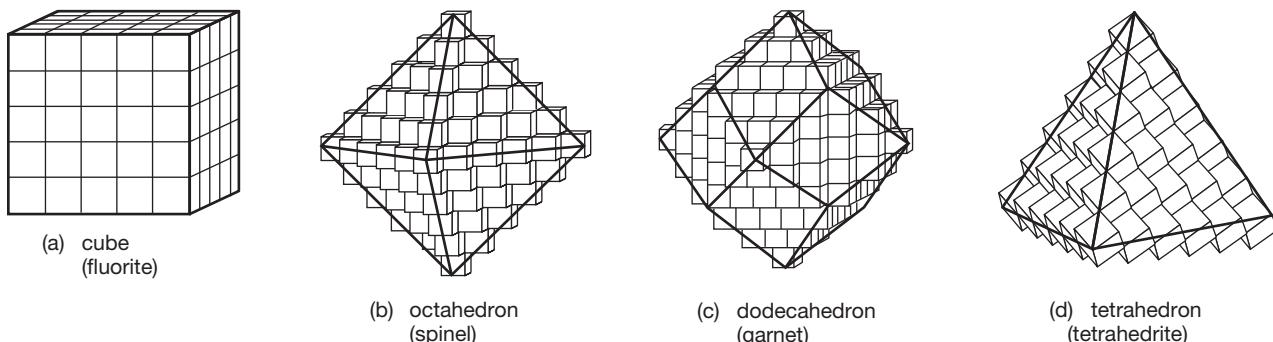
A fourth important law of crystallography is: *If a crystal has certain symmetry, the unit cell must have at least as much symmetry.* As a corollary to this law, because crystals consist of unit cells, the symmetry of a crystal can never be more than that of its unit cell. If a crystal has a 4-fold axis of symmetry, it must have a unit cell that includes a 4-fold axis of symmetry. A mineral that forms cubic crystals must have a cubic unit cell. If a crystal has certain symmetry, it is certain that the unit cell and



**FIGURE 32** The structure of fluorite showing the locations of atoms. Darker spheres are Ca; lighter spheres are F. The eight F atoms are entirely within the unit cell. The Ca atoms are at the corners and in the centers of the faces.

crystal's atomic structure have at least that much symmetry. They may have more, as in the case of tetrahedrite.

It is important to remember that the symmetry of a crystal depends not only on the symmetry of the unit cell, but also on how the unit cells combine to make the crystal. Some minerals, such as halite and other salts, tend to develop euhedral crystals with obvious symmetry, making it easy to infer the symmetry of the unit cell. Others develop crystals with faces that are nearly identical, suggesting the presence of symmetry but leaving some uncertainty. While size and shape of faces can vary because of accidents of crystal growth, the angles between faces vary little from the ideal (Steno's law). Consequently, crystallographers often rely on angles instead of face shapes to infer the symmetry of the unit cell. Even if a crystal is poorly



**FIGURE 33** Cubic unit cells stacking together to make crystals. Cubic unit cells can produce crystals of many shapes: (a) typical fluorite crystals are cubes; (b) typical spinel crystals are octahedra; (c) typical garnet crystals are dodecahedra; (d) typical tetrahedrite crystals are tetrahedra.

formed, its internal structure is orderly and its unit cells all have the same atomic arrangement.

Some minerals appear to have more symmetry than they actually do. Euhedral biotite often appears to have hexagonal symmetry when, in fact, close examination reveals that it does not (Figure 34). This is a good example of **pseudosymmetry**. Biotite is a monoclinic mineral, but is so close to being hexagonal that we call it **pseudohexagonal**. Sometimes we need precise measurements, and sometimes even X-ray studies, to tell pseudosymmetry from real symmetry.

## POINT GROUPS AND CRYSTAL SYSTEMS

Although we often infer unit cell shape from crystal symmetry, inferences do not work the other way. Minerals with cubic unit cells might not form crystals with cubic shape. Halite, spinel, and garnet all have cubic unit cells, but garnet and spinel do not normally grow as cubes (Figure 35). Garnet forms are **dodecahedra**, **trapezohedra**, and, rarely, **hexoctahedrons**. Spinel typically forms octahedra. Halite, fluorite, and garnet crystals all have  $4/m\bar{3}2/m$  symmetry, the same symmetry as their unit

cells. Some minerals with cubic unit cells form crystals with less symmetry. Sphalerite, for example, has a face-centered cubic unit cell, but sphalerite crystals have symmetry  $\bar{4}3m$ ; the most common form is a tetrahedron. Sphalerite has less symmetry than a cube because the cubic unit cells do not stack in an arrangement that preserves a 4-fold axis of symmetry. Instead, a  $\bar{4}$  axis is preserved.

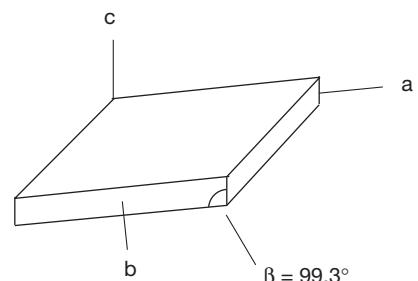
Crystals with cubic unit cells may, in fact, belong to any of the five point groups associated with the cubic system:

$$\begin{array}{l} 4/m\bar{3}2/m \\ 432 \\ \bar{4}3m \\ 2/m\bar{3} \\ 23 \end{array}$$

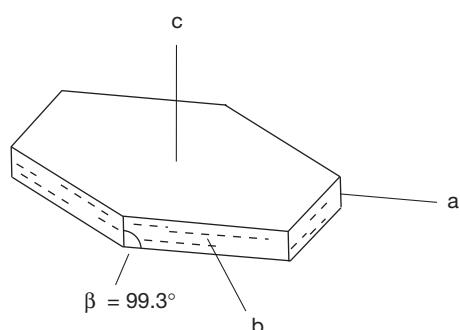
Similarly, crystals with orthorhombic unit cells may belong to any of three point groups of the orthorhombic system:

$$\begin{array}{l} 2/m2/m2/m \\ 222 \\ mm2 \end{array}$$

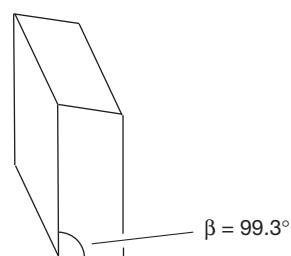

(a)



(b) pseudorhombohedral crystal

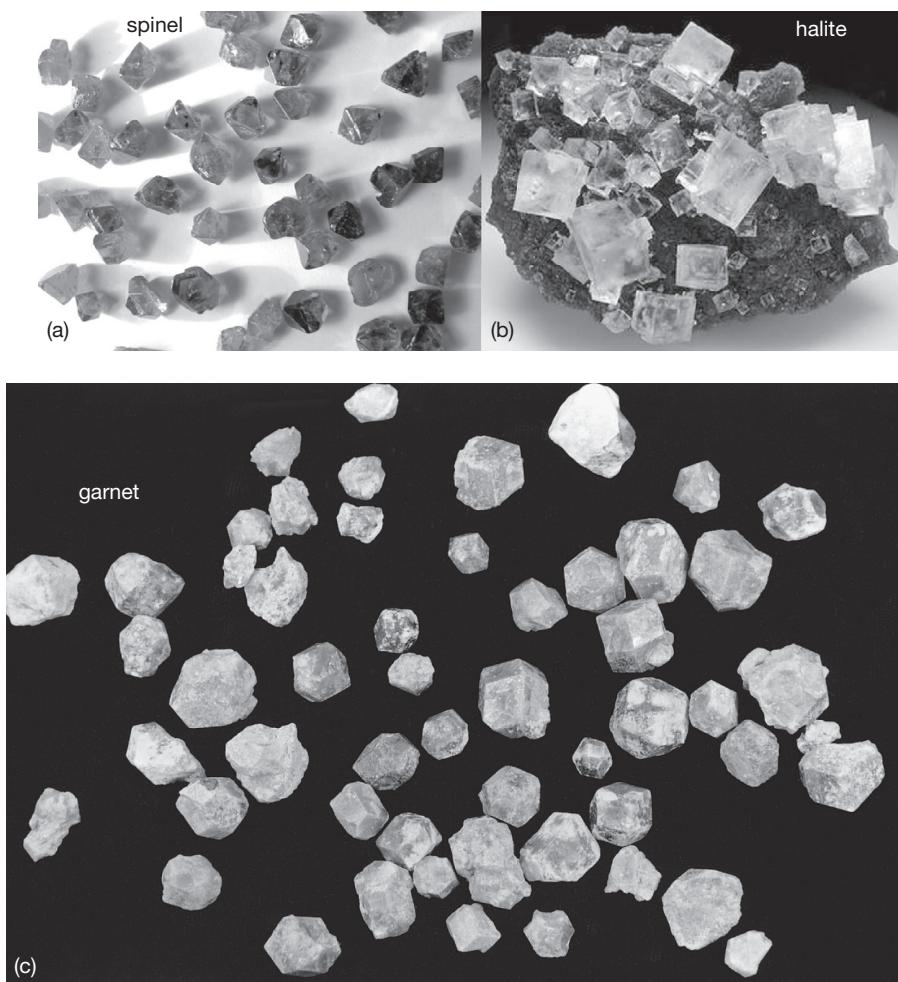


(c) pseudohexagonal crystal



(d) monoclinic unit cell

**FIGURE 34** Biotite crystals often appear to have trigonal or hexagonal symmetry but in fact do not, because  $b$ , the angle between the  $a$  and  $c$  edges of the unit cell, is not  $90^\circ$ . (a) Photograph of a pseudorhombohedral biotite crystal; (b) drawing of a pseudorhombohedral biotite crystal; (c) drawing of a pseudohexagonal biotite crystal; (d) drawing of a monoclinic biotite unit cell. Many unit cells combine to produce the crystals in a, b, and c.



**FIGURE 35** Cubic minerals: (a) spinel crystals; (b) halite crystals; (c) garnet crystals. The spinel crystals are octahedra; the halite crystals are cubes; the garnet crystals are dodecahedra. Compare these photos with the drawings in Figure 33.

We can now explain why we divided the 32 point groups into six crystal systems. Crystals in the same crystal system all have the same-shaped unit cells, even if the crystals themselves do not look the same. The six crystal systems are defined by symmetry and named by their unit cell shape. By examining a crystal's morphology, we can often determine the point group, system, and unit cell shape. Determining whether a unit cell is primitive, face-centered, body-centered, or end-centered, however, is not possible without X-ray studies.

Table 3 gives a complete list of the crystal systems, point groups, and lattices. In this table we have divided the hexagonal system into two subdivisions: hexagonal and trigonal. This is done for convenience to distinguish point groups that contain  $\bar{6}$  axes or 6-fold axes from those that do not. Some crystallographers use the term *rhombohedral* to refer to trigonal point groups that contain rhombohedral forms ( $\bar{3}$  and  $\bar{3}2/m$ ). Note that in all crystal systems the lattice symmetry is equivalent to the

point group with greatest symmetry. An unfortunate and confusing shorthand notation is used to designate lattice types. The symbol 23 denotes lattices corresponding to the cubic system; 23 is used because it is the Hermann-Mauguin symbol for the cubic point group with least symmetry. Cubic lattices are therefore designated 23P, 23I, or 23F, depending on whether they are primitive, body centered, or face centered. They all, however, have symmetry  $4/m\bar{3}2/m$ . Similar symbols are used in the other systems. Although not noted in Hermann-Mauguin symbols, all lattices (and therefore all unit cells) have an inversion center of symmetry. Point groups need not have an inversion center of symmetry. Table 3 lists the number and kinds of symmetry elements of each point group; only 11 contain an inversion center. Some symmetry operators are implied by the presence of others: Point groups containing  $\bar{6}$  symmetry must also have 3-fold symmetry perpendicular to a mirror; point groups containing  $\bar{4}$  symmetry must also have 2-fold symmetry; point groups containing  $\bar{3}$

**TABLE 3** The Relationships Between Crystal Systems, Point Groups, Total Symmetry of Point Groups, Unit Cells, and Lattices

System	Point Group (Crystal Class)	Total Symmetry of Point Group								Unit Cell Symmetry	Unit Cell Parameters	Lattice Symmetry	Possible Lattices				
		Number of Rotation Axes						Number of Mirrors <i>m</i>	Inversion Center? <i>i</i>								
		6	4	3	2	$\bar{6}$	$\bar{4}$	$\bar{3}$									
cubic	$4/m\bar{3}2/m$	3	(4)	6			4	9	<i>i</i>	$4/m\bar{3}2/m$	$a = b = c$ $\alpha = \beta = \gamma = 90^\circ$	$4/m\bar{3}2/m$	$23P$				
	432	3	4	6									$23I$				
	$\bar{4}3m$	4	(6)		3			6					$23F$				
	$2/m\bar{3}$	(4)	3			4		3	<i>i</i>								
	2 3		4	3													
tetragonal	$4/m2/m2/m$	1		4				5	<i>i</i>	$4/m2/m2/m$	$a = b \neq c$ $\alpha = \beta = \gamma = 90^\circ$	$4/m2/m2/m$	$4P$				
	422	1		4									$4I$				
	$4mm$	1						4									
	$\bar{4}2m$			2 (3)	1			2									
	$4/m$	1						1	<i>i</i>								
	$\bar{4}$			(1)	1												
hexagonal (hexagonal)	$6/m2/m2/m$	1		6				7	<i>i</i>	$6/m2/m2/m$	$a = b \neq c$ $\alpha = \beta = 90^\circ$ $\gamma = 120^\circ$	$6/m2/m2/m$	$6P$ or $6C$				
	622	1		6													
	$6mm$	1						6									
	$\bar{6}2m$		(1)	2	1			3 (4)									
	$6/m$	1						1	<i>i</i>								
	6	1															
	$\bar{6}$		(1)		1			(1)									
hexagonal (trigonal)	$\bar{3}2/m$		(1)	3			1	3	( <i>i</i> )	$\bar{3}2/m$	$a = b \neq c$ $\alpha = \beta = 90^\circ$ $\gamma = 120^\circ$	$\bar{3}2/m$	$3R$				
	32		1	3													
	$3m$		1					3									
	$\bar{3}$		(1)			1			( <i>i</i> )								
	3		1														
orthorhombic	$2/m2/m2/m$			3			3		<i>i</i>	$2/m2/m2/m$	$a \neq b \neq c$ $\alpha = \beta = \gamma = 90^\circ$	$2/m2/m2/m$	$222P$				
	222			3									$222I$				
	$mm2$			1			2						$222F$				
													$222A/B/C$				
monoclinic	$2/m$			1			1		<i>i</i>	$2/m$	$a \neq b \neq c$ $\alpha = \gamma = 90^\circ \neq \beta$	$2/m$	$2P$				
	2			1									$2I$				
	$m$						1										
triclinic	$\bar{1}$								<i>i</i>	$\bar{1}$	$a \neq b \neq c$ $\alpha \neq \beta \neq \gamma$	$\bar{1}$	$1P$				
	1																

symmetry must have 3-fold symmetry and an inversion center. In Table 3, the numbers in parentheses include symmetry implied by the presence of other operators, in effect counting some symmetry elements twice.

## SYMMETRY OF THREE-DIMENSIONAL CRYSTAL STRUCTURES

In the preceding sections, we discussed the symmetry of crystals. We now turn our attention briefly to the symmetry of atomic structures, also called *space symmetry*. What possible symmetry can a three-dimensional atomic structure have? There are only 32 possible point groups. The 32 represent the only possible symmetries for a motif or any discrete object, such as a crystal or a collection of atoms. In this chapter we introduced translation as an additional symmetry element and discussed the 14 possible space lattices that extend motifs through three-dimensional space. An atomic structure, then, consists of groups of atoms with one of 32 symmetries being repeated an indefinite number of times according to one of 14 space lattices. Thus, the symmetry of a crystal structure depends on both the arrangement of atoms in a motif and the lattice type.

### Space Group Operators

To describe space symmetry, we must consider two kinds of symmetry operators not previously discussed. Figure 36a shows a unit cell containing three atoms, and Figure 36b shows an entire line of equivalent unit cells. It is apparent from Figure 36b that some sort of symmetry exists that was not

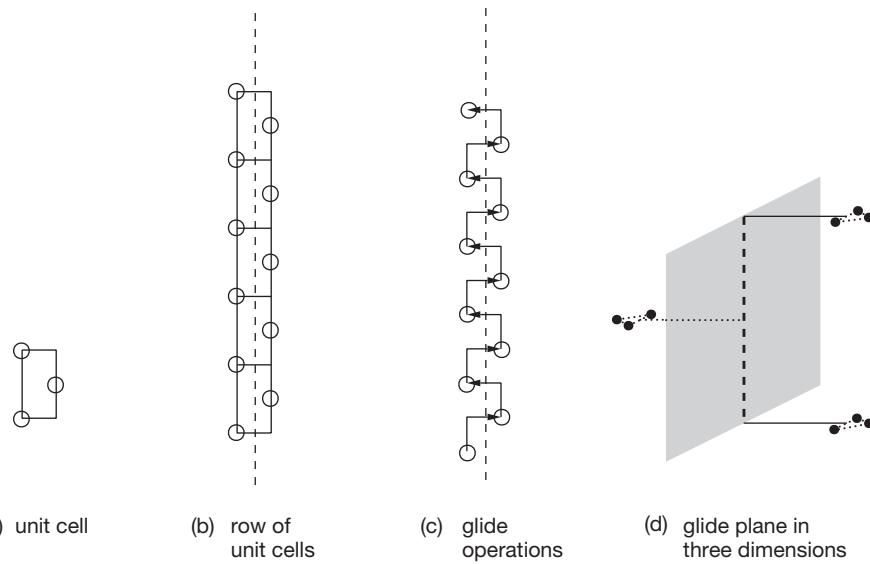
apparent when looking at the single unit cell in Figure 36a. The symmetry depicted in Figure 36c is an example of a **glide plane**; the dashed line shows the location of the glide plane in two dimensions. The sailing ship pattern in the upper left of Figure 17 contains an obvious but more complicated example of a glide plane. Glide plane operations involve combinations of translation plus reflection. Figure 36d shows such a combination in three dimensions; a triangular group of atoms repeats, zigzagging back and forth from one side of the glide plane to the other.

Glide planes are one of the two important kinds of **space group operators**, symmetry elements that atomic structures can have in addition to those already discussed. **Screw axes**, the other kind of space group operator, involve combinations of translation plus rotation. Just as rotoinversion axes are not equivalent to **proper rotation axes**, glide planes are different from mirror planes, and screw axes are different from rotation axes. Glide planes and screw axes are combinations of mirror planes, rotation, and translation that describe the symmetrical placement of atoms in an infinite crystal structure.

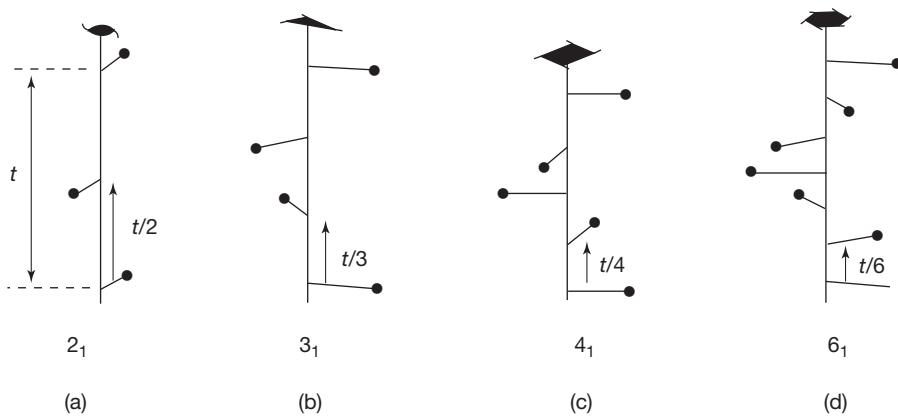
### Screw Axes

Screw axes result from the simultaneous application of translation and rotation. We can combine 2-, 3-, 4-, or 6-fold rotation operators with translation to produce screw axes. Many combinations exist; Figure 37 shows some examples. As with proper rotational axes (rotational axes not involving translation), each  $n$ -fold screw operation involves a rotation of  $360^\circ/n$ . After  $n$  repeats, the screw has

**FIGURE 36** Glide plane:  
(a) single unit cell containing three atoms; (b) multiple unit cells related by a glide plane; (c) arrow showing glide operations; (d) a glide plane (gray) in three dimensions relating a triangular group of atoms.



**FIGURE 37** Four types of screw axes parallel to a unit cell edge with length  $t$ : (a) a  $2_1$  screw axis involves translation of  $1/2t$  and rotation of  $180^\circ$ ; (b) a  $3_1$  screw axis involves translation of  $1/4t$  and rotation of  $120^\circ$ ; (c) a  $4_1$  screw axis involves translation of  $1/4t$  and rotation of  $90^\circ$ ; (d) a  $6_1$  screw axis involves translation of  $1/6t$  and rotation of  $60^\circ$ . Note that the symbols for the axes are related to the symbols for proper rotation axes.

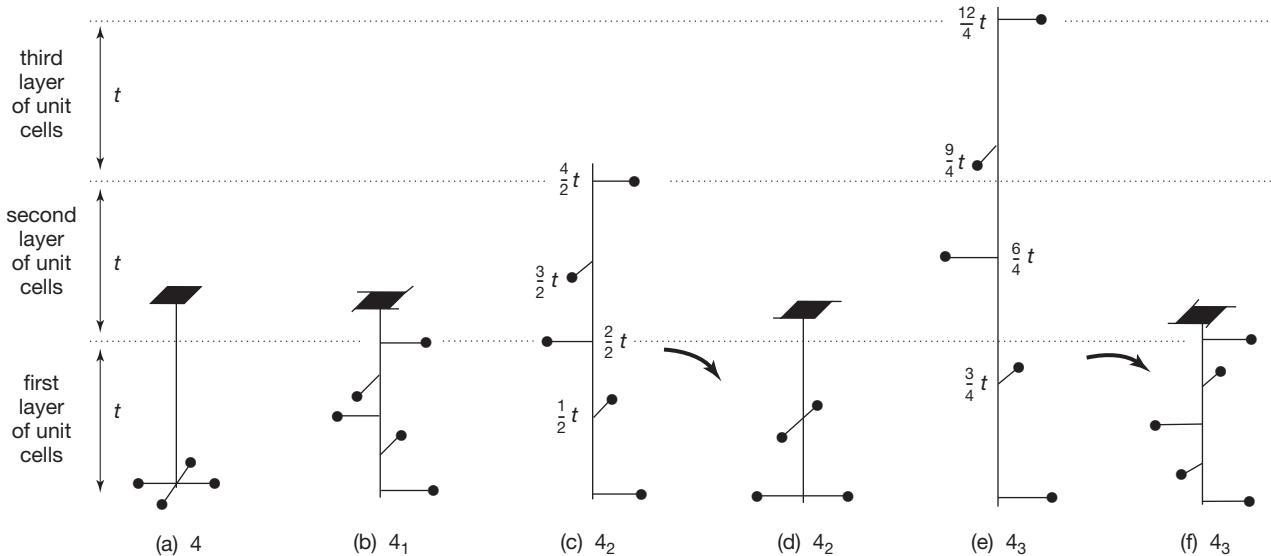


come full circle. Similarly, the translation associated with a screw axis must be a rational fraction of the unit cell dimension or the result will be an infinite number of atoms, all in different places in unit cells.

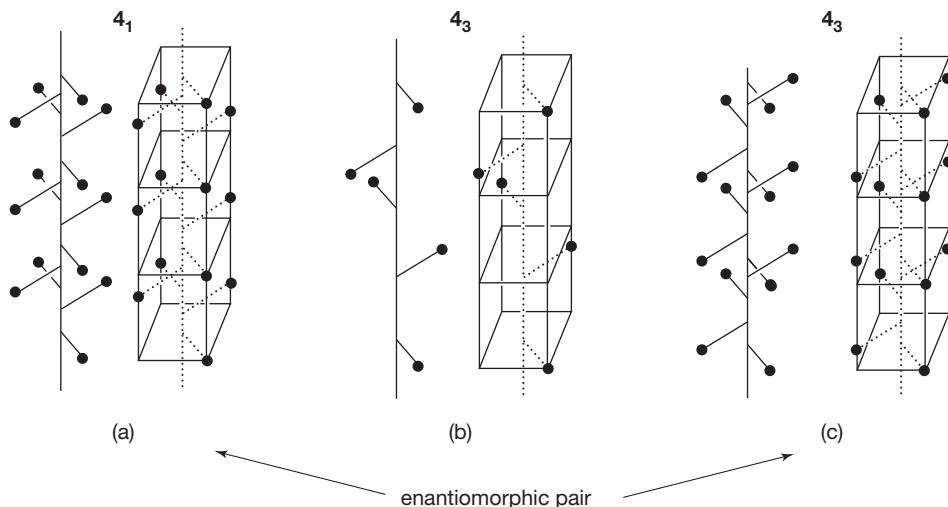
Figures 38a-f show the possible 4-fold screw axes, labeled with conventional symbols. In the labels, the 4 indicates a 4-fold axis, and the subscripts indicate the magnitudes of the translations. A subscript of 1 indicates the translation is  $1/4$  of the unit cell dimension in the direction of the axis. A subscript of 2 indicates the translation is  $2/4$  of the unit cell dimension, and a subscript of 3 indicates the translation is  $3/4$  of the unit cell dimension. All unit cells must be identical, but the  $4_2$  operation shown in Figure 38c results in a

unit cell in the second layer that differs from that in the first. The only way this operator can be made consistent is to add the extra lattice points shown in Figure 38d. In other words, the presence of a  $4_2$  axis requires the presence of a 2-fold axis.

Looking more closely at  $4_1$  and  $4_3$  axes is instructive. Consider a point at the corner of the unit cells shown in Figures 39a and b. After four applications of either operator the total rotation is  $360^\circ$ , bringing the fourth point directly above the first. For the  $4_1$  axis the total translation is equivalent to one unit cell length, but for the  $4_3$  axis it is three unit cell lengths. In Figure 39b, showing the  $4_3$  axis, the three unit cells have points in different locations. This is impossible because all unit



**FIGURE 38** Proper 4-fold axis and all possible 4-fold screw axes parallel to a unit cell edge with length  $t$ . All involve rotation of  $90^\circ$  (a) a proper 4-fold axis involves no translation; (b) a  $4_1$  axis involves translation of  $1/4t$ ; (c) a  $4_2$  axis involves translation of  $2/4t$ ; (d) because all unit cells must be identical, the symmetry of a  $4_2$  axis requires other points to be present; (e) a  $4_3$  axis involves translation of  $3/4t$ ; (f) because all unit cells must be identical, the symmetry of a  $4_3$  axis requires other points to be present.



**FIGURE 39** Application of  $4_1$  and  $4_3$  screw axes: (a) a  $4_1$  axis relating points in unit cells; (b) a  $4_3$  axis relating points in unit cells; the unit cells are not identical in this drawing; (c) a possible arrangement of points that satisfies  $4_3$  symmetry and maintains all unit cells identical.

cells must be identical. The unit cells can only be identical, while also being consistent with a  $4_3$  axis, by adding extra points as shown in Figure 39c. Figure 38e and f shows the same result. If we compare Figure 39a and Figure 39c, we see that the  $4_1$  and  $4_3$  axes are mirror images of each other. The two axes are an **enantiomorphous pair**, sometimes called *right-handed* and *left-handed* screw axes.

When all combinations are considered, there are 20 possible rotation axes (listed in Table 4). As with proper rotational axes, some screw axes are restricted to one or a few crystal systems. For example,  $3_1$  and  $3_2$ , which are an enantiomorphous pair, only exist in the trigonal subdivision of the hexagonal system. Similarly, the  $6_n$  axes only exist in the hexagonal subdivision of the hexagonal system.

### Glide Planes

Glide planes result from the simultaneous application of translation and reflection (see Figure 36). There are six types of glide planes, distinguished by having different magnitudes and directions of translation relative to crystallographic axes. Some glide planes are restricted to certain crystal systems just as some screw axes are. Glide planes may involve translation parallel to the  $a$ ,  $b$ , or  $c$  axis, and for crystals in the cubic and tetragonal systems only, the translation may follow a diagonal from one corner of a unit cell to another. The letters  $a$ ,  $b$ ,  $c$ ,  $n$ , or  $d$  symbolize these glides; Table 5 lists the possibilities.

**TABLE 4** The 20 Possible Space Symmetry Operators Involving Rotation

Operator	Type of Axis	Rotation Angle	Translation Distance*
1	identity	360°	none
$\bar{1}$	inversion center	360°	none
2	proper 2-fold	180°	none
$2_1$	2-fold screw	180°	$1/2t$
3	proper 3-fold	120°	none
$3_1$	3-fold screw	120°	$1/3t$
$3_2$	3-fold screw	120°	$2/3t$
$\bar{3}$	3-fold rotoinversion	120°	none
4	proper 4-fold	90°	none
$4_1$	4-fold screw	90°	$1/4t$
$4_2$	4-fold screw	90°	$2/4t = 1/2t$
$4_3$	4-fold screw	90°	$3/4t$
$\bar{4}$	4-fold rotoinversion	90°	none
6	proper 6-fold	60°	none
$6_1$	6-fold screw	60°	$1/6t$
$6_2$	6-fold screw	60°	$2/6t = 1/3t$
$6_3$	6-fold screw	60°	$3/6t = 1/2t$
$6_4$	6-fold screw	60°	$4/6t = 2/3t$
$6_5$	6-fold screw	60°	$5/6t$
$\bar{6}$	6-fold rotoinversion	60°	none

\* $t$  = unit cell dimension in direction of translation.

### Space Groups

Neither glide planes nor screw axes are present in point groups and lattices. They are only manifested when atomic motifs and lattice types combine to produce structures in three-dimensional space. For that reason we call them *space group*

**TABLE 5** The Possible Space Symmetry Operators Involving Reflection

Operator	Type of Plane	Orientation of Translation	Magnitude of Translation
<i>m</i>	proper mirror	None	None
<i>a</i>	axial glide	Parallel to <i>a</i>	$1/2a$
<i>b</i>	axial glide	Parallel to <i>b</i>	$1/2b$
<i>c</i>	axial glide	Parallel to <i>c</i>	$1/2c$
<i>n</i>	diagonal glide	Parallel to face diagonal	$1/2t$
<i>d</i>	diamond glide	Parallel to main diagonal	$1/4t$

\**t* = unit cell dimension in direction of glide.

operators. When we combine the space group operators in Tables 4 and 5 with the 14 possible space lattices, we get 230 possible space groups (Table 6). They represent all possible symmetries crystal structures can have. Deriving them all is not trivial, and crystallographers debated the exact number until the 1890s when several independent studies concluded that there could only be 230 (Box 4).

Crystallographers use several different notations for space groups; the least complicated is that used in the *International Tables for X-ray Crystallography* (ITX) (Hahn, 1983). ITX space group symbols consist of a letter indicating lattice type (*P*, *I*, *F*, *R*, *A*, *B*, or *C*) followed by symmetry notation similar to conventional Hermann-Mauguin symbols. An example is *P*4<sub>2</sub>/*m*2<sub>1</sub>/*n*2/*m*, the space group of rutile. Rutile has a primitive (*P*) tetragonal unit cell, a 4<sub>2</sub> screw axis perpendicular to a mirror plane, a 2<sub>1</sub> screw axis perpendicular to an *n* glide plane, and a proper 2-fold axis perpendicular to a mirror plane. Rutile crystals have symmetry *4/m*2/*m*2/*m*. Similarly, the space group of garnet, *I*4<sub>1</sub>/*a*3<sub>2</sub>/*d*, implies a body-centered unit cell, a 4<sub>1</sub> screw axis perpendicular to an *a* glide plane, a 3-fold rotoinversion axis, and a

proper 2-fold axis perpendicular to a *d* glide plane. Garnet crystals have point group symmetry *4/m*3<sub>2</sub>/*m*. Rather than using an entire symbol, crystallographers often use abbreviations for space groups (and occasionally for point groups). Thus, they would say that garnet belonged to the space group *Ia*3<sub>d</sub>. A glance at Table 6 shows why we can use this abbreviation: Only one space group, *I*4<sub>1</sub>/*a*3<sub>2</sub>/*d*, includes these symmetry elements. Most mineralogy reference books use abbreviated symbols, so we often need a table, such as Table 6, to interpret them.

The translations associated with lattices, glide planes, and screw axes are very small, on the order of tenths of a nanometer, equivalent to a few angstroms. Detecting their presence by visual examination of a crystal is impossible, with or without a microscope. A crystal with symmetry *4/m*2/*m*2/*m* could belong to the space group *I*4<sub>4</sub>/*a*2/*c*2/*d*, but there are also 19 other possibilities (Table 6). We say that the 20 possibilities are *isogonal*, meaning that when we ignore translation they all have the same symmetry. Without detailed X-ray studies, telling one isogonal space group from another is impossible, and we are left with only the 32 distinct point groups.

## BOX 4

### Why Are There Only 230 Space Groups?

Point groups may have one of 32 symmetries; we determined that crystal structures must have one of 14 Bravais lattices. When point groups are combined with Bravais lattices, and the space group operators in Tables 4 and 5 are considered, 230 possible space groups result (Table 6). The 230 space groups are the only possible symmetries that a crystal structure can have. They were tabulated in the 1890s by a Russian crystallographer, E. S. Fedorov; a German mathematician, Artur Schoenflies; and a British amateur, William Barlow, all working independently.

Why are there only 230 space groups? The answer is that symmetry operators, as we have already seen, can only combine in certain ways. In the discussion of point group symmetry, we concluded that mirrors and rotation axes can only combine in 32 ways. Other combinations led to infinite symmetry, which is impossible. The same is true of space group operators and Bravais lattices; only certain combinations are allowed. For example, triclinic lattices (*P*1 and *P*1̄) may not be combined with 2-fold axes of any sort. Similarly, 3, 3<sub>1</sub>, and 3<sub>2</sub> axes are only consistent with a rhombohedral or hexagonal lattice (3R or 6P).

**TABLE 6** The 230 Possible Space Groups

Crystal System	Point Group	Possible Space Groups
triclinic	1 $\bar{1}$	$P1$ $P\bar{1}$
monoclinic	2 $m$ $2/m$	$P2, P2_1, C2$ $Pm, Pc, Cm, Cc$ $P2/m, P2_1/m, C2/m, P2/c, P2_1/c, C2/c$
orthorhombic	222 $mm2$ $2/m2/m2/m$	$P222, P222_1, P2_12_1, P2_12_12, C222, C222, F222, I222, I2_12_12$ $Pmm2, Pmc2_1, Pcc2, Pma2, Pca2_1, Pnc2, Pmn2_1, Pba2, Pna2_1, Pnn2, Cmm2, Cmc2_1,$ $Ccc2, Amm2, Abm2, Ama2, Aba2, Fmmc, Fdd2, Imm2, Iba2, Im2$ $P2/m2/m2/m, P2/n2/n2/n, P2/c2/c2/m, P2/b2/a2/n, P2/m2/m2/a, P2/n2_1/n2/a,$ $P2/m2/n2_1/a, P2_1/c2/c2/a, P2_1/b2_1/a2/m, P2_1/c2_1/c2/n, P2/b2_1/c2_1/m, P2_1/n2_1/n2/m,$ $P2_1/m2_1/m2/n, P2_1/b2_1/c2_1/n, P2_1/b2_1/c2_1/a, P2_1/n2_1/m2_1/a, C2/m2/c2/m, C2/m2/c2_1/a,$ $C2/m2/m2/m, C2/c2/c2/m, C2/m2/m2/a, C2/c2/c2/a, F2/m2/m2/m, F2/d2/d2/d,$ $I2/m2/m2/m, I2/b2/a2/m, I2/b2/c2/a, I2/m2/m2/a$
tetragonal	4 $\bar{4}$ $4/m$ 422 4mm $\bar{4}2m$ $4/m2/m2/m$	$P4, P4_1, P4_2, P4_3, I4, I4_1$ $P4, I4$ $P4/m, P4_2/m, P4/n, P4_2/n, I4/m, I4_1/a$ $P422, P42_12, P4_122, P4_12_12, P4_22, P4_22_12, P4_322, P4_32_12, I422, I4_122$ $P4mm, P4bm, P4cm, P4_2nm, P4cc, P4nc, P4_2mc, P4_2bc, I4mm, I4cm, I4_1md, I4_1cd$ $P\bar{4}2m, P\bar{4}2c, P\bar{4}2_1m, P\bar{4}2_1c, P\bar{4}m2, P\bar{4}c2, P\bar{4}b2, P\bar{4}n2, I\bar{4}m2, I\bar{4}c2, I\bar{4}2m, I\bar{4}2d$ $P4/m2/m2/m, P4/m2/c2/c, P4/n2/b2/m, P4/n2/n2/c, P4/m2_1/b2/m, P4/m2_1/n2/c,$ $P4/n2_1/m2/m, P4/n2_1/c2/c, P4_1/m2/m2/c, P4_2/m2/c2/m, P4_2/n2/b2/c, P4_2/n2/n2/m,$ $P4_2/m2_1/b2/c, P4_2/m2_1/n2/m, P4_1/n2_1/m2/c, P4_2/n2_1/c2/m, I4/m2/m2/m, I4/m3/c2/m,$ $I4_1/a2/m2/d, I4_1/a2/c2/d$
hexagonal (hexagonal)	6 $\bar{6}$ $6/m$ 622 6mm $\bar{6}2$ $6/m2/m2/m$	$P6, P6_1, P6_5, P6_2, P6_4, P6_3$ $P\bar{6}$ $P6/m, P6_3/m$ $P622, P6_122, P6_522, P6_222, P6_422, P6_322$ $P6mm, P6cc, P6_3cm, P6_3mc$ $P\bar{6}m2, P\bar{6}c2, P\bar{6}2m, P\bar{6}2c$ $P6/m2/m2/m, P6/m2/c2/c, P6_3/m2/c2/m, P6_2/m2/m2/c$
hexagonal (trigonal)	3 $\bar{3}$ 32 3m $\bar{3}2/m$	$P3, P3_1, P3_2, R3$ $P\bar{3}, R\bar{3}$ $P312, P321, P3_112, P3_121, P3_212, P3_221, R32$ $P3m1, P31m, P3c1, P31c, R3m, R3c$ $P\bar{3}1m, P\bar{3}1c, P\bar{3}m1, P\bar{3}c1, R\bar{3}m, R\bar{3}c$
cubic	23 $2/m\bar{3}$ 432 $\bar{4}3/m$ $4/m\bar{3}2/m$	$P23, F23, I23, P2_13, I2_13$ $P2/m\bar{3}, P2/n\bar{3}, F2/m\bar{3}, F2/d\bar{3}, I2/m\bar{3}, P2_1/a\bar{3}, I2_1/a\bar{3}$ $P432, P4_232, F432, F4_132, I432, P4_332, P4_132, I4_132$ $P\bar{4}3m, F\bar{4}3m, I\bar{4}3m, P\bar{4}3n, F\bar{4}3c, I\bar{4}3d$ $P4/m\bar{3}2/m, P4/n\bar{3}2/n, P4_2/m\bar{3}2/n, P4_2/n\bar{3}2/m, F4/m\bar{3}2/m, F4/m\bar{3}2/c, F4_1/d\bar{3}2/m,$ $F4_1/d\bar{3}2/c, I4/m\bar{3}2/m, I4_1/a\bar{3}2/d$

**CRYSTAL HABIT AND CRYSTAL FACES**

Why do halite and garnet, both cubic minerals, have different crystal habits? It is not fully understood why crystals grow together in the ways they do. Cubic unit cells may lead to cube-shaped crystals

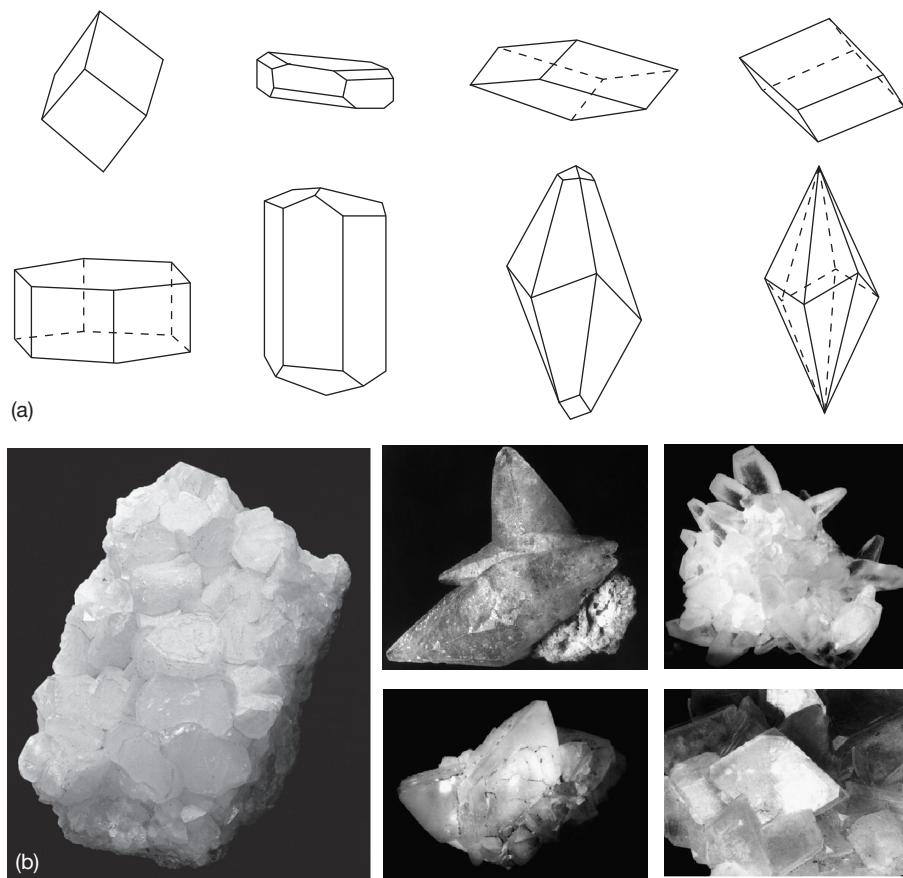
such as halite, octahedral crystals such as spinel, dodecahedral crystals such as garnet, and many other shaped crystals. Why the differences? Crystallographers do not have complete answers, but the most important factor is the location of atoms and lattice points within the unit cell.

Crystals of a particular mineral tend to have the same forms, or only a limited number of forms, no matter how they grow. Haüy and Bravais noted this and used it to infer that atomic structure controls crystal forms. In 1860 Bravais observed what we now call the *Law of Bravais*: Faces on crystals tend to be parallel to planes having a high density of lattice points. This means that, for example, crystals with hexagonal lattices often have faces related by hexagonal symmetry. Crystals with orthogonal unit cells (those in the cubic, orthorhombic, or tetragonal systems) tend to have faces at 90° to each other.

The relationship between lattice symmetry and crystal habit can be seen by comparing Figure 30, showing the possible unit cell shapes for calcite, with Figure 40 showing some common forms for calcite crystals. There is a close resemblance between the unit cell shapes, which represent the lattice symmetry, and some of the crystal shapes. Thus, Bravais's Law works well. Unfortunately, some minerals, such as pyrite ( $\text{FeS}_2$ ) and quartz ( $\text{SiO}_2$ ), appear to violate Bravais's Law. Bravais's observations were based on considerations of the 14 Bravais lattices and their symmetries, but in the

early twentieth century, P. Niggli, J. D. H. Donnay, and D. Harker realized that space group symmetries needed to be considered as well. By extending Bravais's ideas to include glide planes and screw axes, Niggli, Donnay, and Harker explained most of the biggest inconsistencies. They concluded that crystal faces form parallel to planes of highest atom density, a slight modification of the Law of Bravais.

As a crystal grows, different faces grow at different rates. Some may dominate in the early stages of crystallization while others will dominate in the later stages. The relationship, however, is the opposite of what we might expect. Faces that grow fastest are the ones that eventually disappear. Figure 41 shows why this occurs. If all faces on a crystal grow at the same rate, the crystal will keep the same shape as it grows (Figure 41a). However, this is not true if some faces grow faster than others. In Figure 41b, the diagonal faces (oriented at 45° to horizontal) grew faster than those oriented vertically and horizontally. Eventually, the diagonal faces disappeared; they "grew themselves out." The final



**FIGURE 40** Typical calcite crystals: (a) eight idealized drawings of crystals; (b) five photographs of calcite crystals.

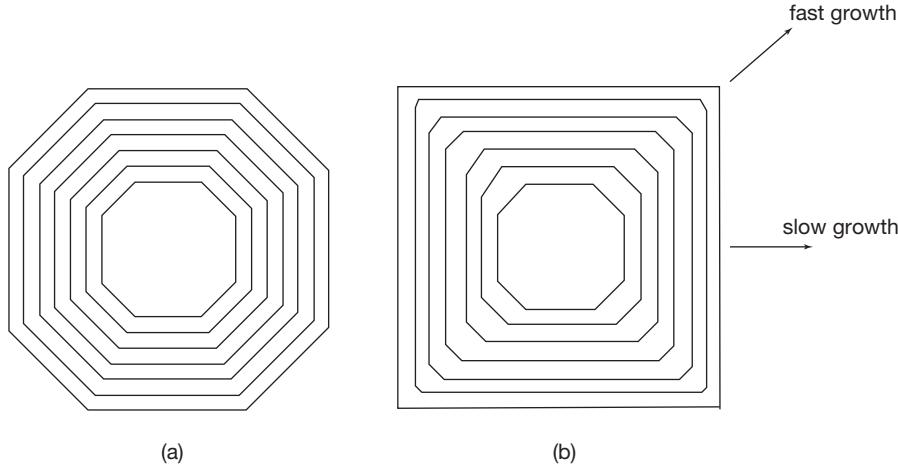
crystal has a different shape, and fewer faces, than when it started growing. We observe this phenomenon in many minerals; small crystals often have more faces than larger ones.

In summary, crystals may have any of 32 possible symmetries corresponding to the 32 point groups. Each requires the lattice and unit cell to have one of six possible symmetries. This allows us to divide crystals into six crystal systems, each characterized by unit cells of different shape. Several lattice types are possible for most crystal systems; there are 14 different Bravais lattices in all. The combination of atomic motif symmetry, lattice type, glide planes, and screw axes defines the space group. The 230 space groups represent the possible symmetries relating atoms in crystals.

Crystal morphology depends on the way unit cells are stacked together. For some crystals, we can infer crystal system and point group by examining morphology. We need X-ray studies to determine lattice type and space group.

We can now explain why we only considered 1-, 2-, 3-, 4-, and 6-fold rotation axes. Crystals can have no more symmetry than their unit cells. Unit cells can have no rotation axes other than the ones we considered. Three-dimensional solids with 5-fold axes of symmetry, for example, cannot be unit cells because they cannot fit together to fill three-dimensional space. We can verify this by drawing equal-sided pentagons on a piece of paper. No matter how we fit them together, space will always be left over.

**FIGURE 41** Growth rates affect crystal shape. These drawings show crystals and the “growth rings” that developed as they grew to full size. (a) If all faces grow at the same rate, the crystal does not change shape as it grows. (b) If the horizontal and vertical faces grow more slowly than the diagonal faces (note thickness of growth bands), eventually the diagonal faces disappear.



## Questions for Thought

Some of the following questions have no specific correct answers; they are intended to promote thought and discussion.

1. Steno's Law is one of the fundamental laws of crystallography. What is Steno's Law and what are its implications for crystal structure?
2. Today we know that crystals are made of unit cells composed of a discrete number of atoms. How do we know this?
3. All crystals with four 3-fold axes of symmetry must belong to the cubic system. Why is this a good way to group crystals? What do crystals with four 3-fold axes have in common that makes grouping them appropriate?
4. Why are there only six crystal systems?
5. What is the relationship between crystal symmetry (point group) and unit cell symmetry?
6. What is the relationship between crystal symmetry (point group) and lattice symmetry?
7. What is the fundamental difference between point group operators and space group operators? Why do we need space group operators to describe the symmetry of crystal structures?
8. What is the relationship between crystal form and crystal structure? How do they both relate to crystal habit?
9. Examine the patterns in Figure 17. Place a piece of tracing paper over them and indicate all symmetry elements. Choose a representative unit cell for each pattern and make a drawing of the lattice.

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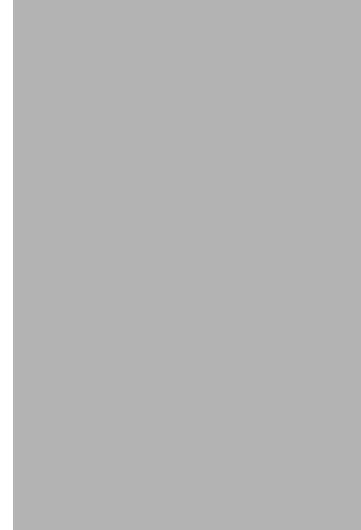
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# Unit Cells, Points, Lines, and Planes



# Unit Cells, Points, Lines, and Planes

To describe the details of crystals and crystal structures, it is necessary to be more quantitative. In this chapter we describe points, lines, and planes in crystal structures using a coordinate system based on unit cell geometry. The most important results are that we can give exact descriptions of crystal structures, and we can label and describe crystal faces and crystal properties in unambiguous ways.

A crystal is composed of many identical building blocks called *unit cells*. To describe a unit cell, we must give its shape, size, and composition. Symmetry axes, crystal faces, and other linear and planar features of crystals depend on the nature of the unit cell and on crystal growth. To describe them, we need some way to describe the orientation of lines and planes in crystals. Furthermore, for complete characterization of a crystal, we must specify the locations of atoms in its structure. We therefore need a quantitative way to describe points (for example, atom locations), lines, and planes in crystals and unit cells. To do this, it is convenient to have a coordinate system. The system used by crystallographers is similar to a **Cartesian coordinate system**, with the exception that the angles between the three axes vary according to the crystal being described, as do the unit lengths along each axis.

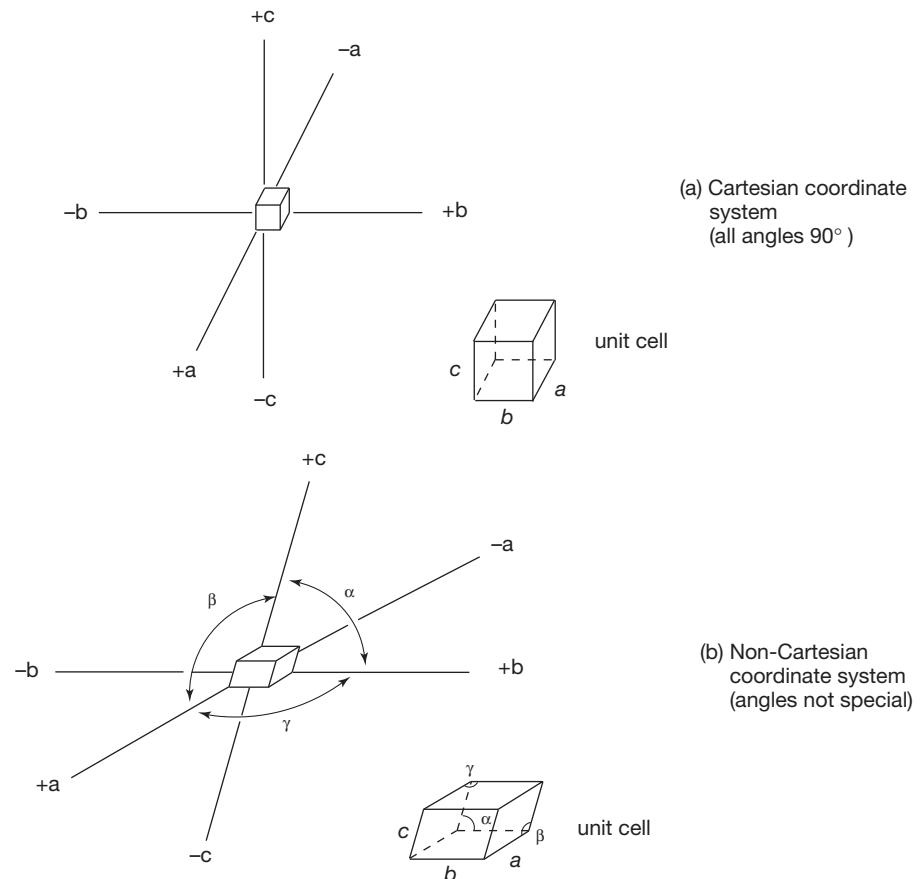
## UNIT CELL PARAMETERS AND CRYSTALLOGRAPHIC AXES

Unit cell parameters are  $a$ ,  $b$ ,  $c$ ,  $\alpha$ ,  $\beta$ , and  $\gamma$ .  $a$ ,  $b$ , and  $c$  are the lengths of unit cell edges;  $\alpha$ ,  $\beta$ , and  $\gamma$  are the angles between the edges,  $\alpha$  being the angle between  $b$  and  $c$ ,  $\beta$  the angle between  $a$  and  $c$ ,

and  $\gamma$  the angle between  $a$  and  $b$ . Mineralogists have traditionally used angstroms ( $1\text{ \AA} = 10^{-10}\text{ m}$ ) but some more recent literature uses nanometers ( $1\text{ nm} = 10\text{ \AA}$ ) to measure  $a$ ,  $b$ , and  $c$ . The angles  $\alpha$ ,  $\beta$ , and  $\gamma$  are today given as a decimal number of degrees (for example,  $94.62^\circ$ ). Typical mineral unit cells have edges of 2 to  $20\text{ \AA}$ ; angles between edges vary greatly, although unit cells are often chosen so that angles are close to  $90^\circ$ .

Unit cell edges define the coordinate system used by crystallographers (Figure 1). Three axes, designated  $a$ ,  $b$ , and  $c$ , run parallel to  $a$ ,  $b$ , and  $c$  length edges of the unit cell. The angles between the axes are therefore  $\alpha$ ,  $\beta$ , and  $\gamma$ . In the cubic, tetragonal, and orthorhombic systems,  $\alpha$ ,  $\beta$ , and  $\gamma$  all equal  $90^\circ$  because the unit cell edges are orthogonal.

Instead of using angstroms to give distances, we may also use unit cell dimensions as a scale. For example, we might say that a certain plane intersects the axes at distances of  $3a$ ,  $2b$ , and  $2c$  from the origin. It is implicit that  $3a$  refers to a distance equal to three unit cell edge lengths along the  $a$  axis,  $2b$  a distance equal to two unit cell lengths along the  $b$  axis, and  $2c$  a distance equal to two unit cell lengths along the  $c$  axis.



**FIGURE 1** Coordinate system used to describe crystals: (a) a standard Cartesian coordinate system; (b) a crystallographic coordinate system in which the angles between axes are  $\alpha$  (the angle between  $b$  and  $c$ ),  $\beta$  (the angle between  $a$  and  $c$ ) and  $\gamma$  (the angle between  $a$  and  $b$ ).

The symmetry of a unit cell always affects the relationships between  $a$ ,  $b$ , and  $c$ . So, in the cubic system,  $a = b = c$ , but in the tetragonal and hexagonal systems  $a = b \neq c$ . The relationships implied by crystal systems mean that, for systems other than triclinic, we need not give six values to describe unit cell shape. Table 1 gives examples of unit cell parameters for minerals from each of the crystal

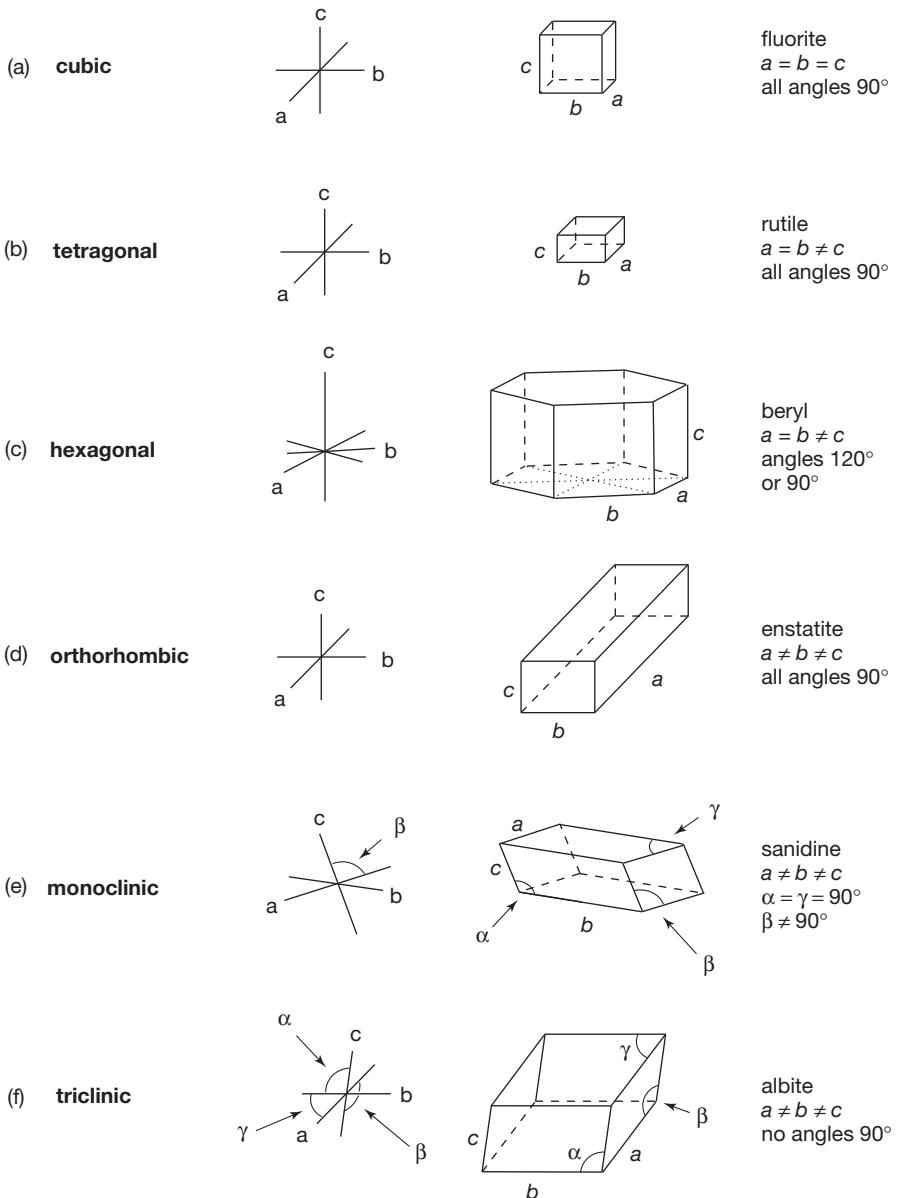
systems; unnecessary information has been omitted. Figure 2 depicts the unit cells.

Consider the triclinic mineral albite, a feldspar with composition  $\text{NaAlSi}_3\text{O}_8$ . The last column in Table 1 gives albite's cell dimensions and Figure 2f shows a drawing of the unit cell with all edges and angles labeled. Because none of the angles are special and none of the cell edges are equal, we need six parameters to describe the unit cell shape. In

**TABLE 1** Unit Cell Parameters ( $a$ ,  $b$ ,  $c$ ,  $\alpha$ ,  $\beta$ ,  $\gamma$ ),  $Z$  (number of formulas per unit cell), and  $V$  (unit cell volume) for One Mineral from Each of the Crystal Systems\*

Fluorite $\text{CaF}_2$	Rutile $\text{TiO}_2$	Beryl $\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$	Enstatite $\text{Mg}_2\text{Si}_2\text{O}_6$	Sanidine $\text{KAlSi}_3\text{O}_8$	Albite $\text{NaAlSi}_3\text{O}_8$
cubic	tetragonal	hexagonal	orthorhombic	monoclinic	triclinic
$Z = 4$	$Z = 2$	$Z = 2$	$Z = 4$	$Z = 4$	$Z = 4$
$a = 5.46$	$a = 4.59$	$a = 9.23$	$a = 18.22$	$a = 8.56$	$a = 8.14$
$V = 162.77$	$c = 2.96$	$c = 9.19$	$b = 8.81$	$b = 13.03$	$b = 12.8$
	$V = 62.36$	$V = 2034.09$	$c = 5.21$	$c = 7.17$	$c = 7.16$
			$V = 836.30$	$\beta = 115.98$	$\alpha = 94.33$
				$V = 799.72$	$\beta = 116.57$
					$\gamma = 87.65$
					$V = 746.01$

\* $a$ ,  $b$ , and  $c$  are in angstroms;  $\alpha$ ,  $\beta$ , and  $\gamma$  are in degrees; and  $V$  is in cubic angstroms.



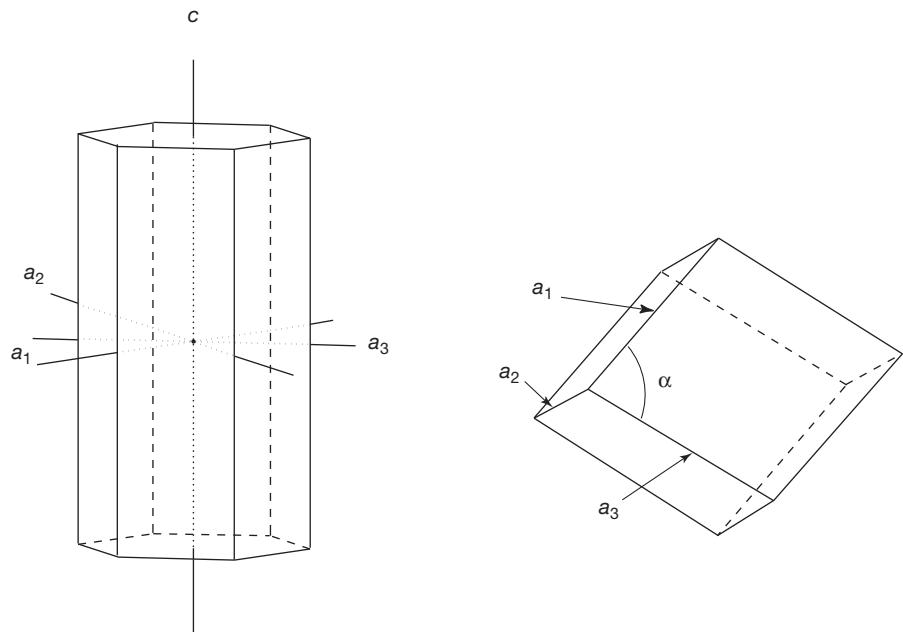
**FIGURE 2** Examples of unit cells for minerals belonging to each of the six crystal systems: (a) fluorite (cubic); (b) rutile (tetragonal); (c) beryl (hexagonal); (d) enstatite (orthorhombic); (e) sanidine (monoclinic); (f) albite (triclinic).

contrast, fluorite (Table 1 and Figure 2a) has a cubic unit cell, so we need to give only one cell parameter, the length of the cell edge. It is implicit that all angles are  $90^\circ$  and all cell edges are the same length.

Although it makes no difference which edges of a unit cell we call  $a$ ,  $b$ , or  $c$ , mineralogists normally follow certain conventions. In triclinic minerals, none of the angles are special and  $a$ ,  $b$ , and  $c$  are all different lengths. Although the literature contains exceptions, by modern convention edges are chosen so that  $c < a < b$ . In monoclinic minerals, such as sanidine, only one angle in the unit cell is not  $90^\circ$ . By convention, the non- $90^\circ$  angle is  $\beta$ , the angle between  $a$  and  $c$ . This convention is the **second setting** for monoclinic minerals. The value of  $\beta$  is the only angle listed in Table 1 because it is implicit that the other two angles are  $90^\circ$ . For

orthorhombic, hexagonal, tetragonal, and cubic minerals, we need not give any angles since they are all defined by the crystal system. In orthorhombic crystals, axes are most often chosen so that  $c < a < b$ . In tetragonal and hexagonal crystals, the  $c$  axis always corresponds to the 4-fold or 6-fold axis. The cell edge is always designated  $a$  in cubic crystals.

In this text we use  $a$ ,  $b$ , and  $c$  to designate the three crystallographic axes, but other conventions are sometimes used. Some crystallographers use subscripts to indicate axes, and thus cell edges, that must be identical because of symmetry. For example, instead of  $a$ ,  $b$ , and  $c$ , the three axes of cubic minerals might be designated  $a_1$ ,  $a_2$ , and  $a_3$ . The axes of tetragonal crystals can be designated  $a_1$ ,  $a_2$ , and  $c$ . For hexagonal crystals, crystallographers have historically used four axes:  $a_1$ ,  $a_2$ ,  $a_3$ , and  $c$  (Figure 3a). The three  $a$  axes,  $a_1$ ,  $a_2$ , or



**FIGURE 3** Using subscripts to denote axes in hexagonal unit cells:  
 (a) nonprimitive hexagonal unit cell with four axes ( $a_1$ ,  $a_2$ ,  $a_3$ ,  $c$ );  
 (b) primitive rhombohedral unit cell with three axes ( $a_1$ ,  $a_2$ ,  $a_3$ ) separated by angle  $\alpha$ .

$a_3$ , are parallel to edges of a nonprimitive hexagonal unit cell (Figure 3a). The third axis is redundant, but has been included in the past to emphasize that there are three identical  $a$  axes perpendicular to the  $c$  axis. A further complication arises for hexagonal crystals because they are sometimes described by a primitive rhombohedral unit cell with three equal edges ( $a_1$ ,  $a_2$ , and  $a_3$ ) and three equal angles ( $\alpha$ ) between edges (Figure 3b). Seldom, however, are these edges used as the basis for a coordinate system. Only three axes are used in much of the modern literature, so we will only briefly mention the fourth axis in the rest of this chapter.

### THE COMPOSITION OF UNIT CELLS

Physical dimensions do not completely describe a unit cell. We must also specify the nature and locations of atoms within the unit cell. To provide some of this information, Table 1 lists two other things: mineral formulas and  $Z$ , the number of formulas in each unit cell. For example, albite has the formula  $\text{NaAlSi}_3\text{O}_8$  and  $Z = 4$ . This means that four  $\text{NaAlSi}_3\text{O}_8$  formulas are in each unit cell. In other words, each unit cell contains 4 Na atoms, 4 Al atoms, 12 Si atoms, and 32 O atoms. Similarly, the three possible calcite unit cells have  $Z = 2$ ,  $Z = 12$ , and  $Z = 4$ .

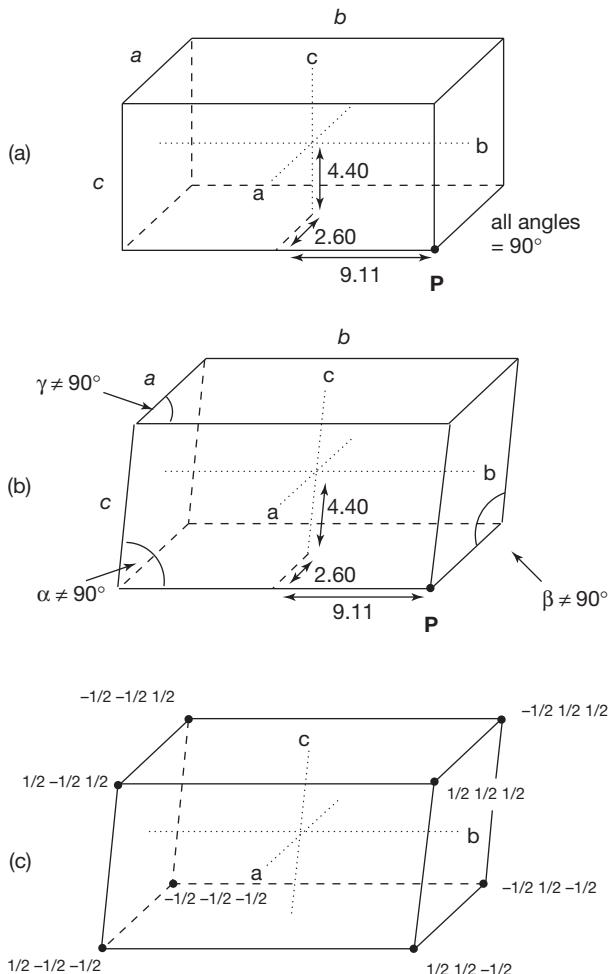
### POINTS IN UNIT CELLS

Mineralogists describe the locations of atoms or other points in unit cells by giving their coordinates. As examples, consider the orthorhombic and triclinic crystals shown in Figure 4a and b. In the

orthorhombic crystal the three axes intersect at  $90^\circ$ , in the triclinic crystal they do not. Assume both crystals have cell dimensions  $a = 5.20\text{\AA}$ ,  $b = 18.22\text{\AA}$ , and  $c = 8.80\text{\AA}$ , and the axes' origins are at the center of the unit cells as shown. The coordinates of point P, at the lower right-hand corner in each drawing, are therefore  $5.20/2 = 2.60\text{\AA}$ ,  $18.22/2 = 9.11\text{\AA}$ , and  $-8.80/2 = -4.40\text{\AA}$ . The negative sign arises because the points are in a negative direction from the origin along the  $c$  axis.

We do not, however, normally report coordinates in angstroms (\text{\AA}). Instead, we report distances relative to unit cell dimensions. Another way to describe the location of point P in Figure 4a and b would be to say they have coordinates  $\frac{1}{2}a$ ,  $\frac{1}{2}b$ ,  $-\frac{1}{2}c$ . We normalize coordinates to unit cell dimensions by dropping the  $a$ ,  $b$ , and  $c$ . The coordinates then become  $\frac{1}{2}$ ,  $\frac{1}{2}$ ,  $-\frac{1}{2}$ . The system to which a crystal belongs does not affect the coordinates. The points at the corners must have coordinates  $\pm\frac{1}{2}$ ,  $\pm\frac{1}{2}$ ,  $\pm\frac{1}{2}$ , if the origin is at the center of the unit cell (Figure 4c).

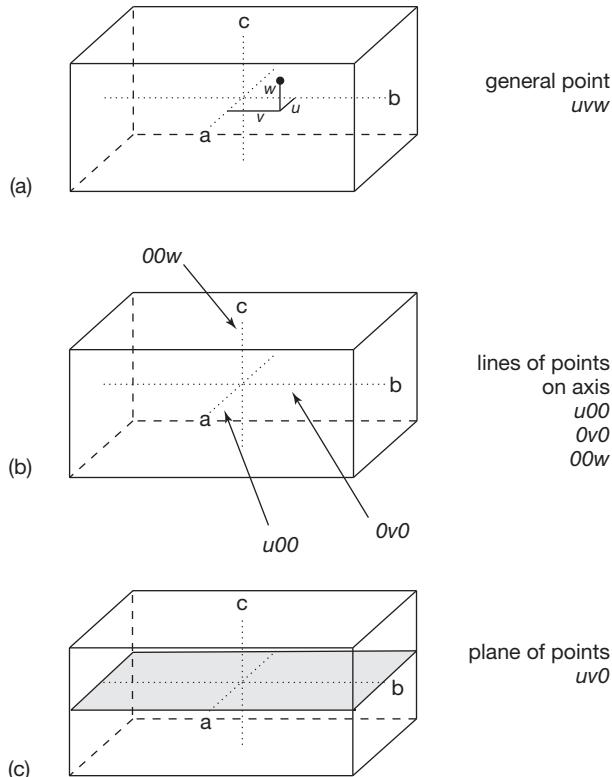
Traditionally, crystallographers have used the characters  $u$ ,  $v$ , and  $w$  to symbolize the coordinates of a point if the coordinates are rational numbers, and  $x$ ,  $y$ , and  $z$  to symbolize the coordinates if irrational. For simplicity, in this text we will use  $uvw$  in all instances (Figure 5a). We can say that  $uvw$  represents a **general point** anywhere in the cell. Suppose two coordinates, for example  $v$  and  $w$ , are zero. All the points described by the coordinates  $u00$  constitute a set of **special points**, lying along the  $c$  axis (Figure 5b). Similarly,  $0v0$  and  $00w$  refer to sets of special points on the  $b$  and  $c$  axes, respectively. If only one coordinate equals zero, a



**FIGURE 4** Points in orthorhombic and triclinic crystals: (a) An orthorhombic unit cell having cell edges of  $a = 5.2$ ,  $b = 18.22$ , and  $c = 8.80 \text{ \AA}$ . Point P has coordinates (in  $\text{\AA}$ ) of  $2.6, 9.11, -4.40$ . These values correspond to the distance along the  $a$ ,  $b$ , and  $c$  axes from the origin to P. In (b), Point P has the same coordinates, although the unit cell is triclinic. In both cases, we can also describe the coordinates of P as  $\frac{1}{2}a$ ,  $\frac{1}{2}b$ ,  $-\frac{1}{2}c$ , or simply as  $\frac{1}{2} \frac{1}{2} -\frac{1}{2}$  and not specify the units. (c) The coordinates of all points at the corners of a cell: They all have coordinate values of  $\frac{1}{2}$  or  $-\frac{1}{2}$  if the origin is at the center of the cell.

point lies in a plane including two axes. We might, for example, talk about special points located at  $uv0$ . These are points located on a plane that includes the  $a$  and  $b$  axes, as shown in Figure 5c. Note that no parentheses or brackets are used when giving coordinates of a point.

Figure 6a shows a unit cell of sphalerite, ZnS, with atom coordinates  $u$ ,  $v$ ,  $w$  given. Because three-dimensional drawings are sometimes difficult to draw and see, crystallographers often use projections, which contain the same information in a less cluttered manner (Figure 6b). In the projection, we need not specify  $u$  and  $v$  values because they can be estimated from the location of

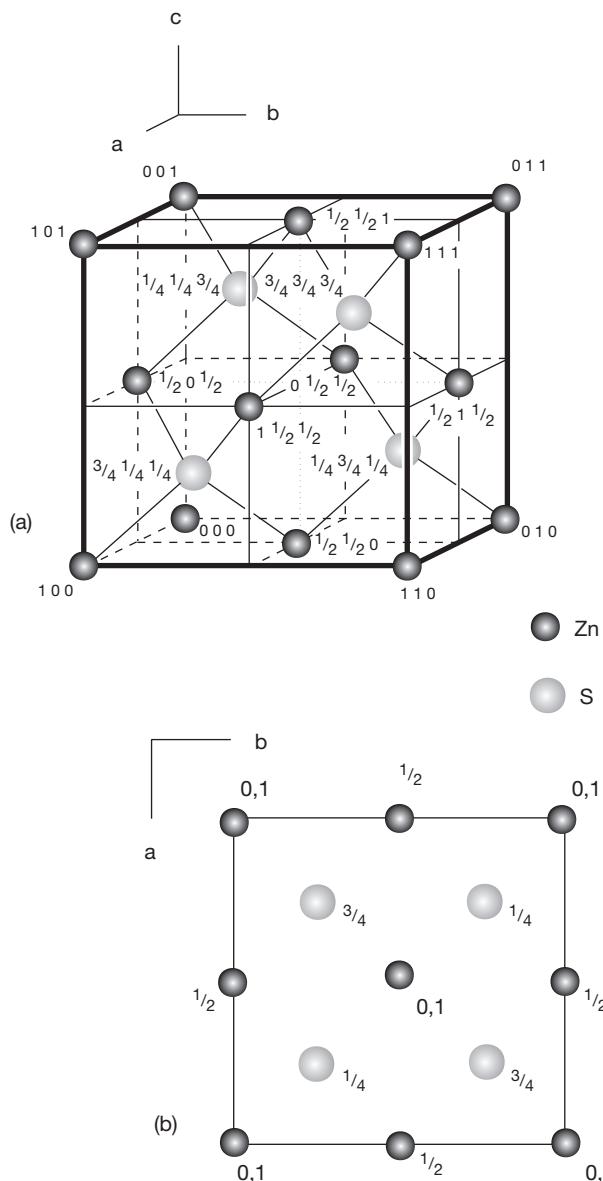


**FIGURE 5** General points and special points in a unit cell: (a) A general point in a unit cell has nonspecial values for its indices  $u$ ,  $v$ , and  $w$ . (b) Special points lying on crystallographic axes must have two indices equal to 0. (c) Special points within a plane including two axes have one index equal to 0.

the atoms in the drawing. Sometimes the  $w$  values for atoms at the corner unit cells are omitted; by convention, this means the atoms are found on both the top and bottom of the cell as it appears in projection.

## LINES AND DIRECTIONS IN CRYSTALS

The absolute location of a line in a crystal is not often significant, but directions do have significance because they describe the orientations of symmetry axes and other linear features. Crystallographers designate directions with three indices in square brackets,  $[uvw]$ . As with point locations, we give numbers describing directions in terms of unit cell dimensions. In Figure 7, direction OA has indices  $[132]$ . In terms of vectors,  $\vec{OA}$  is equivalent to  $1\vec{a} + 3\vec{b} + 2\vec{c}$ .  $[132]$  is the direction from the origin to the point 132. Notice that direction  $[\frac{1}{3} \frac{1}{2} \frac{2}{3}]$  is the same as  $[132]$ . Fractions are cleared and common denominators eliminated when giving the indices of a direction.  $(\frac{1}{3} \frac{1}{2} \frac{2}{3})$  becomes  $[132]$  when we multiply all indices by 3. By convention, commas separate indices only if they have more than one digit.



**FIGURE 6** The atomic structure of sphalerite and *u*, *v*, and *w* values (atomic coordinates) of each atom: (a) the structure in three dimensions with the crystallographic origin at the corner labeled 000; (b) the structure in projection when looking down the *c* axis. *u* and *v* values can be inferred from the location of the atom symbols in the projection. *w* values are given with numbers. The atoms at the corners and center of the unit cell have two *w* values because in this projection two atoms fall on top of each other.

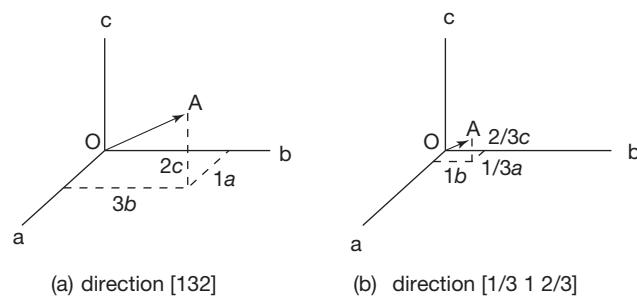
Although no commas are included in [132], reading sequentially, as we do for point locations, we articulate it “one-three-two.”

Figure 8 shows several lines on a two-dimensional lattice. The direction [120] (OC) is the same as [240] (OD), which is consistent with the proportional relationship of the two sets of indices. Parallel lines have identical indices, so the choice of the origin is unimportant and OC, O'C', and O''C'' have indices [120]. Line OF has indices [230], articulated “bar-two-three-zero.” The bar over the 2 is equivalent to a negative sign, indicating that the line goes in the negative *a* direction.

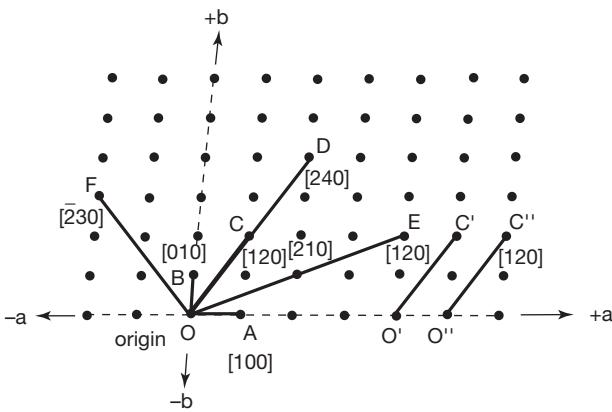
Because all directions in Figure 8 lie in the *a*-*b* plane, they have indices [*uvw*]. This notation indicates that the first two indices may vary, but the third is 0. Whenever the index for one axis is 0, a line or direction must lie in a plane parallel to the other two axes (Figure 9). If two indices are 0, the direction is parallel to an axis: [100] is parallel to *a*, [010] parallel to *b*, and [001] parallel to *c*. Figure 9a, b, and c emphasize that it does not matter where lines are; orientation determines indices. We determine the indices of lines in the same way, even if the axes are not orthogonal. Note that in Figure 9c [1̄1̄1] the line could also be designated as [1̄1̄1̄] because lines, unlike vectors, do not go in any specific direction.

## PLANES IN CRYSTALS

While crystals and crystal faces vary in size and shape, Steno’s law tells us that angles between faces are characteristic for a given mineral. The absolute location and size of the faces are rarely of significance to crystallographers, while the relative orientations of faces are of fundamental importance. We can use face orientations to determine of crystal systems and point groups, so having a simple method to describe the orientation of crystal faces is useful. Consider a plane parallel to a crystal face. Such a plane may intersect all three axes, or it may be parallel to one or two of them (Figure 10). We can describe the orientation of a plane by listing its intercepts with the axes.



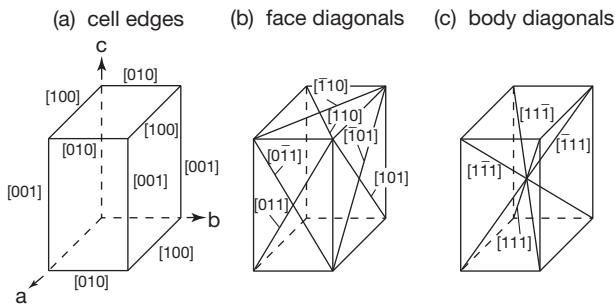
**FIGURE 7** Vector addition to describe a line. (a) Vector  $\vec{OA}$  is described by giving its components in the *a*, *b*, and *c* directions: 1*a*, 3*b*, 2*c*, given in abbreviated form as 132. (b) Vector  $\frac{1}{3} 1 \frac{2}{3}$  parallels 132 but is shorter.



**FIGURE 8** Lines and their indices on a two-dimensional lattice. All lines are assumed to lie in the  $a$ - $b$  plane.

For a face parallel to an axis, the intercept is at  $\infty$ , an infinite distance from the origin. In Figure 10a, a plane (PQR) intersects the axes at distances OQ, OP, and OR from the origin. The dots on the axes show the unit cell lengths, which may in some crystal systems be different along each axis. We could give the distances OQ, OP, and OR in angstroms ( $\text{\AA}$ ) or some other absolute units. As with points and directions, however, it is more convenient to express distances relative to unit cell dimensions ( $a$ ,  $b$ , and  $c$ ). So, we would say that plane PQR (Figure 10a) has axial intercepts  $1a$ ,  $2b$ ,  $4c$ , or just  $1, 2, 4$ .

One problem with describing a plane by giving its axial intercepts is that faces often lie parallel to crystal axes. If parallel to the  $c$  axis, for example, a crystal face has intercepts  $u$ ,  $v$ ,  $\infty$ , where  $u$  and  $v$  can have any values (Figure 10b). A face that is parallel to two axes has two parameters that are infinity (Figure 10c). The use of  $\infty$  can be confusing and awkward. A second problem with listing intercepts is that parallel planes and faces, such as those in Figure 10d, have different indices.



**FIGURE 9** Special directions and indices in a unit cell: (a) directions parallel to unit cell edges; (b) directions parallel to face diagonals; (c) directions parallel to body diagonals.

Crystallographers find this inconvenient because orientation is usually the feature of importance when discussing crystal faces. To avoid these and other problems, crystallographers generally do not report axial intercepts, but instead use **Miller indices**.

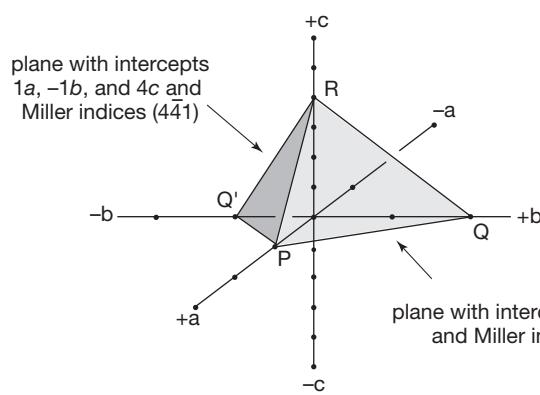
### Miller Indices

Miller indices were first developed in 1825 by W. Whewell, a professor of mineralogy at Cambridge University. We use them to describe the orientation of crystal faces, and also the orientations of cleavages and other planar properties. They are named after W. H. Miller, a student of Whewell's, who promoted and popularized their use in 1839. The general symbol for a Miller index is  $(hkl)$ , in which the letters  $h$ ,  $k$ , and  $l$  each stand for an integer. We calculate Miller indices for a plane from its axial intercepts (Figure 10). The procedure is as follows: Axial intercept values are inverted; fractions are cleared;  $\infty$  becomes 0 upon inversion. Parentheses enclose the resulting Miller index. As with directions, bars show negative values and we do not include commas unless numbers have more than one digit. Conversion of the axial intercepts  $\infty$ ,  $\infty$ ,  $-3$  for the plane in Figure 10c would go as follows: Inversion yields 0, 0, and  $-1/3$ ; multiplying by 3 gives a Miller index of  $(001)$ , articulated as "oh-oh-bar-one." Similarly, plane PQ'R (Figure 10a) has axial intercepts of  $1, -1, 4$  and a Miller index  $(\bar{4}11)$ .

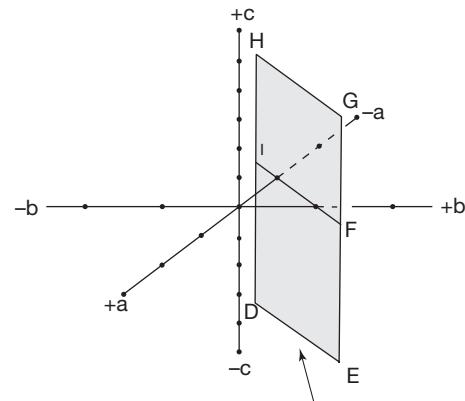
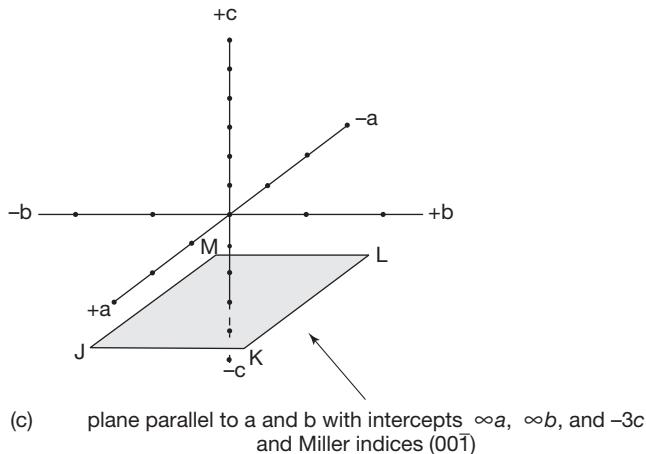
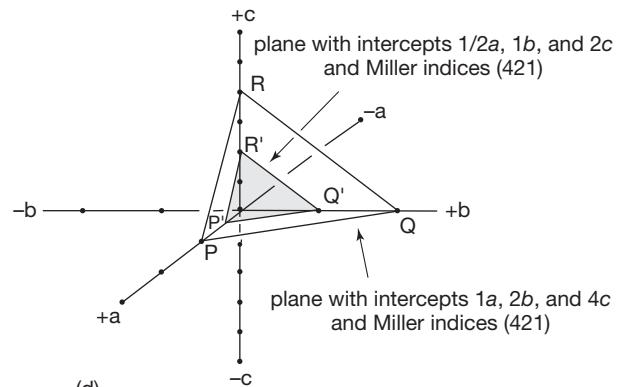
Because crystal faces are parallel to rows of lattice points, they are parallel to planes that intercept crystal axes at an integral number of unit cells from the origin. Consequently, inversion of intercepts and clearing fractions always yields integers. This observation is known as the **law of rational indices**. Another observational law, called **Haüy's law**, says that Miller indices of faces generally contain low numbers. For example,  $(111)$  is a common face in crystals, while  $(972)$  is not. Haüy's law is really a corollary to the law of Bravais, already discussed, which states that faces form parallel to planes of high lattice point density; planes with low values in their Miller index have the greatest lattice point density.

Parallel planes always have the same Miller index. In Figure 10d, both PQR and P' Q' R' have Miller index  $(421)$ . Any face lying parallel to a plane with axial intercepts at  $1, 2, 4$  has this index. Crystallographers would call it the "4-2-1 face," no matter its size or shape. The Miller index describes the orientation of a crystal face with respect to crystallographic axes, but not the absolute size or location of the face.

The replacement of unknown or variable numbers in a Miller index with  $h$ ,  $k$ , or  $l$  allows us to



(a)

(b) plane parallel to  $c$  with intercepts  $-1a$ ,  $1b$ , and  $\infty c$  and Miller indices  $(\bar{1}10)$ (c) plane parallel to  $a$  and  $b$  with intercepts  $\infty a$ ,  $\infty b$ , and  $-3c$  and Miller indices  $(00\bar{1})$ 

(d)

make generalizations. The index  $(hk0)$  describes the family of faces with their third index equal to zero. A Miller index including a zero indicates that a face is parallel to one or more axes. The family of faces described by  $(hk0)$  is parallel to the  $c$  axis; faces with the Miller index  $(00l)$  are parallel to both the  $a$  axis and the  $b$  axis (Figure 10c).

As mentioned previously, crystallographers have in the past used four axes for crystals in the hexagonal system (Figure 11). The general symbols are  $[hki]$  for directions and  $(hkil)$  for planes. One of the first three values ( $h$ ,  $k$ , or  $i$ ) is always redundant because we can always describe the location of a plane in three-dimensional space with three variables. In all cases:

$$h + k + i = 0 \quad (1)$$

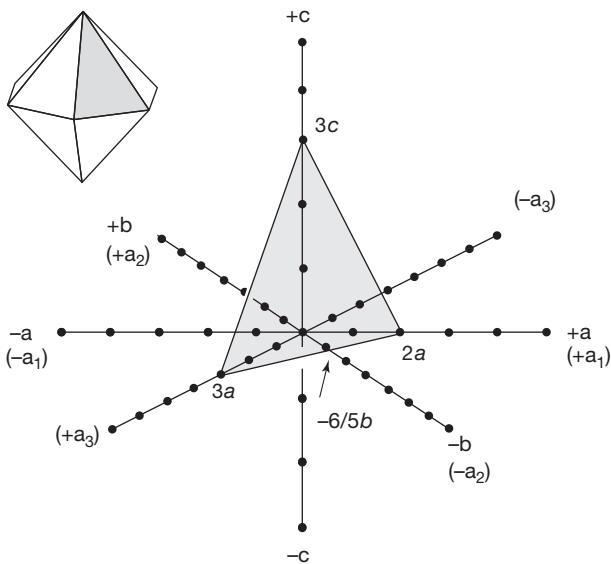
Because of the redundancy, and to be consistent with other crystal systems, many crystallographers today use only three indices for hexagonal minerals.

The relationship between planes and directions in a crystal depends on the crystal system. Except in the cubic system, the direction  $[uvw]$  is neither perpendicular nor parallel to planes with the Miller index  $(uvw)$  (Figure 12 in Box 1).

## CRYSTAL FORMS AND THE MILLER INDEX

Recall that a set of faces related by symmetry comprise a form. Faces of a form always have similar Miller indices. This relationship is especially clear for crystals in the cubic system because high symmetry means that many forms may contain many identical faces. The six identical faces on the cube in Figure 13a have indices  $(001)$ ,  $(010)$ ,  $(100)$ ,  $(0\bar{0}1)$ ,  $(0\bar{1}0)$ , and  $(\bar{1}00)$ . We symbolize the entire form  $\{100\}$ , and the  $\{ \}$  braces indicate the form contains all faces with the numerals 1, 0, and 0 in their Miller index.

The four faces on the tetrahedron in Figure 13b, and the eight faces on the octahedron in



**FIGURE 11** Indexing a crystal face on a hexagonal mineral: The shaded face is shown by itself intersecting the  $a$  and  $b$  axes at  $2a$  and  $-6/5b$  and the  $c$  axis at  $3c$ . Its Miller index is  $(\bar{3}\bar{5}2)$ . If we consider three  $a$  axes (see text), the intercepts are  $2a$ ,  $-6/5a$ ,  $3a$ ,  $3c$ , and the Miller index is  $(\bar{3}\bar{5}22)$ .

Figure 13c are all equilateral triangles. For both, the form is  $\{111\}$ . As Figure 13b and c demonstrate, two crystals of different shapes can have the same form if they belong to different point groups. The tetrahedron in Figure 13b belongs to point group  $\bar{4}3m$ ; the octahedron in Figure 13c belongs to point group  $4/m\bar{3}2/m$ . If we know the point group and the form, we can calculate the orientation of faces. If a crystal contains only one form, we then know the shape of the crystal. Note that the cube (Figure 13a), octahedron (Figure 13c), and dodecahedron (Figure 13d) all belong to point group  $4/m\bar{3}2/m$ . The cubic form is  $\{100\}$ , the octahedral form is  $\{111\}$ , and the dodecahedral form is  $\{110\}$ .

Figure 13e shows a crystal containing three forms: cube  $\{100\}$ , octahedron  $\{111\}$ , and dodecahedron  $\{110\}$ . Because they all belong to point group  $4/m\bar{3}2/m$ , we can calculate that the faces are *oriented* as shown. However, the crystal in Figure 13f belongs to the same point group and contains the same forms, but the *size and shape* of corresponding faces are different. We do not know crystal shape if more than one form is present, unless we know some extra information.

Crystallographers sometimes label faces of the same form with the same letter (Figure 13a–f). For some forms, the letter is just the first letter of the form name. For example,  $o$  indicates the octahedral form and  $d$  the dodecahedral form

in the cubic system. Usually, however, the symbols are less obvious (we normally designate cube faces, for example, by the letter  $a$ ); they also vary from one crystal system to another.

## General Forms and Special Forms

The relationship between special forms and general forms is the same as the one between special points and general points. Faces of a general form are neither parallel nor perpendicular to any symmetry element, while faces of special forms are. Thus, in special forms, symmetry relates fewer equivalent faces. For example, the faces of a cube (Figure 13a) are perpendicular to the 4-fold axes of rotation, and the faces of an octahedron (Figure 13c) are perpendicular to the 3-fold axes of rotation. The presence of zeros, or equal values of  $b$ ,  $k$ , or  $l$ , in the Miller index, suggests that these forms may be parallel or perpendicular to symmetry elements, no matter the crystal system. In the cubic system,  $\{b00\}$  will always be a cube,  $\{bbb\}$  an octahedron, and  $\{bb0\}$  a dodecahedron, for all values of  $b$ . The general form in the cubic system is a hexoctahedron  $\{bkl\}$ , with  $b$ ,  $k$ , and  $l$  all unequal, which has 48 faces (Box 2). Its standard designation,  $\{123\}$ , indicates that  $b \neq k \neq l$  in its Miller index, and that none of the indices is zero. We can think of a hexoctahedron (Figure 15a in Box 2) as an octahedron (Figure 13c) with each of its eight faces replaced by six smaller triangular faces. In all point groups, the general form is the one with the most faces.

## Zones and Zone Axes

A set of faces parallel to a common direction defines a zone. The common direction is the zone axis. Figure 14a, b, and c show examples of forms in the tetragonal and hexagonal systems. The prismatic faces, parallel to  $c$  in all three drawings, form  $[001]$  zones. The zone axes are  $[001]$ . Zones may contain faces from more than one form. In Figure 14c, the  $[010]$  zone comprises eight faces and three forms,  $\{100\}$ ,  $\{001\}$ , and  $\{101\}$ . In all three drawings, additional zones are present besides  $[010]$  and  $[001]$ . The stippled faces in Figure 14a are part of the  $[100]$  zone; the unstippled faces are part of the  $[010]$  zone; the prismatic faces comprise the  $[001]$  zone. In this figure, the zones have simple indices because they are parallel to crystal axes. Zones need not be parallel to axes, and consequently the indices may contain values other than 0 and 1.

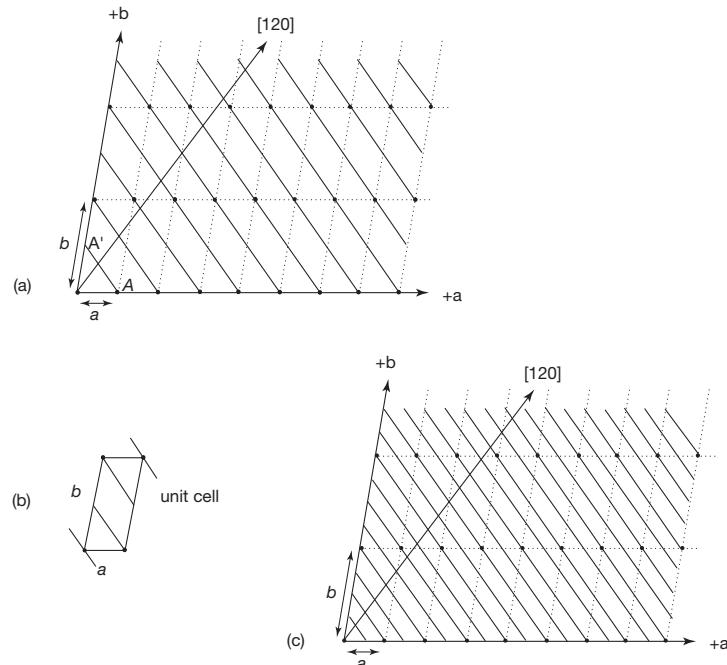
**BOX 1****The Miller Indices of Planes within a Crystal Structure**

We use Miller indices to describe the orientation of crystal faces, but we also use them to describe planes within a crystal structure. We calculate the indices in the same way, with the exception that we do not clear common denominators after inversion of axial intercepts when we are talking about planes within a structure. For example, if we calculate an index of (240) for a set of planes, we do not divide by 2 to give (120), as we do when calculating a Miller index for a crystal face. We do not clear fractions because, besides orientation, the spacing and location of planes are important when we are talking about crystal structure and not crystal faces.

Figure 12a shows some two-dimensional unit cells cut perpendicular to the c axis. The plane passing through points A and A', and perpendicular to the page, has axial intercepts  $1, \frac{1}{2}, \infty$ , so its Miller index is (120). Because all unit cells are equivalent, we know identical (120) planes exist in all the unit cells.

Figure 12a shows the entire family of (120) planes; when we discuss (120) planes in a crystal structure, we refer to this entire family, not just to one plane. Four (120) planes intersect each unit cell, two pass through the inside of the cell, and two through the corners in our drawing (Figure 12b). Note that the axial intercepts of the (120) plane closest to the origin (O) are  $1, \frac{1}{2}, \infty$ , equivalent to  $1/h, 1/k, 1/l$ . This relationship holds true for any family of  $(hkl)$  planes.

Different families of planes, with the same orientation but different spacings, have different indices. Figure 12c shows planes spaced half as far apart as those in Figure 12b. They have the Miller index (240). We do not clear the common denominator (divide by 2) because the families of (240) and (120) planes, although parallel, are not identical. There are twice as many (240) planes.



**FIGURE 12** Planes and Miller indices. (a) AA' is one of a family of (120) planes. Note that the direction [120] is not perpendicular to (120) planes unless the a and b axes are perpendicular. (b) One unit cell and four (120) planes that intersect it. (c) The family of (240) planes. Note the planar spacing is half that of the (120) planes.

The consequence that the  $(hkl)$  plane closest to the origin intercepts the axes at distances  $1/h, 1/k, 1/l$  follows from algebraic considerations. The algebraic equation of a plane cutting three axes ( $X, Y$ , and  $Z$ ) at absolute distances  $x^\circ, y^\circ$ , and  $z^\circ$  from the origin is:

$$\frac{x}{x^\circ} + \frac{y}{y^\circ} + \frac{z}{z^\circ} = 1 \quad (2)$$

In terms of Miller indices, the corresponding equation for a plane is:

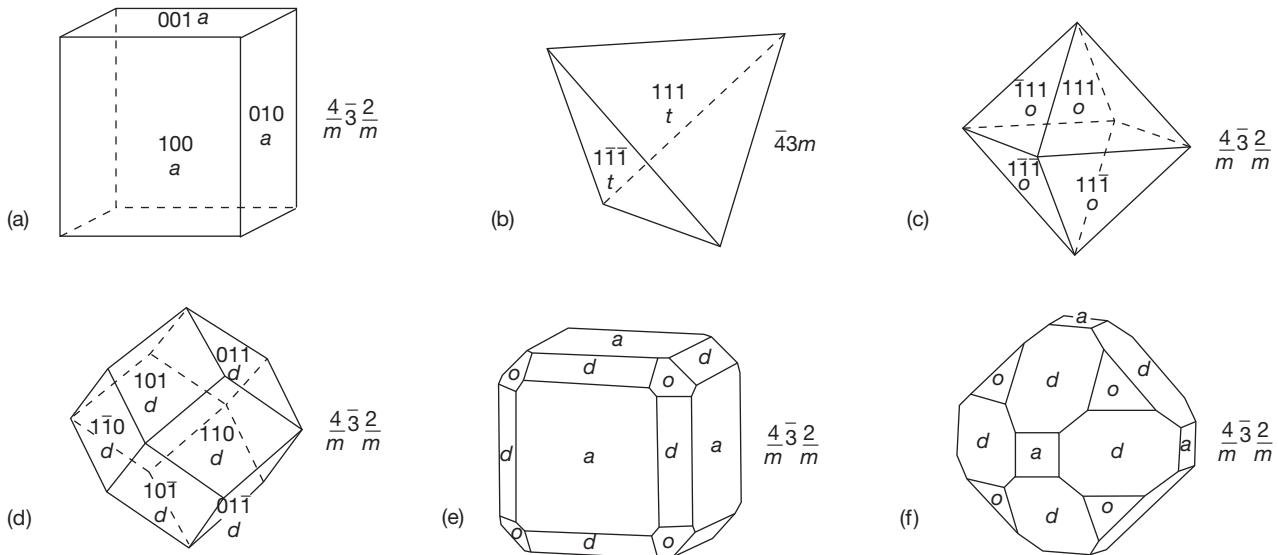
$$hx + ky + lz = Q \quad (3)$$

where  $Q$  is a rational number. In terms of crystallographic axes  $a, b$ , and  $c$ :

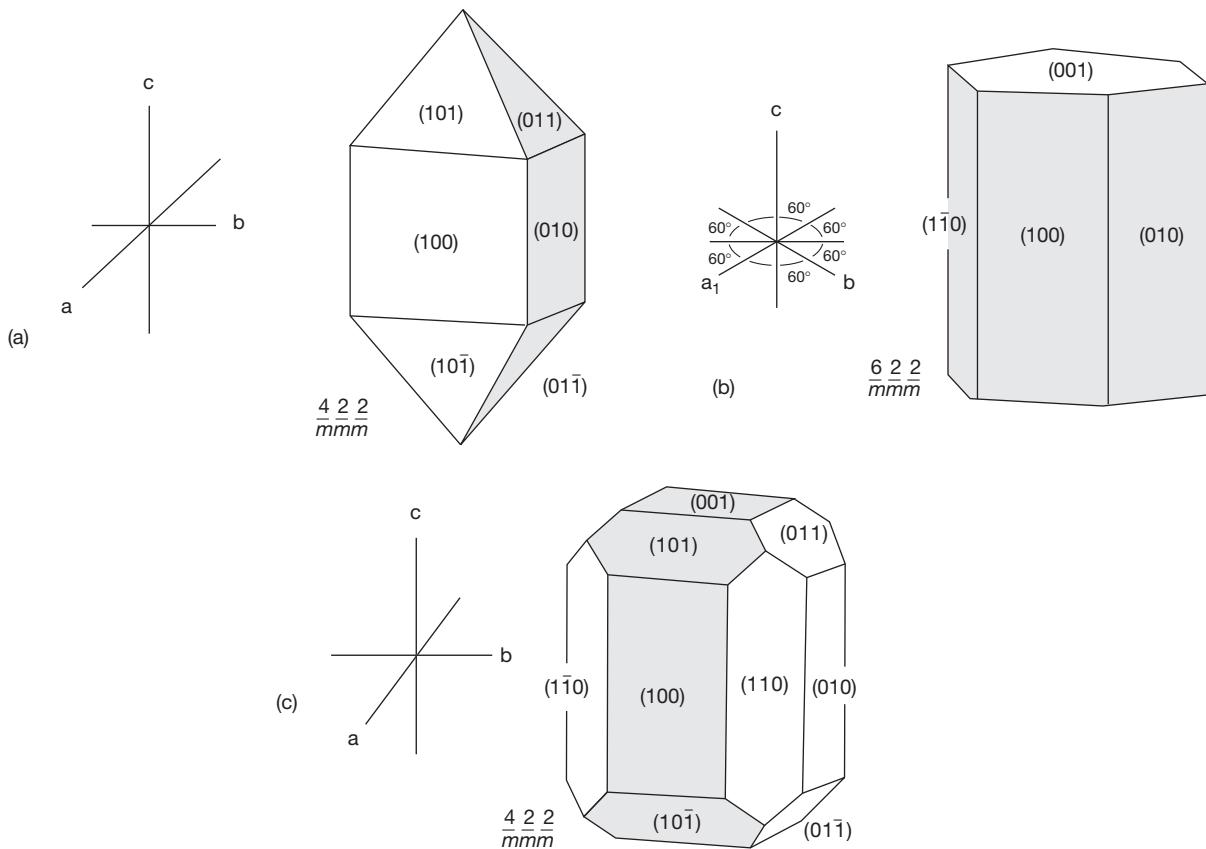
$$ha + kb + lc = Q \quad (4)$$

where  $a, b$ , and  $c$  are coordinates of a point in the plane. This simple relationship is the equation of a plane in  $a$ - $b$ - $c$  space in terms of Miller indices. When  $Q = 1$ , the equation describes the closest plane to the origin with Miller indices  $(hkl)$ . All other values of  $Q$  yield parallel planes farther from the origin.

## Unit Cells, Points, Lines, and Planes



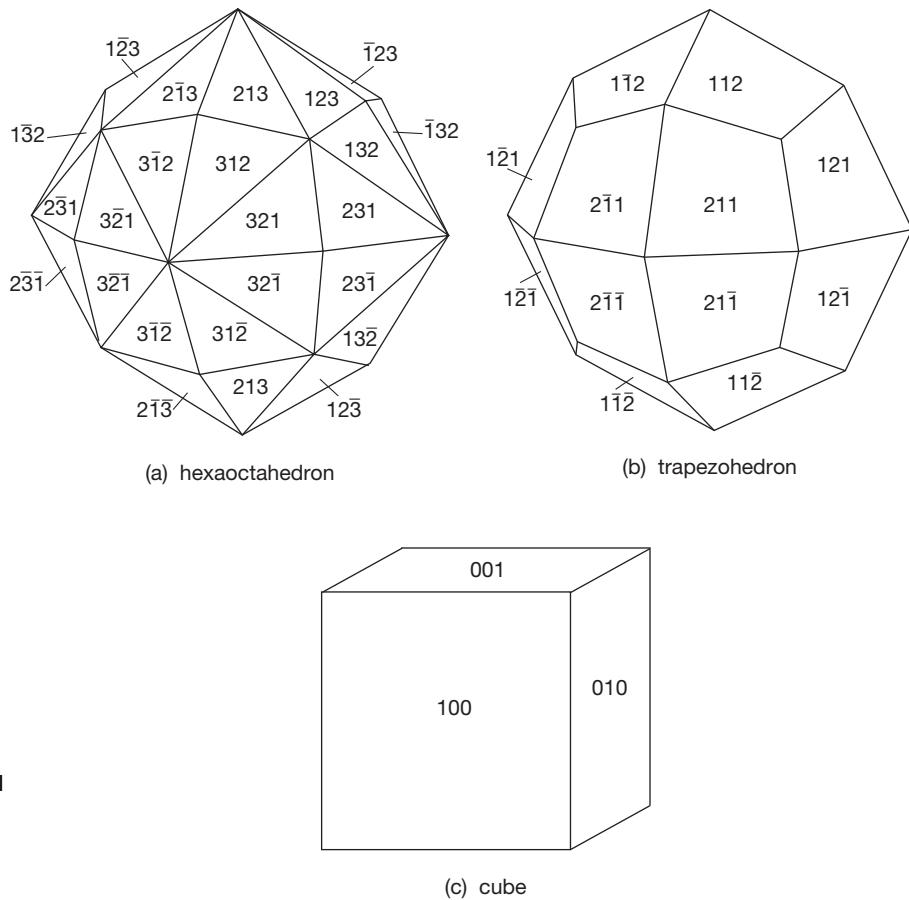
**FIGURE 13** Cubic forms and Miller indices: (a) cube; (b) tetrahedron; (c) octahedron; (d) dodecahedron; (e) a combination of cube, octahedron, and dodecahedron; (f) a different combination of cube, octahedron, and dodecahedron.



**FIGURE 14** Forms and zones in tetragonal and hexagonal crystals. The crystal in (a) is a tetragonal prism and dipyradmid. The gray faces belong to the [100] zone. The crystal in (b) is a hexagonal prism and pinacoid. The gray faces belong to the [001] zone. The crystal in (c) includes a tetragonal prism, dipyradmid, and pinacoids. The gray faces belong to the [010] zone.

**BOX 2****Comparison of a Hexoctahedron with Other Forms in the Cubic System**

The hexoctahedron is the general form in the cubic system; its Miller index contains three different values ( $h \neq k \neq l \neq 0$ ). All other forms are special forms and can be thought of as derivatives. Special forms have two or more identical indices in their Miller index (or have an index with value zero). If groups of faces on a hexoctahedron are systematically combined to produce one face, special forms result with no change in symmetry. Figure 15 shows a hexoctahedron, a trapezohedron, and a cube. The trapezohedron is formed by systematically combining pairs of faces on the hexoctahedron and replacing them with a single face. The cube is formed by systematically combining groups of eight faces and replacing them with a single face. The cube and the trapezohedron are special forms; unlike the hexoctahedron, their faces are perpendicular or parallel to symmetry elements. In the case of the cube, the faces are obviously perpendicular to 4-fold rotational axes. Less clear is that the faces of the trapezohedron are perpendicular to mirror planes. Similar relationships between general forms, symmetry elements, and special forms can be demonstrated for all point groups. The coincidence of faces with symmetry elements means that there can be fewer faces without reducing the symmetry.



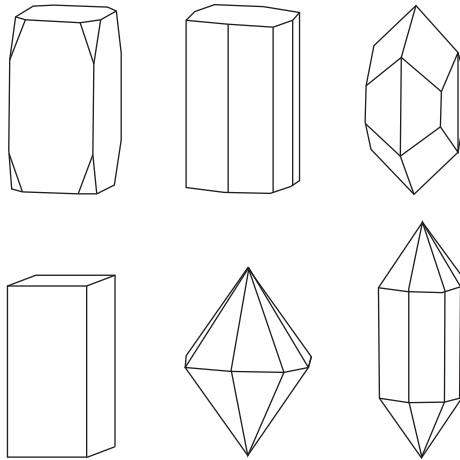
**FIGURE 15** The general form (hexoctahedron) and some special forms (trapezohedron, cube) for point group  $4/m\bar{3}2/m$ . Note that all faces of a form have similar Miller indices.

### Questions for Thought

Some of the following questions have no specific correct answers; they are intended to promote thought and discussion.

1. We use indices to discuss the orientations of lines and planes in crystals. Why?
2. We use unit cell parameters to describe the shape of a unit cell. Why do we need fewer parameters for some crystal systems than for others?
3. When we describe the unit cell of enstatite, we might give its formula as  $\text{Mg}_2\text{Si}_2\text{O}_6$  and say that  $Z = 4$  (Table 1). What does this mean? On the other hand, we could choose a unit cell twice as large, and then  $Z$  would be 16. Why don't we do this? Alternatively, can we choose a smaller unit cell so that  $Z = 1$ ? Why don't we do this?

4. If you look at mineral descriptions you will find that some cleavages are listed using parentheses ( $hkl$ ), and some are listed using braces,  $\{hkl\}$ . For example, the cleavage of chrysoberyl is described as “good  $\{011\}$ , poor  $(010)$ .” Why do we use two different notations?
5. Consider the crystal form with Miller index  $\{111\}$ . Will it be the same for crystals in all point groups? Why? Will it be the same for crystals in point groups belonging to one crystal system?
6. Consider the point group  $4/m2/m2/m$ . Possible forms include pinacoid, tetragonal dipyramid, tetragonal prism, ditetragonal pyramid, and ditetragonal dipyramid. They are all shown in at least one of the drawings in Figure 16, each containing one, two, or three forms. Which of the forms is the general form? Possible Miller indices for these forms are  $\{001\}$ ,  $\{010\}$ ,  $\{0k\}$ ,  $\{bk\}$ , and  $\{hk0\}$ . Which forms and which of the faces in the drawings have these indices?
7. Draw stereo diagrams and plot the locations of all the faces in the crystals shown in Figure 16.



**FIGURE 16** Some possible crystals belonging to point group  $4/m2/m2/m$ .

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# X-ray Diffraction and Mineral Analysis

Until about 1960, the most important methods for identifying minerals were wet chemical analysis, X-ray diffraction, and optical microscopy. These three approaches yield distinctly different kinds of information. Wet chemical analysis and other kinds of chemical analyses tell us the chemical composition of a mineral but not its atomic arrangement. In contrast, X-ray diffraction studies provide information about the arrangement of atoms in a crystal, but little direct information about composition. Optical microscopy allows us to determine, sometimes quantitatively, the optical properties of individual mineral grains, information that often permits mineral identification. Today, X-ray diffraction and optical microscopy remain very important. Wet chemical analyses, however, have for the most part been replaced by a number of new techniques. In this chapter we consider X-ray diffraction and ways to obtain chemical analyses.

## THE DISCOVERY OF X-RAYS AND DIFFRACTION

Mineralogists studied minerals for hundreds of years before the discovery of **X-rays**. By the late nineteenth century, they believed that crystals had ordered and repetitive crystal structures. They hypothesized about atomic arrangements and the nature of crystal structures, but they lacked direct evidence. Some ideas about crystal structure were generally accepted, while others were poorly understood and hotly debated. Without a way to test hypotheses, the development of an acceptable theory of the crystal structure of minerals was stalled. Wilhelm Conrad Röntgen's discovery of X-rays in 1895 allowed mineralogists to proceed with their studies and eventually led to a greater understanding of crystal structures. Mineralogists quickly discarded many hypotheses disproved by X-ray studies; just as quickly, they developed and tested new ones. In less than two decades, scientists

developed a firm theoretical basis for understanding how atoms are arranged in minerals.

Today we accept without question the idea that atoms bond together in regular arrangements to make crystals. We draw pictures, make enlarged models, and study the details of crystal structures of thousands of minerals. All this knowledge would have been unobtainable if Röntgen and his coworkers had not recognized the importance of some curious phenomena they observed while studying **cathode ray tubes** (early versions of television tubes) in 1895.

Röntgen taught and studied physics at the University of Würzburg in Germany. He was studying the relationship between matter and force as charged particles flowed from a heated filament in an evacuated glass tube. By chance, he observed that a nearby piece of barium platinocyanide fluoresced when he turned on the tube. Röntgen deduced that electrons interacting with the walls of the tube produced a high-energy form of radiation, and he showed that the radiation could

penetrate paper and even thin metals. Because the radiation seemed to behave differently from light, he thought it a completely different phenomenon, calling it **X-radiation**. Various physicists searched for an understanding of the nature of X-radiation. X-rays became inextricably involved with mineralogy when Max von Laue successfully used crystals as a tool in this search.

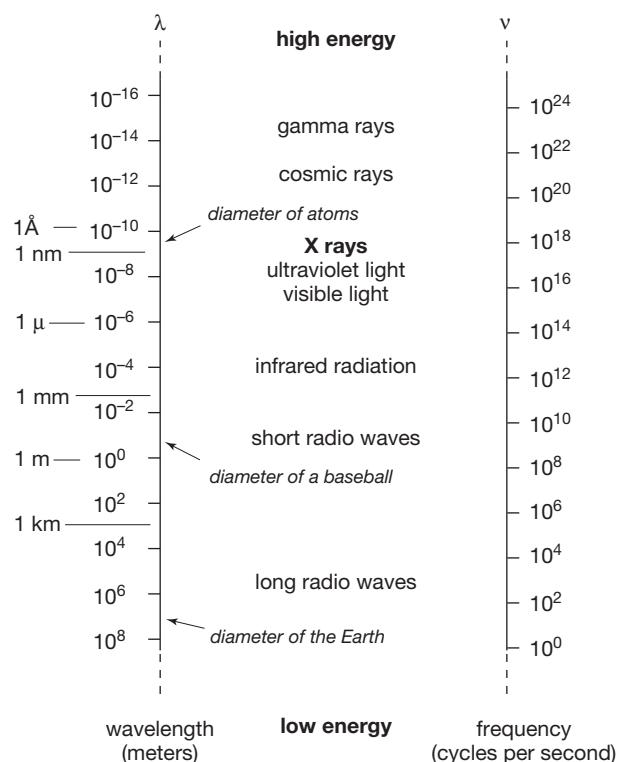
The diffraction of light was well understood at the time. Physicists routinely measured the wavelengths of colored light using finely spaced **diffraction gratings**. In 1911 von Laue, a physics professor in München, determined that lines in diffraction gratings were not spaced closely enough to diffract X-rays. This partly explained Röntgen's confusion about the relationship between light and X-rays. Von Laue hypothesized that the distance between atoms in crystals, being much less than the distance between lines in diffraction gratings, could lead to X-ray diffraction.

Walter Friedrich and Paul Knipping confirmed von Laue's ideas in 1912 when they caused X-rays to pass through crystals of copper sulfate ( $\text{CuSO}_4$ ) and sphalerite ( $\text{ZnS}$ ) and recorded diffraction patterns on film. Their studies showed that X-rays are electromagnetic waves similar to light, but with much shorter wavelengths. They also confirmed that crystals must have a regular crystal structure. The impact of the work by von Laue and his students was immense. Paul Debye and Paul Scherrer soon improved X-ray techniques. They showed that all crystals have a lattice and that lattices vary in their symmetry. In 1913 William H. Bragg and his son William L. Bragg determined the arrangement of atoms in sphalerite,  $\text{ZnS}$ , using data obtained with X-ray studies. For the first time, mineralogists knew the actual locations of atoms within a crystal. Other crystal structure determinations soon followed as Linus Pauling and other scientists realized the power of X-ray diffraction.

Early X-ray studies were tedious. Scientists could spend an entire career determining the crystal structure of only a few minerals. Today, with sophisticated equipment and high-speed computers, crystal structure determinations are often routine and sometimes can be done in less than a day. It is important to remember, however, that without the pioneering work of Röntgen, von Laue, the Braggs, Pauling, and others, we would have no detailed knowledge of how atoms are arranged in minerals. In 1901 Röntgen received the first Nobel Prize for Physics; von Laue was awarded the same prize in 1914, and both Braggs were the recipients in 1915.

## WHAT ARE X-RAYS?

X-rays are a form of electromagnetic radiation (Figure 1). Whereas the wavelengths of visible light are  $10^{-6}$  to  $10^{-7}$  meters, X-ray wavelengths are only  $10^{-2}$  to  $10^{-12}$  meters. Long-wavelength X-rays



**FIGURE 1** Electromagnetic radiation covers a spectrum of wavelengths ranging over 24 orders of magnitude. Short-wavelength radiation, equivalent to gamma rays or cosmic rays, has high energy. Long-wavelength radiation has low energy. X-rays, which are relatively high-energy forms of radiation, have wavelengths between those of cosmic rays and visible light.

grade into ultraviolet light; shorter wavelengths grade into cosmic and gamma rays. Mineralogists usually give X-ray wavelengths in angstroms (1 Å equals  $10^{-10}$  meters). The copper radiation commonly used in X-ray studies has  $\lambda = 1.5418\text{\AA}$ .

The frequency ( $v$ ) and wavelength ( $\lambda$ ) of electromagnetic radiation are inversely related. **Planck's law** relates them to energy:

$$E = hv = hc/\lambda \quad (1)$$

In this equation  $h$  is Planck's constant and  $c$  is the speed of light in a vacuum. Because of their short wavelengths and high frequencies, X-rays have high energy compared with visible light and most other forms of electromagnetic radiation. High energy allows X-rays to penetrate many natural materials, as observed by Röntgen in 1895. X-rays of highest energy, called **hard radiation**, are used in many manufacturing and industrial applications, such as checking steel for flaws. X-rays of relatively low energy, called **soft radiation**, are used by mineralogists and for medical diagnoses. Soft radiation is the most dangerous to people because rather than passing

through tissue like many hard X-rays and gamma rays, soft X-rays interact with atoms in cells and tissues, causing damage. Because of the potential health hazards, crystallographers take special care to avoid exposure to the X-rays in their experiments.

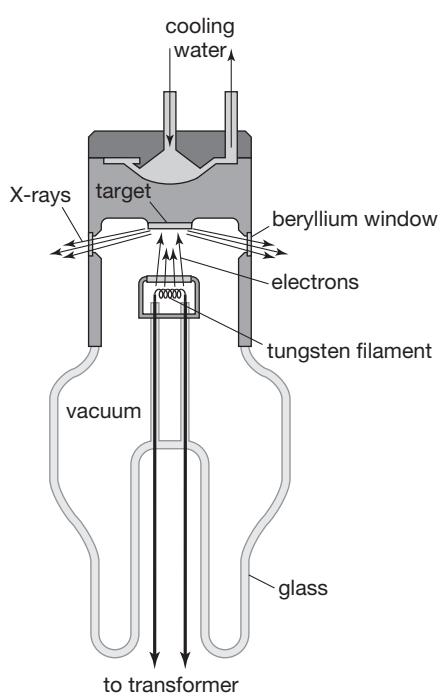
A beam of high-velocity electrons striking a metal target in an X-ray tube generates X-rays for diffraction studies (Box 1). Some of the high-velocity electrons that hit the target produce an emission of a continuous spectrum of X-rays called **continuous radiation** or **white radiation** (Figure 3). Other electrons collide with electrons orbiting atomic nuclei in the target material and bump them temporarily into a high energy

level. As the target electrons return to a lower energy level, they emit energy as X-rays. The energy difference between the two levels is proportional to the energy and frequency, and inversely proportional to the wavelength, of X-rays emitted. Because some electrons are elevated to higher levels than others, and because they do not all return to the same levels, typical X-ray tubes emit **characteristic radiation** having several different wavelengths. The wavelengths of the characteristic radiation depend on the metal in the target of the X-ray tube. So, X-ray tubes emit **polychromatic** radiation, radiation having a range of wavelengths, but most of the energy is channeled at specific wavelengths (Figure 3).

## BOX 1

### X-ray Tube

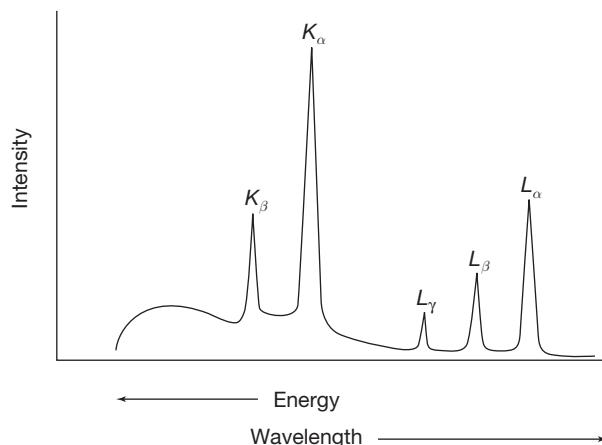
For diffraction studies, X-rays are generated in an evacuated X-ray tube (Figure 2). Within the tube, a tungsten cathode filament releases electrons that accelerate and travel at high velocity to strike a metal anode. The accelerating voltage is typically tens of kilovolts, but the current is always very low. Mineralogists generally use a



**FIGURE 2** Drawing of an X-ray tube. Electrons are emitted when current passes through a tungsten filament. The electrons, when they strike the target anode cause it to emit characteristic X-radiation which exits the tube through beryllium windows.

copper-anode X-ray tube, but they use molybdenum, iron, or other tubes in special applications.

When the high-velocity electrons strike the target metal with sufficient energy, they cause electrons in target atoms to temporarily jump to higher energy levels. As the electrons naturally return to lower levels, the energy difference between the two levels is given off as X-rays. Depending on the target (anode) metal, X-ray tubes emit characteristic radiation at multiple specific wavelengths. While operating, X-ray tubes generate a tremendous amount of heat and must be constantly cooled by flowing water.



**FIGURE 3** Output from an X-ray tube. The peaks are the characteristic radiation. The wavelengths of the characteristic radiation depend on the target metal in the X-ray tube.

We designate the different characteristic X-ray wavelengths using combinations of English (*K*, *L*, *M*) and Greek ( $\alpha$ ,  $\beta$ ,  $\gamma$ ) letters. The most intense peaks are designated  $K\alpha$ .

We use copper  $K\alpha$  radiation for most routine X-ray studies. Copper has several characteristic wavelengths, but interpretation of X-ray diffraction is easiest if we use one wavelength (**monochromatic radiation**). To isolate  $K\alpha$  radiation from the other wavelengths, most X-ray machines have filters, monochromators, or solid-state monochromatic detectors. X-ray tubes emit two nearly equal wavelengths of Cu- $K\alpha$  radiation:  $K\alpha_1 = 1.5401\text{\AA}$  and  $K\alpha_2 = 1.5443\text{\AA}$ . They are so similar that, even if both wavelengths are present, for most applications the radiation is effectively monochromatic, and we take a weighted average of  $K\alpha_1$  and  $K\alpha_2$  wavelengths and assume a  $\lambda$  value of  $1.5418\text{\AA}$ .

## INTERACTIONS OF X-RAYS AND ATOMS

When an X-ray strikes an atom, the wavelike character of the X-ray causes electrons, protons, and neutrons to vibrate. Heavy protons and neutrons vibrate less than much lighter electrons. The oscillating electrons reemit radiation, called **secondary radiation**, at almost the same frequencies and wavelengths as the incoming beam. This process, called **scattering**, is not the same for all elements, nor is it the same in all directions. Since heavy elements have atoms with more electrons, they scatter more efficiently than light elements, and scattering by heavy elements can completely mask scattering by light ones. As a result, X-ray crystallographers often have trouble determining the location of light atoms, such as hydrogen, in crystal structures. As X-rays scatter in different directions, they interact with electron clouds in various ways. Overall, those scattered at high angles to the incident beam are less intense than those scattered at low angles.

Besides being scattered, when X-rays interact with atoms in a crystal, some electrons temporarily bump up to higher energy states. As the electrons return to their normal state, a release of radiation characteristic of the target atom (in the crystal) occurs. This process, called **X-ray fluorescence (XRF)**, is similar to the interaction of electrons and atoms in the target metal of an X-ray tube, but results from interaction of X-rays and atoms in the crystal. X-ray fluorescence, while not widely used by mineralogists, is the basis for a common analytical method used by petrologists and geochemists.

## INTERFERENCE OF X-RAY WAVES

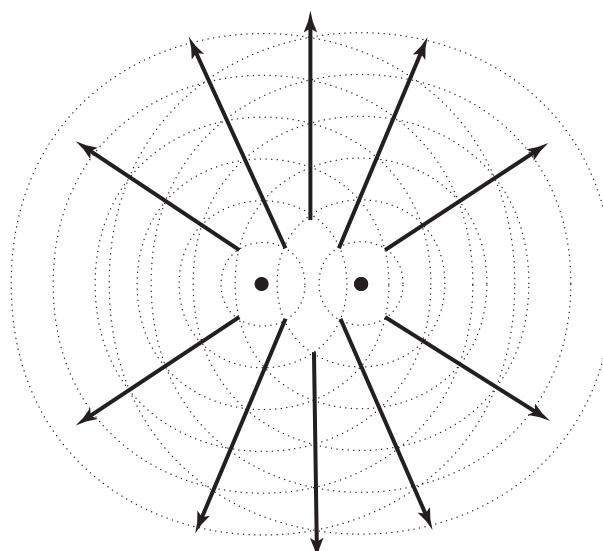
Just like visible light, X-rays propagate in all directions and interact, or **interfere**, with each other while they produce **constructive interference** or **destructive interference**. If we could move an X-ray detector around two point sources emitting monochromatic

X-rays, we would find that energy is intense in some directions because the waves interact constructively. In other directions, the detector would register no X-rays due to destructive interference (Figure 4). This channeling of energy in specific directions is *diffraction*. The directions depend on X-ray wavelength and distance between the two X-ray sources.

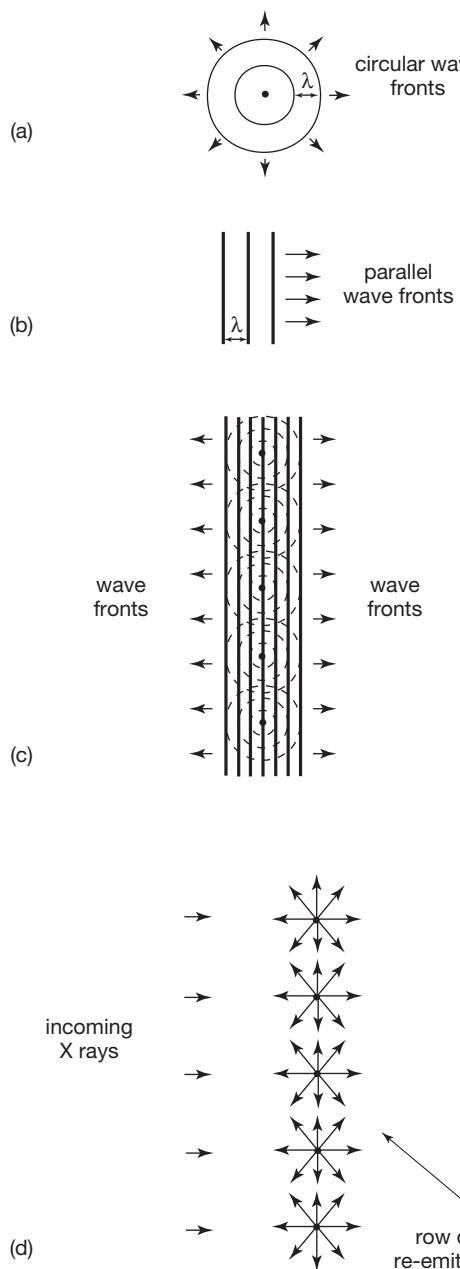
A narrow slit, a series of parallel grooves in a diffraction grating, regularly spaced atoms in a crystal, and many other things can cause diffraction. The main requirement is that two or more sources emit, or scatter, monochromatic waves. Diffraction resembles **reflection** in many ways, but reflection refers to the coherent scattering of energy by atoms in a two-dimensional surface such as a mirror. In principle, all electromagnetic radiation can be diffracted but unless the spacing of atoms, slits, or gratings is similar to the wavelength of the radiation, diffraction will not occur. Ionic radii are all on the order of angstroms, about the same as the wavelength of X-rays. Because atoms pack closely together in crystals, their spacing is of the same magnitude and X-ray wavelengths, and atoms in crystals can produce intense X-ray diffraction. This is the understanding that led von Laue and his coworkers to their successful experiments.

## DIFFRACTION BY A ROW OF ATOMS

To discuss diffraction by a row of atoms, we can use the analogy of a group of campers standing on a lake dock. One camper throws a rock in the water, and a series of waves propagate across the lake. The front of the moving wave, the **wave front**, will have a circular



**FIGURE 4** Two point sources interfere constructively in some directions (arrows) and destructively in others. The dotted-line circles show the wave fronts from both sources. Energy is channeled (diffracted) in directions (arrows) where the wave peaks coincide because the waves add constructively.



**FIGURE 5** Wave fronts in a lake. (a) A circular wave front is created by a rock dropped into water. (b) Parallel wave fronts result when a long log is dropped into water. (c) Parallel wave fronts can also be caused by multiple rocks dropped in the water. (d) When an X-ray beam strikes a row of atoms, the atoms reemit X-rays to produce wave fronts similar to those in Figure 5c.

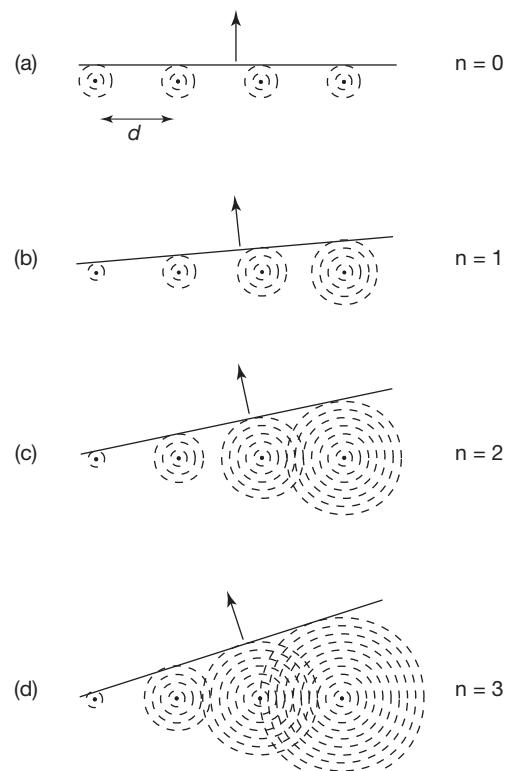
or arc shape (Figure 5a). It loses energy and dies out as it propagates, but a canoeist might feel a small ripple as it passes by. Next, the campers roll a very long log off the dock and create a more pronounced wave that propagates across the lake. This wave front is straight, instead of curved (Figure 5b). Canoeists might notice the straight wave front as it passes underneath their boat.

Now, the campers on the dock all drop rocks into the water at different times, making many circular

wave fronts. The wave fronts work with each other constructively in some directions and destructively in others. Most are out of phase and die out quickly. The canoeists hardly notice the waves. Finally, the campers drop their rocks simultaneously, creating a wave similar to the one created by the log (Figure 5c). All of the individual waves are in phase, and they add to make a straight wave front moving across the lake. The canoeists cannot determine whether a log or rocks generated the wave.

When a row of atoms scatters an X-ray beam, the atoms can produce a coherent wave front similar to the one produced when rocks hit water simultaneously. Figure 5c could be showing a row of atoms each emitting an X-ray wave with identical wavelength. If all the atoms emit a wave simultaneously, the waves will create a straight wave front moving in a direction 90° from the row of atoms. A situation similar to Figure 5c might arise if an incident monochromatic X-ray beam strikes a row of atoms at 90°. As shown in Figure 5d, the incident beam excites all the atoms at the same time, causing them to scatter coherent X-rays. Constructive interference then yields wave fronts moving perpendicular to the row of atoms as shown in Figure 5c, and, as we will see shortly, in other directions.

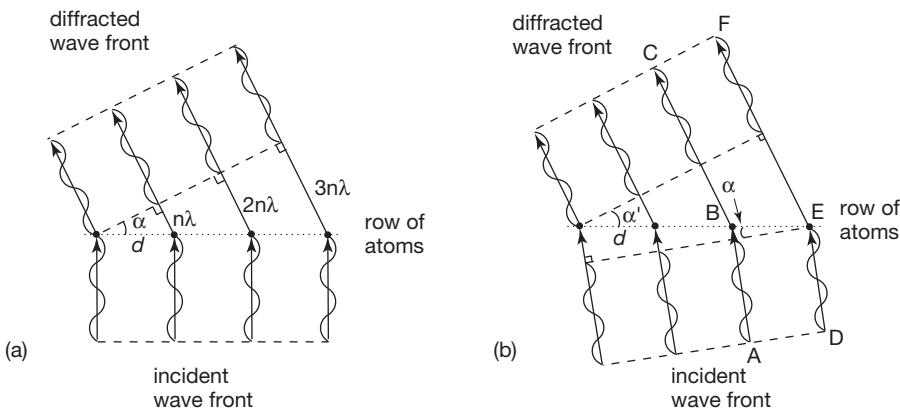
Figure 6a shows circular wave fronts emitted by atoms in a row. The waves, which have all trav-



**FIGURE 6** Wave fronts generated by a row of atoms.

(a) Atoms emitting circular wave fronts that may combine to form one front moving away from the row at 90°. Drawings (b), (c), and (d) show wave fronts moving in other directions.

**FIGURE 7** A closer look at diffraction by a row of atoms. For diffraction to occur, the re-emitted X-rays must all be in phase. (a) An incident wave front strikes a row of atoms at  $90^\circ$  and causes diffraction at angle  $\alpha$ . (b) An incident beam strikes a row of atoms at angle  $\alpha$  and causes diffraction at angle  $\alpha'$ .



eled the same distance, combine to form straight wave fronts moving perpendicular to the row. Figure 6 b, c, and d show that coherent wave fronts also travel in other directions. In Figure 6b, waves emitted by adjacent atoms differ in travel distances by  $1\lambda$  in c by  $2\lambda$ , and in d by  $3\lambda$ . Because one cycle of a wave is the same as any other, it does not matter that they have traveled different distances if they are in phase.

The geometry in Figure 6 yields a simple relationship between wavelength, atomic spacing, and the angle of diffraction. If  $\alpha$  is the angle between the diffracted wave front and the row of atoms,  $d$  is the distance between atoms, and  $n$  is the number of wavelengths that each wave is behind (or ahead of) the one next to it, then as pictured in Figure 7a:

$$n\lambda = d \sin \alpha \quad (2)$$

$n$  is the **order of diffraction**. When  $n = 0$ , 0th order diffraction occurs and  $\alpha$  must be 0. When  $n = 1$ , first-order diffraction occurs; when  $n = 2$ , second-order diffraction occurs, and so on. As  $n$  increases, the angle between the diffracted wave front and the row of atoms increases. The maximum value of  $n$  corresponds to  $\sin \alpha = 1$  (when  $\alpha = 90^\circ$ ), so  $n$  must always be less than  $d/\lambda$ . If  $\lambda = d$ , no diffraction can occur. This explains why atoms in crystals do not diffract visible light: The wavelengths are too long compared with the atomic spacings.

The preceding discussion assumed that an incident X-ray beam struck a row of atoms at  $90^\circ$ , but this is rarely the case. When the incident radiation strikes a row of atoms at another angle, coherent diffraction will occur in any direction where X-rays are in phase. To analyze this situation, we need only consider two rays (Figure 7b). They will be in phase if the difference in their path lengths, the difference between paths ABC and DEF, is an integral

number of wavelengths ( $n$ ) For the geometry shown in Figure 7b, we can easily verify that:

$$d(\sin \alpha' - \sin \alpha) = n\lambda \quad (3)$$

where  $d$  is the atomic spacing,  $\alpha'$  and  $\alpha$  are the angles of the diffracted and incident wave with the row of atoms,  $n$  is the order of diffraction, and  $\lambda$  is the wavelength. This is the general equation for diffraction by a row of atoms.

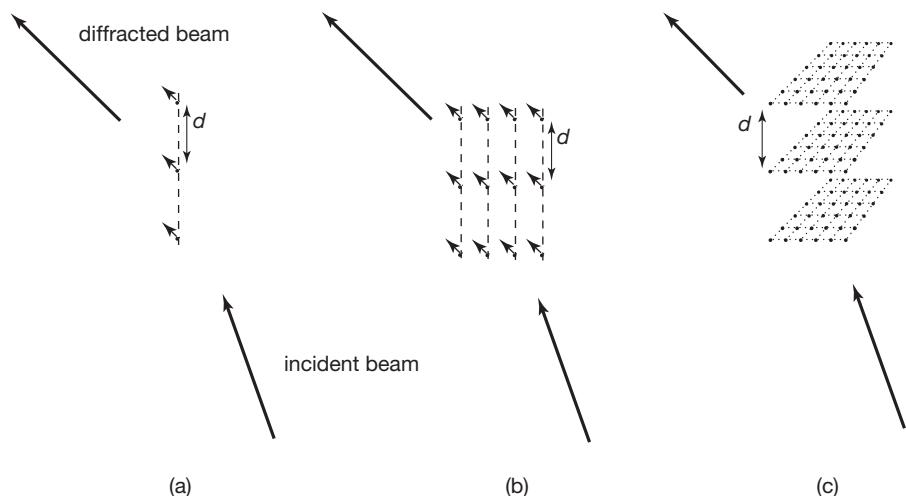
## PLANES OF ATOMS

### The Distance Between Planes in Crystals

A regularly spaced row of atoms that causes diffraction is only part of a crystal structure (Figure 8a). In two dimensions, adjacent unit cells combine to create many parallel rows, all causing diffraction at the same angle (Figure 8b). In three dimensions, an entire crystal contains many identical unit cells containing atoms with identical spacing that diffract at the same angle (Figure 8c). The regular spacing defines a family of planes, all separated by the same distance. Thus, diffraction involves sets of planes of atoms, diffracting at angles we can calculate with Equation 3.

Crystallographers use Miller indices ( $hkl$ ) to describe planes of atoms in crystals. We use the symbol  $d_{hkl}$  for the perpendicular distance between  $(hkl)$  planes. Figure 9a shows a single  $(120)$  plane; Figure 9b shows an entire family of  $(120)$  planes separated by the perpendicular distance  $d_{120}$ . Different families of planes, with the same orientation but different indices, have different  $d$ -values. Figure 9c shows the family of  $(240)$  planes; they parallel  $(120)$  but are half as far apart. For all crystal systems,  $d_{120}$  is twice  $d_{240}$ , and in general:

$$d_{hkl} = n d_{h'k'l'} \quad (4)$$



**FIGURE 8** Diffraction by a row of atoms (a), by parallel rows of atoms (b), and by planes of atoms (c).

where

$$b' = n b \quad (5)$$

$$k' = n k \quad (6)$$

$$l' = n l \quad (7)$$

The relationship between Miller indices, unit cell lengths ( $a$ ,  $b$ ,  $c$ ), and  $d$ -values depends on the crystal system. Box 2 gives equations relating unit cell parameters to  $d$ -values. Derivation of equations for orthogonal systems (cubic, tetragonal,

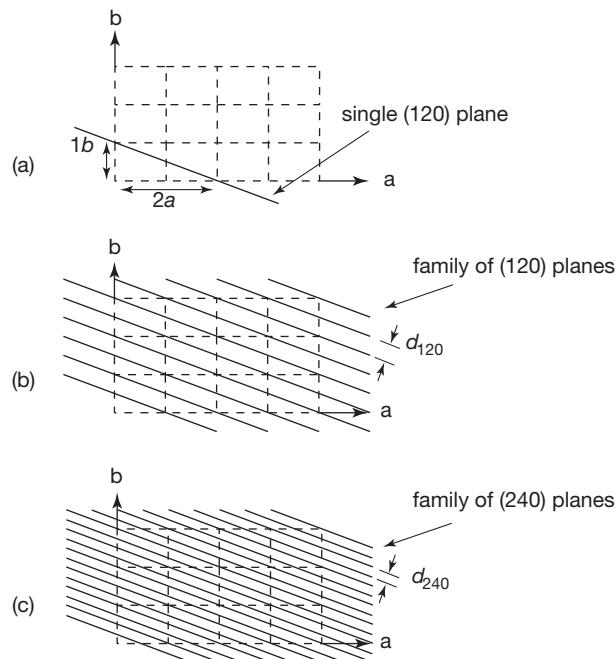
and orthorhombic) is relatively simple compared with derivations for the other systems. For orthogonal systems:

$$d_{100} = a \quad (8)$$

$$d_{010} = b \quad (9)$$

$$d_{001} = c \quad (10)$$

For the other systems, the angles  $\alpha$ ,  $\beta$ , and  $\gamma$  must also be considered. Figure 10 shows this by comparing  $d$ -values to unit cell lengths for square, rectangular, and monoclinic cells.



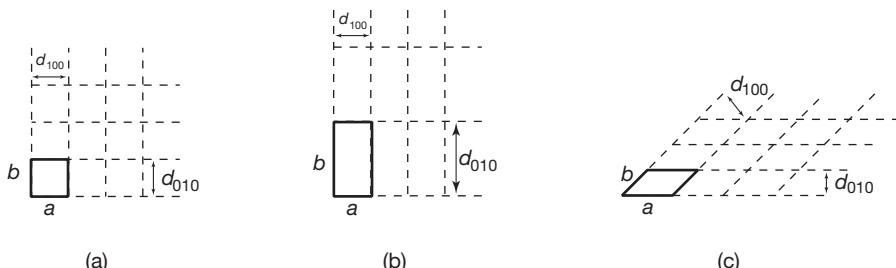
**FIGURE 9** Planes and  $d$ -values: (a) a single (120) plane; (b) the family of (120) planes; (c) the family of (240) planes. In these drawings, the  $c$ -axis and the planes are perpendicular to the plane of this page.

### Diffraction by Planes of Atoms

Von Laue derived equations similar to Equation 3 that describe diffraction by three-dimensional structures. We call these the **Laue equations**. W. L. Bragg developed a simpler and more easily understood mathematical treatment. His final equations are just as valid as von Laue's, but the derivations avoided some unnecessary complexities. Although diffraction and reflection are two different processes, Bragg noted that diffracted X-rays behave as if they were reflected from planes within a crystal. To model this "reflection," Bragg considered two parallel planes of atoms separated by distance  $d_{hkl}$  (Figure 11). ABC and DEF represent monochromatic parallel X-ray beams striking and reflecting from the planes. The angle of incidence and the angle of reflection are both  $\theta$ . Because path lengths of the beams must vary by an integral number of wavelengths if diffraction is to occur, the sum of distances GE and EH must equal  $n\lambda$ , so:

$$n\lambda = 2d_{hkl} \sin\theta \quad (11)$$

**FIGURE 10** Comparison of  $d$ -values to unit cell parameters: (a) in a square cell  $d_{100} = d_{010} = a = b$ ; (b) in a rectangular cell  $d_{100} = a$  and  $d_{010} = b$ ; (c) in a monoclinic cell  $d_{100}$  and  $d_{010}$  are not equal to unit cell parameters.



Equation 11 is known as the Bragg law. Bragg went on to prove it unnecessary to consider situations in which incident and diffraction angles are different (Figure 12a). We can always describe diffraction using reflection geometry, even though true reflection is not occurring (Figure 12b). The angle of “reflection”  $\theta$  is related to the incident angle ( $\alpha$ ) and the diffraction angle ( $\alpha'$ ) by

$$\theta = (\alpha - \alpha')/2 \quad (12)$$

For conventional X-ray diffraction studies, we assume the  $n$  in the Bragg law is 1. Because first-order diffraction by planes with spacing  $d_{bkl}$  occurs at the same angle as second-order diffraction by a set of planes spaced twice as far apart, we cannot distinguish the two, and assuming first order is simplest when we are talking about X-ray diffraction (Figure 12c, d). In other applications of the Bragg law, the order of diffraction is important.

In standard X-ray diffraction studies, we allow the incident X-ray beam to strike the sample at many different angles so that many different  $d$ -values will satisfy the Bragg law and cause diffraction (Figure 13). After being diffracted, the X-ray beam travels at an angle of  $2\theta$  from the incident beam. Because a crystal contains many differently spaced planes with atoms on them, diffraction occurs at many  $2\theta$  angles. In most X-ray devices used today, the sample is at a fixed location (although it may rotate), and the detector, which measures X-ray intensity, moves through an entire range of angles from near 0 to some high angle. In some diffractometers, the X-ray tube moves as well. If a diffracted beam is to hit the detector, two requirements must be met:

- A family of planes with  $d_{bkl}$  must be oriented at an angle ( $\theta$ ) to the incident beam so the Bragg law is satisfied.
- The detector must be located at the correct angle ( $2\theta$ ) from the incident beam to intercept the diffracted X-rays.

## BOX 2

### Cell Parameters and $d$ -values

Each diffraction peak on a diffractogram, corresponds to a specific set of  $(hkl)$  planes having spacing  $d_{hkl}$ .  $d_{hkl}$  is a function of  $h$ ,  $k$ , and  $l$ , and of the unit cell parameters  $a$ ,  $b$ ,  $c$ ,  $\alpha$ ,  $\beta$ , and  $\gamma$ :

$$d_{hkl} = \sqrt{\frac{A}{B + C}} \quad (6)$$

where

$$A = 1 - \cos^2\alpha - \cos^2\beta - \cos^2\gamma + 2 \cos\alpha \cos\beta \cos\gamma \quad (7)$$

and

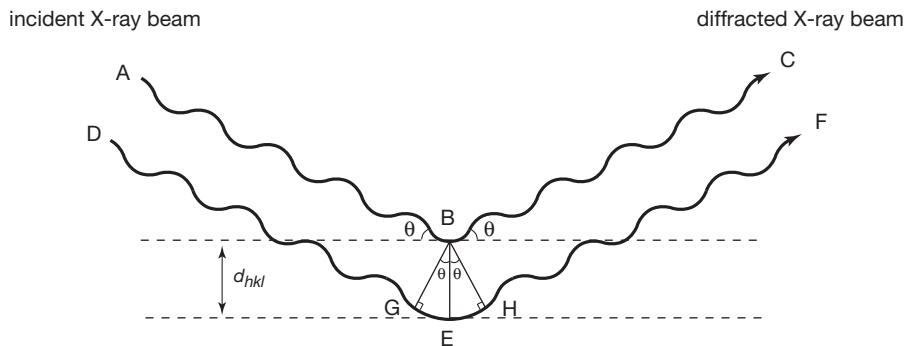
$$B = h^2 \sin^2\alpha/a^2 = k^2 \sin^2\beta/b^2 + l^2 \sin^2\gamma/c^2 \quad (8)$$

and

$$C = 2hk(\cos\alpha \cos\beta - \cos\gamma)/ab + 2lk(\cos\gamma \cos\alpha - \cos\beta)/ca + 2kl(\cos\beta \cos\gamma - \cos\alpha)/bc \quad (9)$$

This equation is greatly simplified for orthogonal systems (cubic, tetragonal, and orthorhombic) because all angles are  $90^\circ$ ,  $A = 1$ , and  $C = 0$ . For these systems, then:

$$d_{hkl} = \sqrt{\frac{1}{\left(\frac{h^2}{a^2} + \frac{k^2}{b^2} + \frac{l^2}{c^2}\right)}} \quad (10)$$



**FIGURE 11** Reflection geometry. Two rays in an X-ray beam must differ in path length by an integral number of wavelengths if they are to be in phase after “reflection.” This observation results in the Bragg law.

Because the angle between the detector and the X-ray beam is  $2\theta$ , mineralogists usually report X-ray data in terms of  $2\theta$ . For example, reference books list the two most intense diffraction peaks of fluorite (using  $\text{Cu-K}\alpha$  radiation) as  $28.3^\circ$  and  $47.4^\circ 2\theta$  (see Figure 15). We must remember to divide  $2\theta$  values by 2 before we use them with the Bragg law to calculate  $d$ -values.

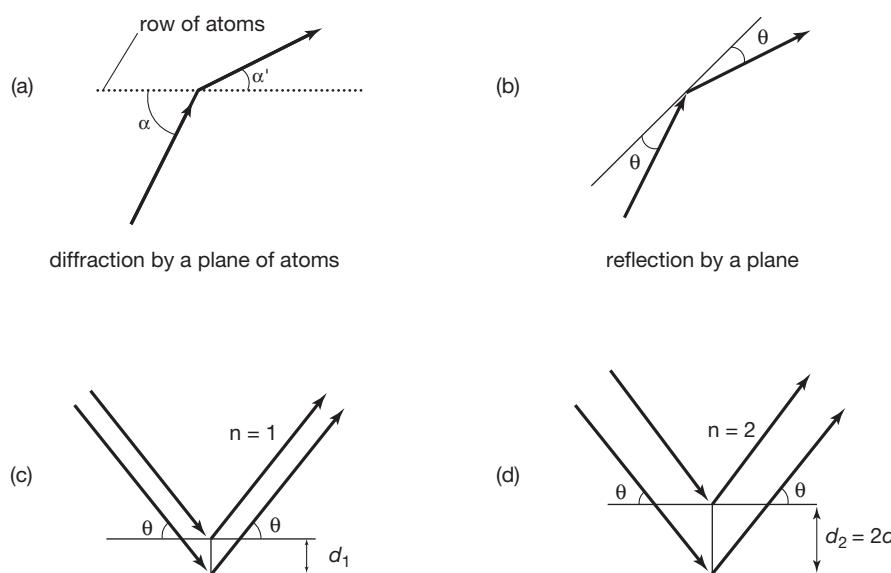
## INTENSITY OF DIFFRACTION

### Diffraction at Different Angles

The Bragg law allows us to calculate the angle at which diffraction occurs for any particular  $d_{hkl}$  value. However, intense diffraction will only occur if many atoms occupy the  $(hkl)$  planes; without atoms no electrons are present to scatter X-rays. When discussing families of planes in unit cells,  $b$ ,  $k$ , and  $l$  may have any integer value, which implies the possibility of an infinite number of  $d_{hkl}$  values that could satisfy the Bragg law. However, mineral unit

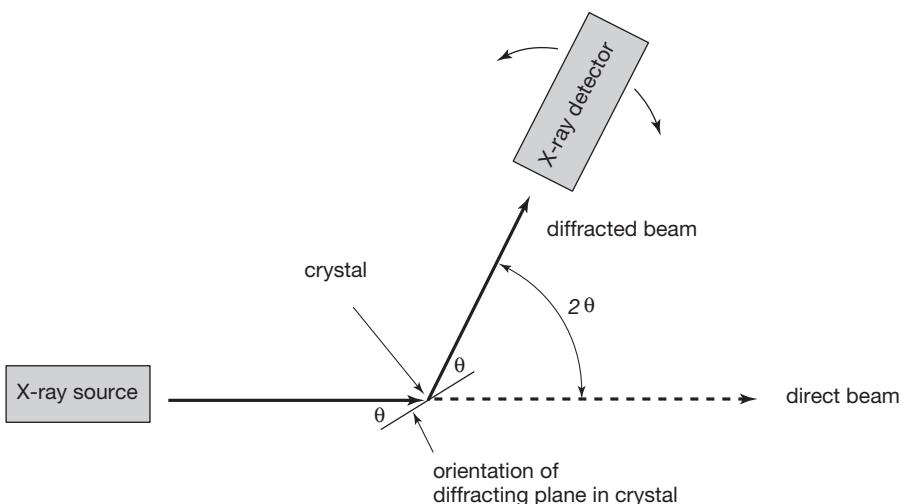
cells contain a small number of atoms, which in turn limits the number of  $d$ -values corresponding to planes of high atomic density. Therefore, the number of angles at which intense diffraction occurs is limited, although weak diffraction occurs in many, sometimes more than 1,000, directions for a single crystal. An example in two dimensions will make this point.

Consider the hypothetical unit cell shown in Figure 14a, with all atoms on two opposite edges. It has dimensions of  $3.0\text{\AA} \times 5.0\text{\AA}$ . Ignoring the third dimension (or assuming that all planes are perpendicular to the page), we can say that  $d_{100} = 3.0\text{\AA}$  and  $d_{010} = 5.0\text{\AA}$ . If we imagine a structure made of many of these unit cells (Figure 14b), we see that many atoms are in rows  $5.0\text{\AA}$  apart, and diffraction corresponding to  $d_{010}$  ( $5.0\text{\AA}$ ) should be quite intense. We can also expect apparent diffraction by the  $(020)$  planes to be intense, although no atoms occupy every other  $(020)$  plane, because second-order ( $n = 2$ ) diffraction by  $(010)$  planes occurs at the same angle as first-order diffraction by



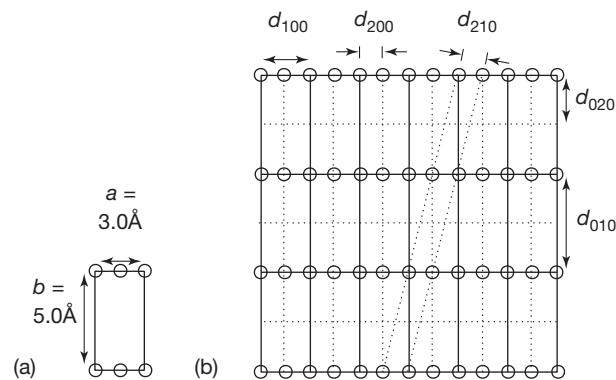
**FIGURE 12** Why we can use the Bragg law: Diffraction by a row of atoms (a) can be modeled as reflection by an imaginary plane. (b), (c), and (d) show that the angle of diffraction (or reflection) is the same for first-order diffraction by planes separated by  $d_1$  and for second-order diffraction by planes spaced twice as far apart ( $d_2$ )

**FIGURE 13** Bragg law geometry. In most conventional X-ray diffractometers, the detector rotates around the sample to measure intensity of diffracted beams over a wide range of  $2\theta$  values. Compare this with Figure 18.



(020) planes. In addition, (200) diffraction ( $d_{200} = 1.5\text{\AA}$ ) will be quite intense because many atoms occupy the (200) planes. Diffraction for other  $d$ -values, such as  $d_{210}$ , will be weaker.

Because the locations and natures of atoms are different in different minerals, diffraction patterns depend on atomic arrangement and composition. But symmetry also affects diffraction patterns. High crystal symmetry means identical spacing of atoms in multiple directions, so fewer  $d$ -values cause diffraction, and thus diffraction occurs at fewer angles with relatively uniform intensity. Low crystal symmetry means diffraction occurs in many directions, with variable intensity because atoms and atomic spacings differ in all directions. Figure 15 compares X-ray patterns for fluorite (a cubic mineral) and barite (an orthorhombic mineral). As predicted, the pattern for fluorite is more regular, with fewer but more intense diffraction peaks.

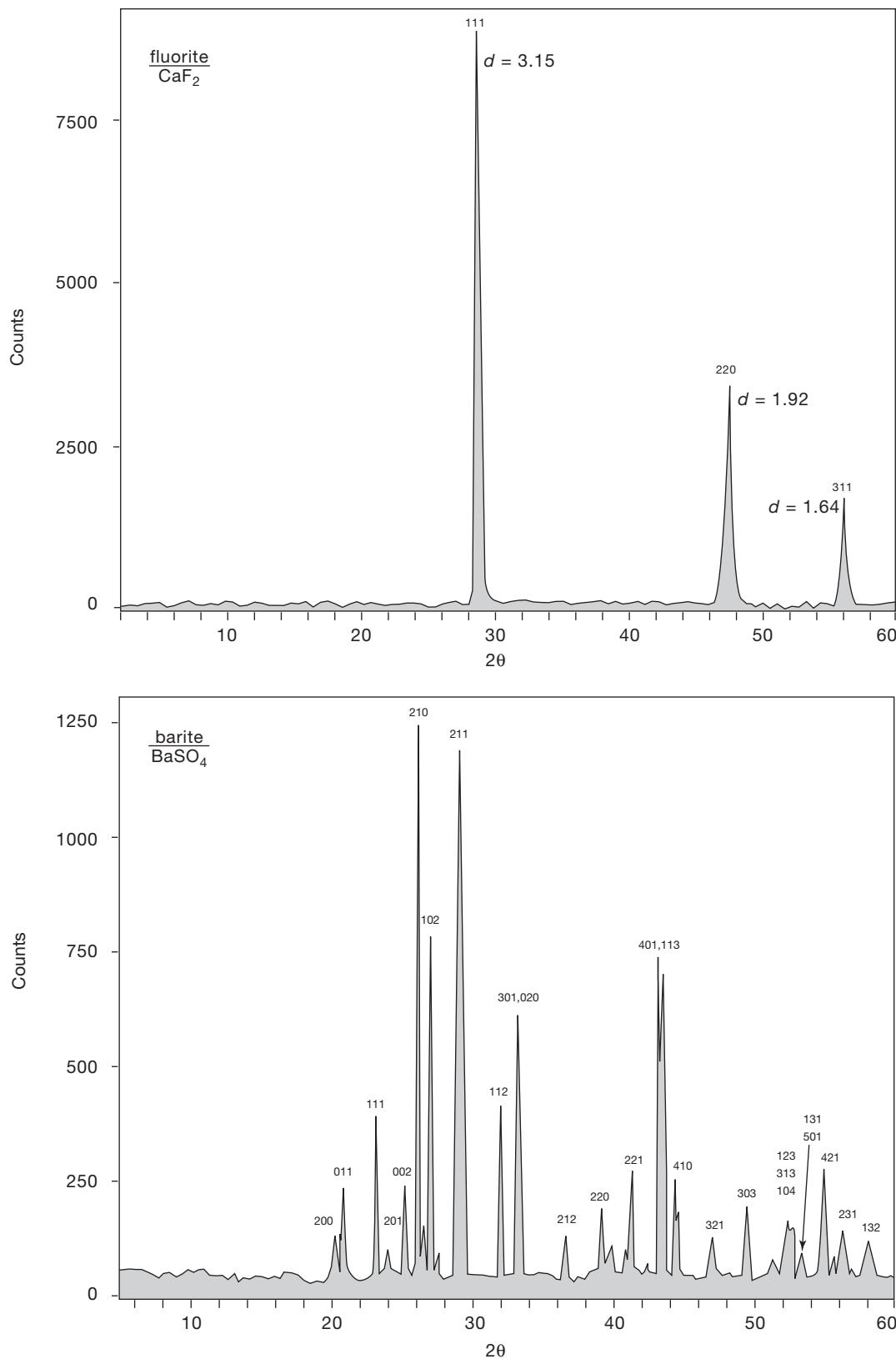


**FIGURE 14** Prediction of X-ray peaks: (a) a unit cell with atoms only on two opposing sides; (b) a collection of unit cells showing some of the families of planes with many atoms on them. These are the planes that will produce the strongest diffraction.

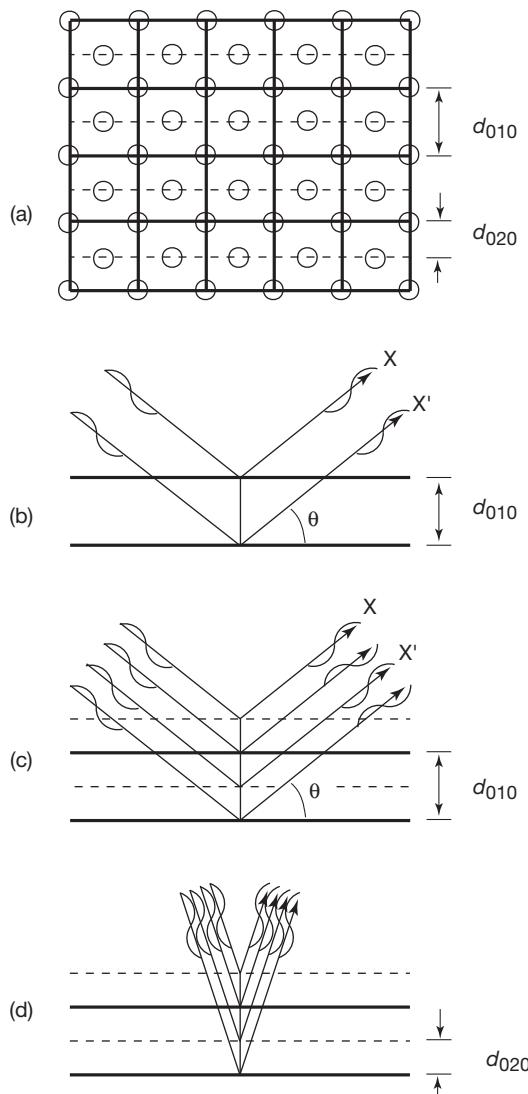
### Extinctions

Sometimes, due to destructive interference, planes containing many atoms do not produce diffraction. We term this phenomenon a *systematic absence*, or an *extinction*. Figure 16a shows a two-dimensional drawing of a cubic structure in which atoms occupy the corners and the center of each unit cell. When (010) diffraction occurs at angle  $\theta$ , beam X and  $X'$  are completely in phase as shown in Figure 16b. If the diffraction is first order, beam X travels exactly  $1\lambda$  farther than beam  $X'$ . However, the constructive interference cannot prevail when we account for the atoms between the (010) planes. X-rays scattered by these atoms travel  $1/2\lambda$  more or less than those scattered by the adjacent (010) planes to create perfect destructive interference (Figure 16c). No X-rays will be found at the angle  $\theta$ , though it satisfies the Bragg law for  $d_{010}$ . This effect is extinction, and we would say the (010) diffraction peak is *extinct*. Although (010) planes do not diffract, (020) planes do, but the smaller  $d$ -value results in a larger diffraction angle (Figure 16d). The structure shown in Figure 14 also produces extinctions. (100) diffraction is absent because additional atoms occur halfway between the (100) planes.

Figures 14 and 16 show two-dimensional examples of structures that result in extinctions due to end-centered and body-centered unit cells. In three dimensions, end-centered and body-centered structures also produce extinctions. We often describe extinctions using arithmetical rules. For body centering, the rule is that an  $(hkl)$  peak will be extinct if  $b + k + l$  is an odd number. Besides centering, other symmetry elements lead to extinctions. They all involve symmetry in which planes of atoms are found between other planes; screw axes and glide planes are two examples. The systematic



**FIGURE 15** Comparison of X-ray patterns for fluorite and barite. The barite pattern is more complex and has more peaks because barite's atomic structure has less symmetry than fluorite's. The numbers above the peaks are  $hkl$  values.



**FIGURE 16** Extinctions occur when diffracted rays are out of phase. (a) Some cubic unit cells with atoms (open circles) at their corners and centers. (b) (010) diffraction produces some rays that are in phase and diffract at an angle  $\theta$ . (c) Atoms between the (010) layers produce other rays diffracting at the same angle but  $180^\circ$  out of phase, so the rays interfere destructively and the intensity of diffraction is 0. (d) (020) diffraction does occur, but the angle of diffraction is greater than that for (010).

extinction of certain X-ray peaks, then, is one way we determine space group symmetry.

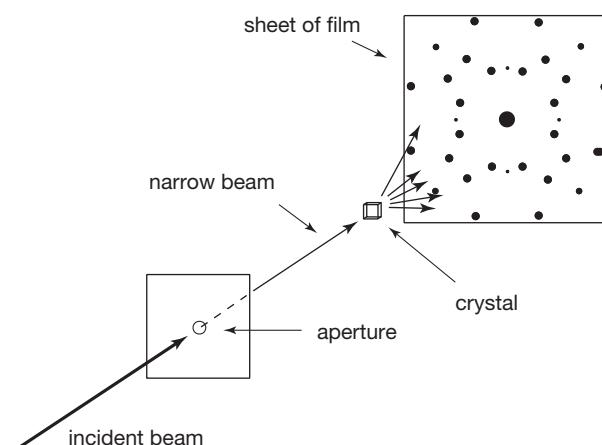
### SINGLE CRYSTAL DIFFRACTION

When X-raying single crystals, determining diffraction directions can be quite complicated. In the preceding discussions and figures we only considered two dimensions; both the incoming X-ray beam and the diffracted beam were in the plane of the paper because we assumed the planes causing diffraction were perpendicular to the page. Suppose the diffracting planes

are not perpendicular to the page of the paper. If so, diffraction might still occur, given an appropriate angle of incidence, but the diffracted beam could go off in any direction, including straight out of the page. In an experiment where we place a stationary single crystal of a mineral in front of an X-ray beam, unless we carefully orient the crystal, the odds of the beam hitting planes of atoms at angles that satisfy the Bragg law are very small. Diffraction is unlikely, but if it occurs, the diffracted beam could travel in any direction. The odds that it will hit a detector, even if the detector is moving in a plane, are minuscule. So how can we expect to measure diffraction directions and intensities?

Several techniques overcome this problem. When they made their pioneering studies in 1912, Friedrich and Knipping used what we now call *the Laue technique*. They carefully oriented a single crystal in front of a polychromatic X-ray source so that principal crystal faces and lattice planes were perpendicular or parallel to the X-ray beam. Due to the careful orientation and multiple X-ray wavelengths, many different families of planes satisfied the Bragg law. Behind the crystal, Friedrich and Knipping placed a piece of film, shielded from light in a black envelope (Figure 17). After several hours, the film developed black spots where hit by diffracted beams. The size and density of each spot varied according to the intensity of the diffracted beam that created it.

The Laue technique reveals interesting information. For example, two isostructural minerals, if oriented the same way, yield similar patterns. Laue patterns also reveal specific information about crystal structures. Of most importance, the symmetry of the X-ray pattern is always greater than or equal to that of the crystal. If a pattern reveals no symmetry, the crystal's structure is not constrained; but if, for example, a pattern shows



**FIGURE 17** The Laue technique. A focused X-ray beam hits an oriented crystal and the diffracted rays produce dark spots on a piece of film that is shielded from light by a black envelope.

6-fold symmetry, the crystal must belong to the hexagonal system. A shortcoming of the Laue technique is that although it reveals angles of diffraction, we cannot determine which diffraction peaks correspond to which X-ray wavelengths. Therefore, using the Bragg law to learn  $d$ -values is not possible. On the other hand, if we use monochromatic radiation, we get few, if any, spots on the film.

The Laue method is one kind of **single crystal diffraction**, and there are many variations. Modern

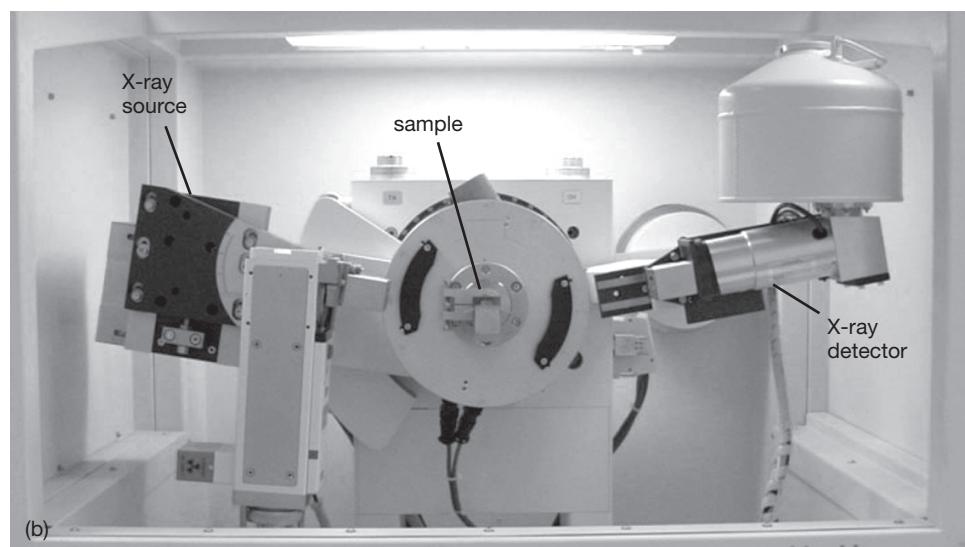
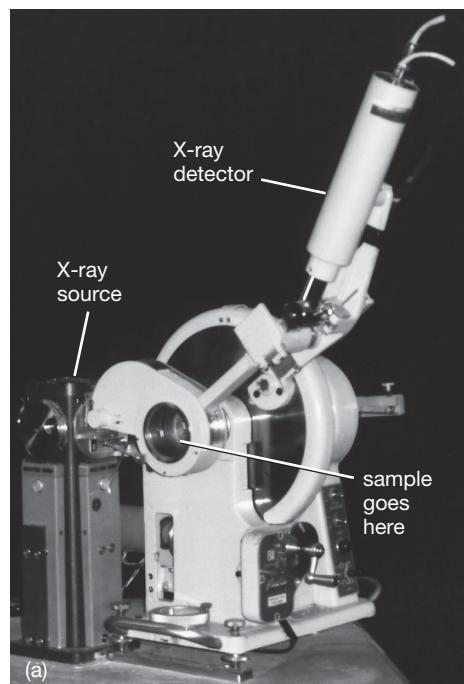
X-ray **diffractometers** generally use monochromatic radiation and a solid state X-ray detector instead of film. The diffractometer rotates the crystal and moves the detector to measure intensities of all diffraction peaks. Computers controlling the diffractometer store data directly on disk. Because the process is completely automatic, the  $d$ -values and intensities of thousands of different peaks may be measured for a single crystal.

We use the data obtained from single-crystal diffraction studies to determine crystal structures. If we know the composition of a mineral, we know how many atoms of which elements are present. Computer programs can determine where atoms are in the structure, based on the diffraction data. We call this process a *crystal structure determination*. Crystal structure determination involves many complexities, but automation and high-speed computers have simplified the process considerably since the Braggs determined the first crystal structure in 1913.

## ROUTINE X-RAY ANALYSES

### Powder Diffraction

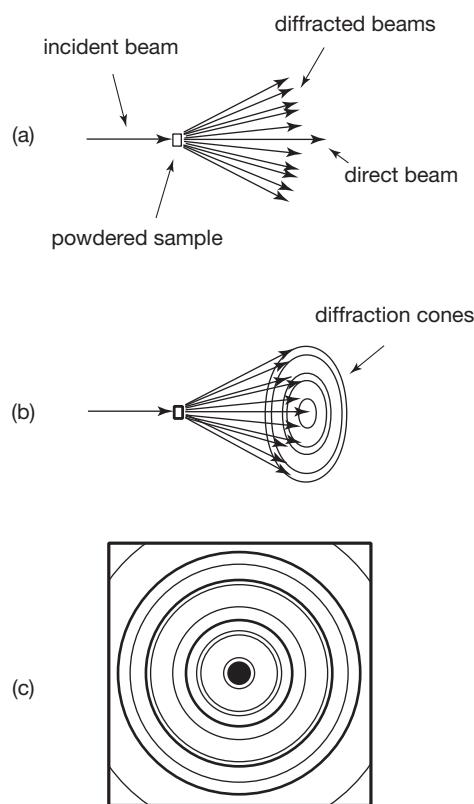
Single-crystal X-ray studies provide information necessary for structure determination. Simpler techniques exist for mineral identification (Figure 18). The most common is **powder diffraction**, the X-raying of a finely powdered sample mounted on a slide or in a holder. A powdered sample consists of a near-infinite number of small crystals in random orientations.



**FIGURE 18** Powder diffractometers have been a mainstay for routine mineral analyses for many years. The instrument shown in (a) is the standard kind used until the 1990s. The X-ray source is stationary relative to the sample. The detector moves around the sample to measure X-rays diffracted at different angles. The diffractometer in (b) is a modern instrument. For safety reasons the device is enclosed in an X-ray proof box. In most modern diffractometers, such as the one shown here, the sample remains stationary but both the X-ray source and the detector move.

When so many crystals in so many orientations are X-rayed, for any set of  $(hkl)$  planes there will be many crystals that satisfy the Bragg law.

Powdered samples diffract beams in many directions, as shown in the two-dimensional drawing in Figure 19a. In three dimensions, they produce diffraction cones (Figure 19b). The angles between the cones and the direct X-ray beam are  $2\theta$  values for different  $(hkl)$  planes. Consider a powdered sample of some mineral with a set of  $(111)$  planes having a  $d$ -value of  $5.0\text{\AA}$ . For  $\text{Cu}-K\alpha$ , then, the Bragg law tells us this corresponds to a  $2\theta$  value of  $17.74^\circ$ . When the sample is X-rayed, a sufficient number of crystals will be oriented to cause diffraction in all directions  $17.74^\circ$  from an X-ray beam; the result is a cone of diffraction. In most crystals, many  $d$ -values cause measurable diffraction. Each produces a cone at a different angle ( $2\theta$ ) to the X-ray beam (Figure 19b). If we measure all angles, we can use the Bragg law to calculate all  $d$ -values corresponding to planes with atoms on them. The intensity of each diffraction peak depends on the number and kind of atoms on the planes causing the diffraction.



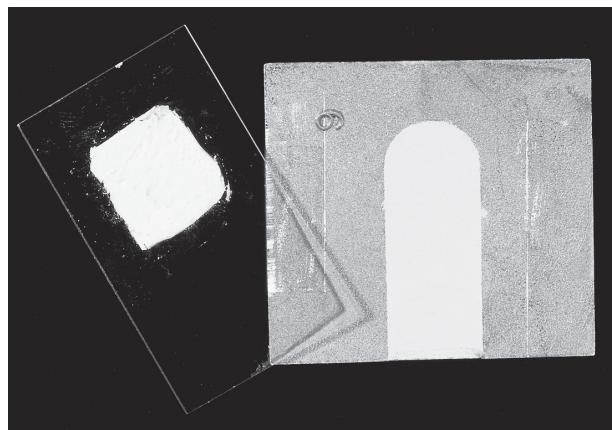
**FIGURE 19** Geometry of powder diffraction. (a) Diffraction occurs in many directions but is symmetrical with respect to the direct X-ray beam. (b) In three dimensions this leads to cones of diffraction at many different angles to the direct X-ray beam. (c) If a flat piece of film is placed behind the crystal, it can be used to record circles corresponding to each cone.

Mineralogists originally used film to record powder diffraction patterns (Figure 19c), but today most mineralogists use an X-ray powder diffractometer instead of a camera. We mount the powdered sample on a slide or in a well in a sample holder. (Figure 20). A focused X-ray beam strikes the sample, and the detector moves in a circular arc, usually vertically, to measure diffraction intensities for  $2\theta$  values from very low angles to more than  $150^\circ$ . In practice, most diffractometers cannot measure peaks at angles below  $1$  or  $2^\circ$   $2\theta$  because the direct X-ray beam bombards the detector. The upper  $2\theta$  limit of measurement usually depends on the need of the mineralogist, but for most purposes we do not need data above  $60^\circ$  to  $70^\circ$   $2\theta$ . Figure 18a shows a typical powder diffractometer used by mineralogists.

In the past, diffractometers were connected to strip chart recorders to produce diffraction patterns that typically contained 10 to 50 identifiable peaks. A mineralogist would then measure the diffraction angles on the chart and calculate  $d$ -values. Today we connect diffractometers to computers that can analyze data and print diffraction patterns. The diffraction patterns in Figure 15 were produced that way. For simple mineral identification, powder diffractometers connected to computers generally require a few to 30 minutes. For extremely precise results, however, data collection may take hours or even days.

### Identifying Minerals from Powder Patterns

Powder patterns are not normally used to determine crystal structures because powder diffraction data are more difficult to interpret than single crystal data. Different X-ray peaks correspond to different crystals



**FIGURE 20** Powder diffraction is the most commonly used X-ray technique today. Powdered samples may be mounted on glass slides or (less commonly) in wells on metal plates, for X-ray analysis.

in the powdered sample, and the data do not reveal the orientations of planes causing diffraction. A relatively new technique for interpreting powder patterns, called the **Rietveld method**, sometimes overcomes these complications and is gaining popularity today. However, powder patterns do yield a list of *d*-values and peak intensities that mineralogists routinely use to identify minerals. Each *d*-value corresponds to sets of planes, and the intensity is a measure of how many atoms are on those planes. Because each mineral has a different atomic arrangement, each yields a different pattern. For mineral identification, we compare measured *d*-values and intensities to reference data sets. The most complete reference, the X-ray Powder Diffraction File (PDF) compiled by the International Centre for Diffraction Data, is available in computerized databases and contains information on almost 6,000 minerals and tens of thousands of other inorganic and organic crystalline compounds.

Box 3 gives an example of data that are retrievable from most X-ray databases. The data are for fluorite and barite, minerals with diffraction patterns displayed in Figure 15. The data include a complete list of *d*-values and relative intensities (in the right-hand column); the intensity of the strongest peak is always assigned a value of 100%. Box 3 follows the standard practice of listing the *d*-values corresponding to the most intense diffraction peaks, and the *d*-value corresponding to the lowest angle diffraction peak, at the top of the record. These *d*-values are the most useful for mineral identification. Basic crystallographic information, including cell parameters, space group, point group, and other ancillary data are also included in most databases. Additionally, references to pertinent X-ray investigations are given.

The X-ray patterns in Figure 15 match the reference *d*-values in Box 3 quite well. The minor discrepancies probably stem from slight compositional differences between the samples X-rayed. The relative intensities of peaks do not match as well. For example, the most intense peak for fluorite in Figure 15 is listed as the second most intense peak in Box 3. X-ray peak intensities listed in databases commonly do not exactly match those obtained when we X-ray samples in the laboratory. Different samples, different methods of sample preparation, and many other things can lead to deviations. *d*-values corresponding to strong peaks, however, will always match closely, even if the intensities are not quite in the same order.

Once we learn *d*-values and intensities for an unknown mineral, it may seem an overwhelming task to find a match in a large reference file. It sometimes is. However, often we need only consider a

few of the most intense diffraction peaks. Mineralogists have used several different schemes when manually comparing an unknown pattern to reference files; the **Hanawalt method**, developed by J. D. Hanawalt in 1936, has been most popular (Box 4). Today, instead of doing the matching manually, most mineralogists use computer databases to match unknown patterns with PDF data. This has two main advantages: It is rapid, and many more reference patterns can be considered. On the other hand, computer searches are “black box” procedures; they do not improve our knowledge or understanding of powder diffractometry. In addition, computers sometimes give absurd answers that a human would have rejected at a glance.

Powder diffraction is not an exact process, and many things cause X-ray patterns to deviate from those in reference files. Proper sample preparation is crucial to obtaining accurate patterns. Complications arise when we do not grind a sample properly, or when powdered crystals are not in truly random orientations. For example, because micas are hard to grind and their tiny flakes tend to pile up parallel to each other, obtaining random orientation and a good X-ray pattern is difficult. A second problem, more so for natural materials than for synthetics, is that small compositional and crystal structural variations can affect X-ray patterns. Despite these complications, the PDF data contain adequate reference patterns for most mineralogical uses.

### **Indexing Patterns and Determining Cell Parameters**

We have labeled the peaks on the X-ray patterns in Figure 15 with *(hkl)* indices corresponding to the planes causing diffraction. For identifying unknown minerals, we do not need to know which *(hkl)* indices correspond to which *d*-values, but for other purposes, such as determining unit cell dimensions, we must. We call the process of matching *d*-values and *(hkl)* *indexing*. The easiest way to index a pattern is to compare it with one for a similar mineral that is already indexed. For instance, if we measured a pattern of an unknown garnet, we could compare it with the pattern for almandine (Box 5). This is quick and simple. Without a pattern to compare, the process becomes more complex and, except perhaps for cubic minerals, computer programs are desirable or necessary.

When indexing a cubic pattern by hand, a good general approach is to start with the largest *d*-values (peaks at lowest  $2\theta$  angles) and most intense peaks. Large *d*-values always correspond to small indices, and high intensity usually suggests simple indices, for example (100), (110), or (111). We may not be able to detect some low-angle peaks

**BOX 3****Example of Data from the Powder Diffraction File Data Set****Fluorite (CaF<sub>2</sub>)****Three strongest peaks, largest *d*-value, and relative intensities**

<i>d</i>	1.93	3.15	1.65	3.15
<i>I/I</i> <sub>100</sub> %	100	94	35	94

**Crystal structure determination**

Z:	4
Crystal system:	cubic
<i>a</i> :	5.463 Å
Space group:	<i>F</i> 4/ <i>m</i> 32/ <i>m</i>
Point group:	4/ <i>m</i> 32/ <i>m</i>
Ref. index ( <i>n</i> ):	1.4338
Specific gravity:	3.181

Bragg, W. L. The structure of some crystals as indicated by their diffraction of X-rays. *Proc. Roy. Soc.* 115 (1914): 705.

**Complete list of diffraction peaks and relative intensities (%)**

<i>d</i> Å	<i>I/I</i> <sub>100</sub>	<i>hkl</i>
3.153	94	111
1.931	100	220
1.647	35	311
1.366	12	400
1.253	10	331
1.115	16	422
1.051	16	422
0.966	5	440
0.923	7	531
0.911	1	600
0.864	9	620
0.833	3	533

**Barite (BaSO<sub>4</sub>)****Crystal structure determination**

Z:	4
Crystal system:	orthorhombic
<i>a</i> :	8.87 Å
<i>b</i> :	5.45 Å
<i>c</i> :	7.14 Å
Space group:	<i>Pnma</i>
Point group:	2/m2/m2/m
Ref. index ( $\alpha$ , $\beta$ , $\gamma$ ):	1.636, 1.637, 1.648
Specific gravity:	4.50

Basche, W., and H. Mark. Über die struktur von verbindungen des typus MeXO<sub>4</sub>. *Zeit. Krist.* 64 (1926): 1; James, R. W., and W. A. Wood. The crystal structure of barites, celestine and anglesite. *Proc. Roy. Soc.* 109A (1925): 598; Rinne, F., H. Hentschel, and E. Schiebold. Zum feinbau von anhydrit und schwespat, *Zeit. Krist.* 61 (1924): 164.

**Complete list of diffraction peaks and relative intensities (%)**

<i>d</i> Å	<i>I/I</i> <sub>100</sub>	<i>hkl</i>	<i>d</i> Å	<i>I/I</i> <sub>100</sub>	<i>hkl</i>
5.58	2	101	2.106	75	122,312
4.440	16	200	2.057	19	410
4.339	30	011	1.949	1	222
3.899	50	111	1.932	7	321
3.773	12	201	1.858	18	303
3.577	30	002	1.789	4	004
3.445	100	210	1.762	8	031
3.319	70	102	1.758	10	123,313
3.103	95	211	1.754	8	104
2.836	50	112	1.728	4	131
2.735	15	301	1.724	5	501
2.729	45	020	1.682	8	230
2.482	13	212	1.674	14	421
2.447	2	121,311	1.670	11	114
2.325	14	220	1.660	2	204
2.305	6	103	1.644	3	511
2.282	8	302	1.638	8	231
2.211	25	221	1.626	1	403
2.169	3	022	1.594	8	132
2.121	80	113,401	1.591	6	502

**Three strongest peaks, largest *d*-value, and relative intensities**

<i>d</i>	3.45	3.10	2.12	5.58
<i>I/I</i> <sub>100</sub> %	100	95	80	2

if they are very weak or extinct. For primitive lattices, the lowest angle diffraction peak (the largest *d*-value) may correspond to (100). Due to extinctions, for body-centered and face-centered lattices, respectively, the largest possible *d*-values correspond to (110) and to (111). Once we assume indices for some low-angle peaks, we can check to

see if they are consistent with other indices for higher angle peaks. Having indexed a pattern, we can derive the unit cell parameters (*a*, *b*, *c*,  $\alpha$ ,  $\beta$ ,  $\gamma$ ). With *d*-values for many (*hkl*) peaks, we use the equations in Box 2 and a least-squares approach to derive the six cell parameters. For crystals belonging to systems with high symmetry, our task

**BOX 4****Identification of Minerals from X-ray Patterns the Old Way**

Before the development of computer databases to identify minerals from powder diffraction patterns, identification was done by hand with catalogs and other lists of  $d$ -values and  $2\text{u}$  values. One of the more popular sets of search manuals is available from the International Centre for Diffraction Data. This set of manuals is still sometimes used today to supplement or replace computer searching methods.

The search manuals consist of three large books: *Alphabetical Indexes—Inorganic Phases*; *Hanawalt Search Manual—Inorganic Phases*; and *Organic and Organometallic Phases*. Minerals are included in the two inorganic volumes. The books also list chemical formulas, the  $d$ -values (to the nearest 0.01 Å) of the three most intense peaks for each compound, and the Powder Diffraction File (PDF) number of each compound, which allows users to obtain a complete list of  $d$ -values from PDF databases or reference cards. The alphabetized manual is most useful if you want to compare the data from your sample with a few selected minerals. If you do not know the identity of a sample, the Hanawalt search manual is more useful. The Hanawalt search manual lists the names and formulas of thousands of compounds, ordering them first by the  $d$ -values of their most intense peak and then by the  $d$ -values of their second most intense peak. The Hanawalt search manual also includes the  $d$ -values of the third through the eighth most intense peaks.

is simplified because we know some of the six parameters and others may be redundant. Box 5 gives an example of deriving the single unit cell parameter ( $a$ ) for a garnet.

**Obtaining a Mineral Analysis**

X-ray diffraction has historically been, and still is, a very important technology used by mineralogists. It

also has important applications in solid-state physics, biophysics, medical physics, chemistry, and biochemistry. It allowed Watson and Crick to discover the structure of DNA in 1953. Yet, diffraction rarely tells us what elements a mineral contains, instead telling us how atoms are arranged. So, petrologists and mineralogists use other approaches to obtain chemical analyses.

**BOX 5****Indexing a Garnet Pattern and Determining a**

To calculate unit cell dimensions from an X-ray pattern, we must first determine which  $hkl$  values go with which X-ray peaks. The process, called *indexing*, is best accomplished by comparing the “unknown” pattern to one that is already indexed. The table below lists the  $d$ -values for the five most intense peaks from a powder X-ray diffraction pattern of an unknown garnet. For comparison, the  $d$ - and  $hkl$ -values for a “known” almandine are given. By comparing the two lists, we can assign  $hkl$  values to the peaks in the unknown’s pattern.

Garnets are cubic, so  $a$  is the only unit cell parameter to determine. We can derive the relationship between  $d_{hkl}$  and  $a$  from the equations in Box 2:

$$a^2 = (h^2 + k^2 + l^2)d^2 \quad (16)$$

Once we index the peaks in the unknown’s pattern, we calculate the value of  $a$  from each of the  $d_{hkl}$  values. The table below lists results for five peaks. The five values range from 11.82 to 11.90 Å. The range is due to inaccuracies in determining  $2\text{u}$  from the X-ray pattern. Checking in a reference section we find that our unknown garnet is probably grossular.

***d*-values and Miller Indices for an Unknown Garnet and for Almandine**

<b><i>d</i>-values for the unknown garnet</b>	<b>Similar <i>d</i>-values for the “known” almandine</b>	<b><i>hkl</i> values for the “known” almandine</b>	<b>Calculated values of <i>a</i> for the unknown garnet</b>
1.583	1.540	642	11.82
1.652	1.599	640	11.90
1.924	1.866	611	11.84
2.653	2.569	420	11.85
2.961	2.873	400	11.84

Until about 1960, geologists obtained mineral and rock analyses primarily using an approach called “wet chemistry.” To obtain a wet chemical analysis, we dissolve samples in acid and then analyze them by reactions involving precipitation, titration, or colorimetry. **Gravimetric analysis** involves reacting the acid solution with reagents to produce a precipitate. We then weigh the precipitate, and the weight tells how much of an element of interest was present in the original sample. **Volumetric analysis** involves titrating the sample until a specific reaction occurs. The volume of reagent necessary to make the reaction occur is proportional to the amount of the element of interest that is present. **Colorimetric analysis** involves reaction with a reagent that changes the color of the solution. The color intensity is proportional to the amount of the element of interest present, which we quantify by comparison to standards. The advantage of wet chemical analysis is that we can analyze just about any element. However, different elements require different approaches, the technique requires large samples that are destroyed during analysis, and analyses are difficult and time-consuming to do with accuracy. For these reasons and because other, simpler techniques are now available for most purposes, wet chemical analysis is rarely done today.

In the 1960s, researchers developed several new kinds of instruments that made mineral and rock characterization and analysis easier, also providing new and different kinds of information at the same time. The development of electron microscopes and electron microprobes was of particular importance.

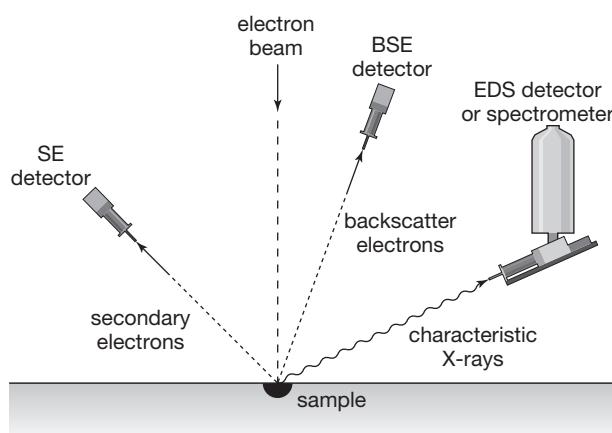
## Electron Microscopes

Conventional microscopes use either transmitted light, as when looking at a thin section, or reflected light to examine a specimen. An **electron microscope** (Figure 21), uses a beam of electrons instead of light. Electron microscopes can magnify samples thousands of times more than conventional light microscopes, allowing us to see very fine mineral grains and details. The greater magnification and resolution are possible because the effective wavelength of an electron is much smaller than the wavelength of light. There are several different kinds of electron microscopes; **scanning electron microscopes (SEMs)** are by far the most common. In a scanning electron microscope, high energy (typically 15–20 keV) electrons are focused into a narrow beam that scans back and forth (rasters) across a sample. SEMs can scan very small areas, operating over a wide range of magnifications, up to 250,000 $\times$  when properly optimized. They can resolve topographical or compositional features just a few nanometers in size.

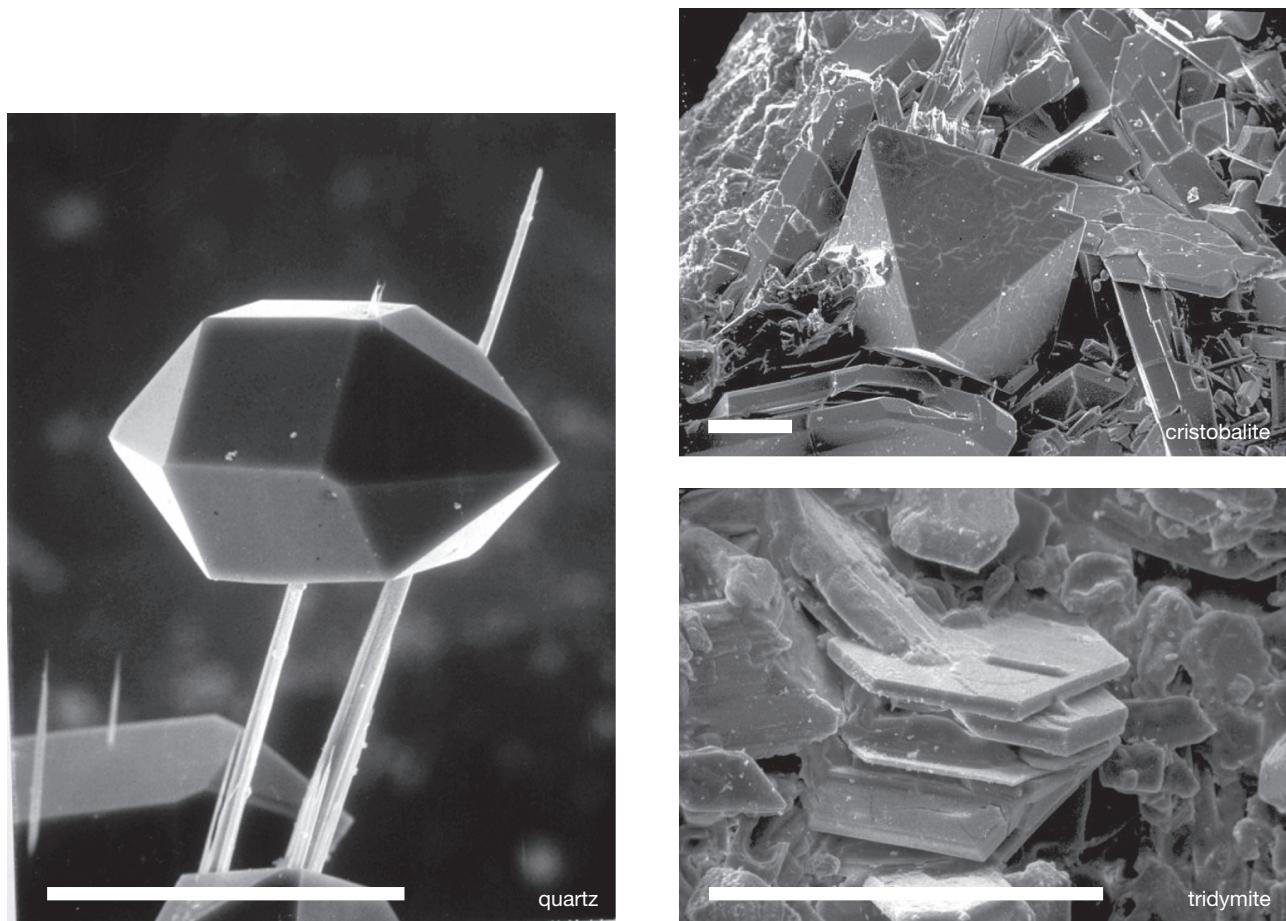


**FIGURE 21** A typical SEM instrument, showing the electron column, sample chamber, EDS detector, electronics console, and visual display monitors. FIGURE from [http://serc.carleton.edu/research\\_education/geochemsheets/techniques/SEM.html](http://serc.carleton.edu/research_education/geochemsheets/techniques/SEM.html).

Several important things occur as the electron beam interacts with the sample (Figure 22). The sample will reflect some electrons with no loss of energy. We call these electrons **backscatter electrons**. Additionally, ionization produces lower-energy **secondary electrons** when the original high energy electrons interact with valence electrons in the sample. To obtain standard SEM images, a detector measures the intensity of secondary electrons (SE) emitted by the sample as the beam rasters across it. This allows creation of an image with brightness proportional to the number of electrons reaching the detector (Figure 23).



**FIGURE 22** When an electron beam strikes a sample, it produces backscatter electrons, secondary electrons, and X-rays. Detectors measure the intensities of the two kinds of electrons to produce secondary electron or backscatter electron images. The X-rays are analyzed by a solid-state detector, or by spectrometers, to determine the composition of the sample.



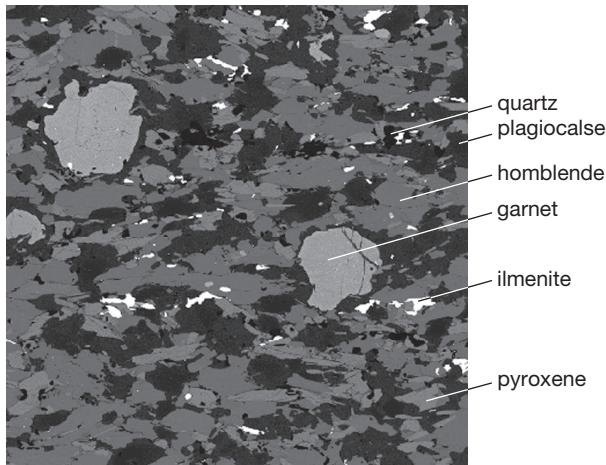
**FIGURE 23** Secondary electron images of some SiO<sub>2</sub> minerals. The white bars in each image are 0.01 mm long. These images used courtesy of George R. Rossman, California Institute of Technology.

Most SEMs also have a separate detector for creating backscatter electron (BSE) images. For both SE and BSE images, the number of electrons emitted, and thus the brightness or darkness of an image, depends on sample topography and also on the composition of the sample. The emission of secondary electrons is particularly sensitive to topography, and only slightly affected by composition. In contrast, the emission of backscatter electrons depends significantly on the composition of the sample. Heavier elements backscatter electrons more efficiently than light elements. So, BSE images show compositional variations within a sample as well as surficial features (Figure 24). Both kinds of images (SE and BSE) sometimes look like conventional photographs but are not the same thing because they do not involve light reflection.

An additional important phenomenon occurs when beam electrons hit atoms in the sample. The electrons cause atoms to emit characteristic X-rays, depending on the element, in the same way that the target in an X-ray tube emits X-rays. If the sample contains

several different elements, it may emit X-rays at many wavelengths corresponding to different energies. Because different elements give off characteristic X-rays with different energies, the emission spectrum displays the chemical composition of the specimen. Iron, for example, emits its strongest characteristic radiation (called **K<sub>α</sub> radiation**) at 6.4 keV. So, the spectrum for a sample that contains iron emits energy at 6.4 keV, and the intensity of the emission is proportional to the amount of iron in the specimen. Iron also emits characteristic X-rays of other energies, but the intensities are much less than K<sub>α</sub> radiation. Because, the electron beam typically excites a sample volume of only 30 cubic microns, it can resolve very fine compositional features. Additionally, individual X-ray peaks may be isolated to construct elemental maps, showing the distribution of different elements within a sample.

Most SEMs are equipped for **energy dispersive X-ray spectroscopy (EDS)**, having a detector that measures X-ray energy and intensity over a wide range of energies simultaneously. EDS spectra can be collected, and quick chemical analyses obtained, in



**FIGURE 24** BSE image of a garnet-hornblende-pyroxene amphibolite, showing major silicate and oxide phases. This image was obtained from a thin section so the color contrast is almost entirely due to compositional differences. In order of darkest to brightest, the main minerals are quartz (black), plagioclase, hornblende, pyroxene, garnet and ilmenite (white). Image courtesy of John Goodge.

just a few seconds (Figure 25). Overall, however, EDS analyses are only qualitative or semiquantitative at best. They allow identification of elements and minerals but do not produce precise or accurate analytical results.

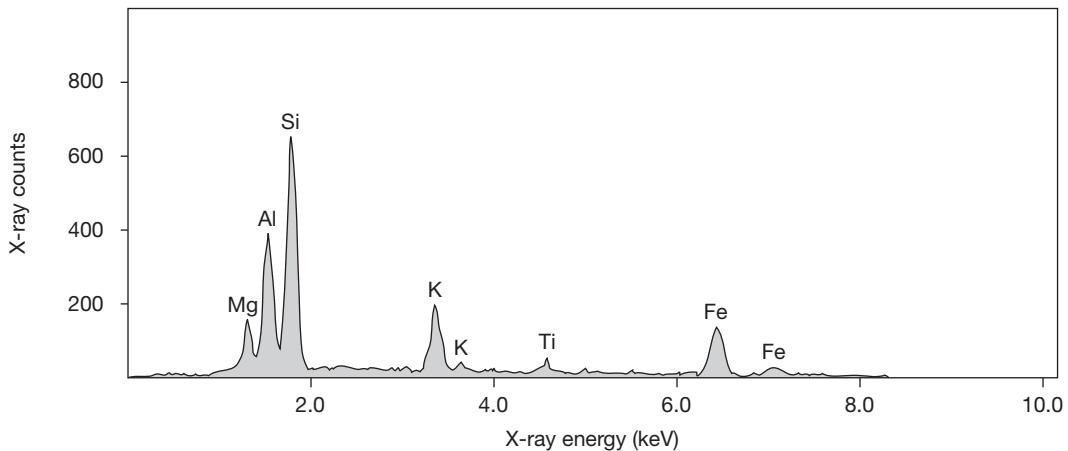
### Electron Microprobe

For the most accurate analyses, we use **wavelength dispersive X-ray spectroscopy (WDS)** instead of

EDS. Special detectors called **spectrometers** measure the intensity of X-rays having specific wavelengths, characteristic of specific elements. Because most scanning electron microscopes do not have spectrometers, they cannot produce WDS analyses.

Electron microprobes, more properly called **electron probe microanalyzers (EPMAs)**, are instruments similar to SEMs but specifically designed for obtaining WDS analyses (Figure 26). Microprobes have a more intense electron beam than SEMs, and may have four or more spectrometers besides imaging and EDS analytical capabilities. However, we cannot obtain WDS analyses as quickly as EDS analyses because a spectrometer only measures one element at a time. For the most accurate results, we analyze standards with unknowns, adding additional time to the procedure. The WDS approach is much more accurate than EDS and can detect elements present in smaller amounts, with precision about 1 to 2% of the amount present (for major elements). The analytical accuracy depends primarily on how well the microprobe has been standardized.

Scanning electron microscopy and electron microprobe analysis have several major advantages over wet chemical and most other analytical techniques. First, they allow us to examine rocks, mineral grains, or thin sections with little sample preparation. Second, microprobe analysis is a non-destructive analytical technique. So, we analyze samples without destroying them. Perhaps most important, microprobe analyses focus on very small spots. We can analyze single mineral grains, or many spots in the same grain, to look at very small-scale changes in chemistry.



**FIGURE 25** X-ray spectrum for a sample of biotite, collected with an EDS detector. The X-ray peaks show characteristic radiation of elements present in the biotite (Mg, Al, Si, K, Ti, Fe). These elements emit radiation of other energies but with intensities too low to be measured or show on this graph. Some EDS detectors can record characteristic X-rays generated by oxygen, but many, like the one used to collect this spectrum, cannot. So, even though oxygen is present in biotite, oxygen peaks are not seen here.



**FIGURE 26** An electron microprobe in the Department of Geological Sciences at the University of Michigan. The monitor screens show images of the sample, and also EDS spectra revealing composition. The two sloping “wings” on the sides of the microprobe contain spectrometers for analyzing X-ray emissions.

One shortcoming of both EDS and WDS analysis is that elements with low atomic number are hard or impossible to analyze. This problem arises because low-numbered elements emit X-rays of low energy. For several reasons, such X-rays may not make it to the detector or spectrometer, or may not be measurable once they get there. Technology varies, but even the best EDS detectors cannot analyze elements lighter than boron. WDS analysis can, in principle, analyze elements from Be to U but technical complications occur at both extremes.

An additional complication arises because most geological materials do not conduct electricity. Unless we coat them with a conducting material static charge builds up, distorting images and analyses. So, we vaporize gold, carbon, or some other conducting material in a vacuum and let it precipitate on our specimen. Gold coatings work very well for some applications, producing excellent images. However, we cannot easily remove the gold, and it interferes with analyses. So mineralogists and petrologists generally use carbon coating instead. Unlike gold, we can remove the carbon coating from a thin section by light polishing. Instead of coating samples, we can reduce or eliminate charging problems by using an **environmental scanning electron microscope (ESEM)** instead of a standard SEM. ESEM is a recently developed technology that, unlike a conventional SEM, does not require that the sample be under a high vacuum. A small amount of gas (up to 20 torr/2.7 kPa) provides a medium to conduct electrons away from the sample. ESEMs require no sample coating and many permit examination of

large samples, larger than conventional SEMs. The quality of images and analyses, however, is reduced.

### Other Analytical Techniques

Mineralogists and petrologists use many other analytical techniques besides those described above. All are destructive techniques, and most are more useful for analyzing rocks than individual minerals because they require large samples. Some of the most important are:

**X-ray fluorescence (XRF)** is a technique used mainly for analyzing rock samples. It requires relatively large samples melted with a flux to make a glass disk. The disc is placed in the machine, and a high-energy X-ray beam hits it. Atoms in the sample fluoresce, producing characteristic X-rays that are analyzed using EDS or WDS detectors. We compare unknowns with well-characterized standards to obtain quantitative results.

**Atomic absorption spectroscopy (AAS)** is based on the absorption of light by an atomized sample. We dissolve samples in an acid solution or flux that we then introduce to a hot (2,000 °C/3,600 °F) flame or graphite furnace. The flame atomizes the liquid, converting it to a gas phase. We use special light sources to pass light of different wavelengths, characteristic of different elements, through the gas. The light absorption is compared with absorption by standards to determine the concentration of the element of interest. We can use AAS to analyze most metals but not non-metals.

**Inductively coupled plasma (ICP)** is used mostly to analyze rocks, not individual minerals. After we dissolve it in acid, or in a flux, the sample is heated in a plasma (6,000 °C/11,000 °F), ionizing its atoms. At 6,000 °C, the atoms emit light at wavelengths that depend on the elements present. We measure the intensity of light emission at different wavelengths to calculate the concentrations of each element present. ICP analysis is very sensitive and can measure elements present at the parts-per-billion level.

**Inductively coupled plasma mass spectrometry (ICP-MS)** is a variant of ICP analysis. Instead of analyzing the emitted light, displaced ions are analyzed using a mass spectrometer to determine concentrations of individual isotopes. ICP-MS can be used with a laser that ionizes small spots on individual min-

eral grains. ICP-MS is very sensitive and can analyze many elements at concentrations as low as 1 part per trillion.

**Ion microprobes**, also called **secondary ion mass spectrometers (SIMS)**, analyze small spots (on the order of a few microns) on a sample. A focused beam of ions bombards the sample, burning a pit as it creates a plasma and releases ions. The ions then travel to a mass spectrometer where they are analyzed. Ion microprobes are much more sensitive than electron microprobes and can be used to measure the abundances of very light elements that cannot be analyzed with a microprobe. However, standardization is problematic and limits accuracy.

**Mössbauer spectroscopy** is a limited but very valuable analytical technique. We use it to determine the oxidation state and coordination of Fe in minerals. A sample is exposed to gamma radiation emitted by an  $^{57}\text{Fe}$  source, and a detector measures how much of the radiation is absorbed by Fe as it passes through the sample. The gamma-ray source is accelerating back and forth, changing the energy slightly due to the Doppler effect. The absorption at different velocities (energies) reflects Fe valence and coordination number in the specimen. We could use Mössbauer spectroscopy to analyze a few

other elements besides Fe, but none are generally of geological interest.

**Visible and infrared spectroscopy** is an analytical technique based on the absorption of visible light or infrared radiation (IR) by a sample. Samples are prepared in one of several ways to make them thin enough for light/radiation to pass through. We shine a beam of light through the sample and measure the absorption of different wavelengths. Absorption of visible light can tell us the oxidation state and coordination number of important transition metals. Absorption of IR radiation helps identify minerals, and reveals the relative amounts of  $\text{H}_2\text{O}$  and  $\text{OH}^-$ , or of  $\text{CO}_2$  and  $\text{CO}_3^{2-}$ , in a specimen.

**Raman spectroscopy** is based on inelastic (Raman) scattering of light from a sample. A monochromatic laser beam is focused on a small spot on the sample, and most light photons bounce off with the same wavelength as the original light (elastic scattering). The few that do not will have slightly increased or decreased wavelengths and energies. The difference in energy, called the **Raman shift**, reflects the presence of specific ions and atoms in the sample. It also tells us the coordination numbers of some elements, helps distinguish polymorphs from each other, and provides a measure of the crystallinity of a specimen.

## Questions for Thought

*Some of the following questions have no specific correct answers; they are intended to promote thought and discussion.*

1. Why was the discovery of X-rays a “key” to crystallography? What was missing before the discovery of X-rays?
2. Shortly after Linus Pauling did some pioneering X-ray studies, he wrote a book on the nature of the chemical bond. What is the connection between X-ray studies and bonding theory?
3. What process does a crystallographer follow to determine a crystal’s atomic structure? Are the results interpretations, or do crystal structure studies yield exact answers? Why?
4. Fluorite and sodalite are both cubic minerals, yet fluorite has a much simpler X-ray pattern. Why?
5. Do all crystals, including nonminerals, diffract X-rays? Do all minerals diffract X-rays? Why?
6. We use single crystal diffraction for most crystal structure studies. We normally use powder diffraction for mineral identification. Why are different methods used for each?
7. In the diffraction pattern for barite (Figure 15), some of the strongest diffraction peaks are at 20.167, 25.081, 26.056, 27.063, 28.967, 33.033, 42.805, and 43.104  $2\theta$ . The pattern was obtained using copper  $K_\alpha$  radiation ( $\lambda = 1.5418\text{\AA}$ ). If you convert the angles to  $d$ -values using the Bragg law (Equation 14) and compare the  $d$ -values to those listed in Box 3, you can index these peaks. Use the  $d$ -values for peaks with indices containing two zeros to determine  $a$ ,  $b$ , and  $c$  for barite using Equation 10 in Box 2. How do your values compare to the reference values given in Box 3? Explain any discrepancies.
8. Petrologists routinely examine rocks using thin sections and optical microscopy. We can also look at thin sections using a scanning electron microscope. What are the advantages or disadvantages of each?
9. We can obtain a chemical analysis of a mineral using an electron microprobe. Yet, sometimes this information is inadequate to identify the mineral. Describe at least two things that can cause this problem.
10. Contrast and compare the sample preparation required to make a thin section, to analyze a mineral using X-ray diffraction, to examine a mineral using a scanning electron microscope, and to collect a mineral analysis using an electron microprobe.

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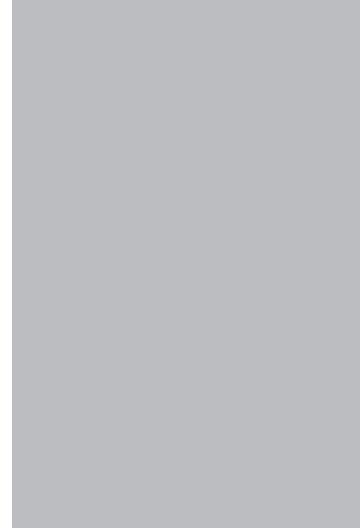
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# Atomic Structure



# Atomic Structure

With the development of X-ray diffraction techniques, mineralogists and chemists could directly investigate the nature of crystal structures. While they were conducting their studies, others were investigating the nature of chemical bonds. The combined results led to a new understanding of crystals and their structures. In this chapter we look at some of the details of crystal structure. We find that minerals have highly ordered atomic arrangements and that most can be described as spherical atoms held together by ionic, covalent, or metallic bonds. In some, the atoms are packed tightly together, while in others they are arranged in networks of geometric shapes. In most cases, they obey some simple and fundamental rules related to ionic size and charge.

## THE IMPACT OF X-RAY CRYSTALLOGRAPHY

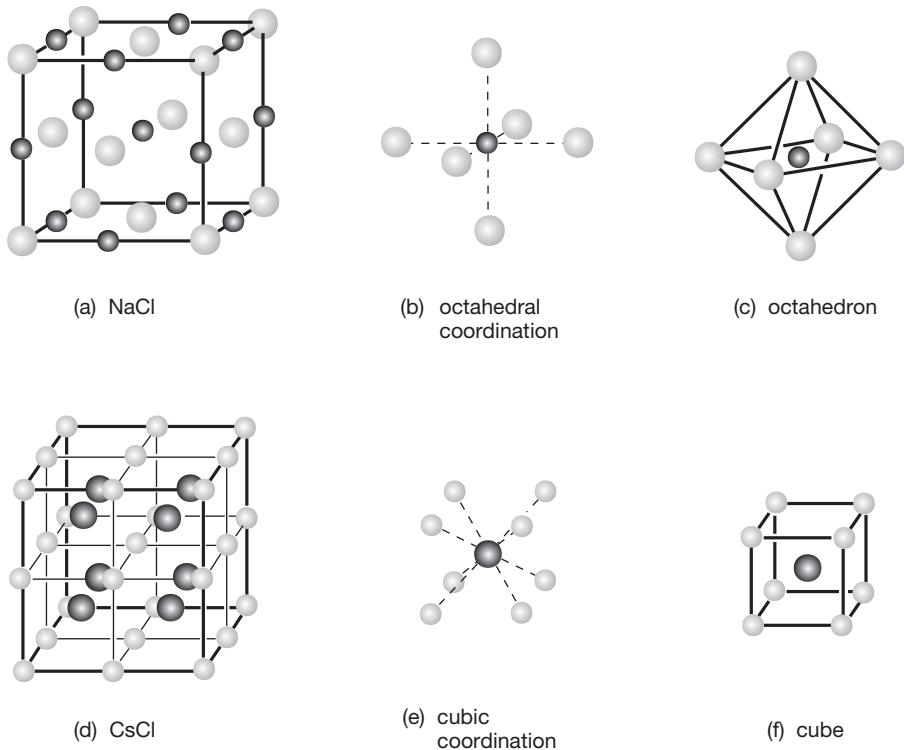
We cannot overstate the importance of the discoveries by Röntgen, von Laue, and the Braggs. Before their pioneering work, scientists could not test competing hypotheses for the nature of crystal structures. Within a few decades of the discovery and development of X-ray diffraction techniques, most of the basic principles of crystal structures were well known. While crystallographers were working on crystals, chemists were developing atomic theory. The Bohr model of the atom, the Schrödinger wave equation, and theories of ionic and covalent bonding were firmly established by the 1920s. Chemists such as Linus Pauling, realizing the importance of X-ray techniques, conducted X-ray studies in efforts to further understand crystal structure and bonding. In 1939 Pauling published *The Nature of the Chemical Bond*; he subsequently won the Nobel Prize in Chemistry in 1954.

## IONIC CRYSTALS

**Ionic crystals** are those composed of cations and anions held together primarily by ionic bonds. They

have overall electrical neutrality, or else electrical current would flow until they obtained charge balance; so the total number of electrons in the structure is equal to the total number of protons. Anions repel anions, cations repel cations, so ions of similar charge stay as far apart from each other as possible. Consequently, an organized and repetitive atomic arrangement, with cations packed around anions and anions packed around cations, typifies ionic crystals.

Consider the mineral halite, NaCl, which contains an equal number of Na and Cl atoms (Figure 1a–c). Mineralogists have determined its atomic arrangement through X-ray studies, finding that  $\text{Na}^+$  and  $\text{Cl}^-$  ions pack around each other in an alternating three-dimensional structure. Each  $\text{Na}^+$  bonds to six  $\text{Cl}^-$  and vice versa. Bonds around one ion are all equal length and at  $90^\circ$  to each other. Unit cells are therefore cubic, containing four  $\text{Na}^+$  and four  $\text{Cl}^-$  ions in a face-centered arrangement. Salt crystals, including the ones that come out of your salt shaker, are often perfect cubes. CsCl is also cubic, but in contrast with the halite structure, the alkali cation ( $\text{Cs}^+$ ) is surrounded by eight anions



**FIGURE 1** Halite and CsCl: (a) ball-and-stick model showing the halite structure (black spheres are Na<sup>+</sup>, light spheres are Cl<sup>-</sup>); (b) Na<sup>+</sup> in octahedral coordination; (c) an octahedron surrounding Na<sup>+</sup>; (d) ball-and-stick model showing the structure of CsCl (dark spheres are Cs<sup>+</sup>); (e) Cs<sup>+</sup> in cubic (8-fold) coordination; (f) a cube surrounding Cs<sup>+</sup>.

(Figure 1d–f). The difference is because Cs<sup>+</sup> is larger than Na<sup>+</sup>.

The ionic bonds between alkalis and Cl<sup>-</sup> are not terribly strong, and they break easily when salts dissolve in water, releasing free alkalis and Cl<sup>-</sup> ions. High solubility in water is characteristic of highly ionic crystals, especially those in which the ions only have charges of  $\pm 1$ . If concentrations of dissolved Na<sup>+</sup> and Cl<sup>-</sup> reach high enough levels, perhaps due to evaporation, halite may precipitate from solution. Other minerals have different atoms but have atomic structures and bonding similar to halite's; sylvite (KCl) and periclase (MgO) are both examples. In periclase, however, the ions are divalent, having a charge of  $\pm 2$  (in contrast with halite and sylvite) and the bonds are 25% covalent. The stronger, more covalent bonds mean that periclase is harder and has lower solubility than sylvite and halite.

In some minerals, tightly bonded anion complexes such as carbonate (CO<sub>3</sub>)<sup>2-</sup>, sulfate (SO<sub>4</sub>)<sup>2-</sup>, or phosphate (PO<sub>4</sub>)<sup>3-</sup> are present instead of simple anions. The complexes may not dissociate, even if the mineral dissolves in water, because covalent bonds hold the complexes together. Calcite, CaCO<sub>3</sub>, is a good example. In the calcite structure, carbonate groups and Ca<sup>2+</sup> ions alternate in three dimensions. However, the carbonate complexes are triangular, so

the crystals cannot be isotropic and cubic like halite. When calcite dissolves, the ionic bond between calcium and the carbonate complex breaks easily, but the carbonate group itself does not dissociate into C and O. Consequently, dissolved species are Ca<sup>2+</sup> and (CO<sub>3</sub>)<sup>2-</sup>.

## IONIC RADII

Ions consist of nuclei with electron clouds around them. The electrons are constantly moving; sometimes they are farther away from the nucleus than at other times, so we can never know the exact size of the electron cloud. However, ions often behave as if they have fixed radii, and we can understand many crystal properties by thinking of crystals as collections of spherical ions packed together. The spacing between them, and the way they pack together, are directly related to their size. Knowing their **effective ionic radius** is therefore useful.

How can we determine ionic radii if ions really do not have a fixed radius? We estimate them by studying bond length in crystals. Consider the mineral periclase, MgO. Through X-ray diffraction studies we learn that the distance between the centers of the Mg<sup>2+</sup> and O<sup>2-</sup> ions is about 2.11 Å, so the sum of the effective ionic radii of Mg<sup>2+</sup> and O<sup>2-</sup>

**TABLE 1** Radii of Alkali Cations in Alkali Oxides

Cation	$\text{Li}^+$	$\text{Na}^+$	$\text{K}^+$	$\text{Rb}^+$	$\text{Cs}^+$
<b>Atomic Number</b>	3	11	19	37	55
<b>Cation Radius (Å)</b>	0.82	1.40	1.68	1.81	1.96

is 2.11Å. Assuming for the moment that the radius of  $\text{O}^{2-}$  is 1.32Å, this yields a radius of 0.79Å for  $\text{Mg}^{2+}$  in periclase. An alternative way to find the radius of an Mg atom is to determine the distance between neighboring Mg atoms in Mg metal. Mg metal is not, however, ionically bonded, and the results do not tell us the radius of  $\text{Mg}^{2+}$ , although they do tell us that metallic Mg has a radius of about 1.60Å.

If we study many compounds, it becomes possible to learn the effective ionic radii of all individual elements. Consider the alkali oxides, which have the general formula  $\text{R}_2\text{O}$ , where R can be any alkali element. Each alkali ion is bonded to oxygen; chemists and mineralogists have determined the bond lengths through X-ray studies. Since the radius of  $\text{O}^{2-}$  is common to all alkali oxides, variations in bond length must be due to variations in the radii of the alkalis. If we assume  $\text{O}^{2-}$  has a constant radius of 1.32Å, we get the cation radii in Table 1. It should be no surprise that alkali radius increases with atomic number because we know elements with higher numbers have more protons and electrons, and so are larger atoms.

Radii also vary systematically across a row of the Periodic Table as shown in Table 2. As we move from the margins of the Periodic Table toward the center, cations get smaller because as cation charge increases, attraction between electrons and protons increases. Cation radii are always smaller than uncharged atoms of the same species. Table 2 also includes two anions ( $\text{S}^{2-}$  and  $\text{Cl}^-$ ) from the right-hand side of the Periodic Table; they are larger than the cations because they contain extra electrons in outer orbitals. Anion radii are always larger than uncharged atoms of the same species. Note that we cannot list an ionic radius for argon because it is a noble gas and does not ionize to enter ionic structures.

**TABLE 3** Average Radii Manganese Atom and Ions

Cation	$\text{Mn}^0$	$\text{Mn}^{2+}$	$\text{Mn}^{3+}$	$\text{Mn}^{4+}$	$\text{Mn}^{6+}$	$\text{Mn}^{7+}$
<b>Cation Radius (Å)</b>	1.12	0.97	0.70	0.62	0.35	0.34

**TABLE 4** Average Radii of Vanadium Atom and Ions

Cation	$\text{V}^0$	$\text{V}^{2+}$	$\text{V}^{3+}$	$\text{V}^{4+}$	$\text{V}^{5+}$
<b>Cation Radius (Å)</b>	1.31	0.87	0.72	0.67	0.53

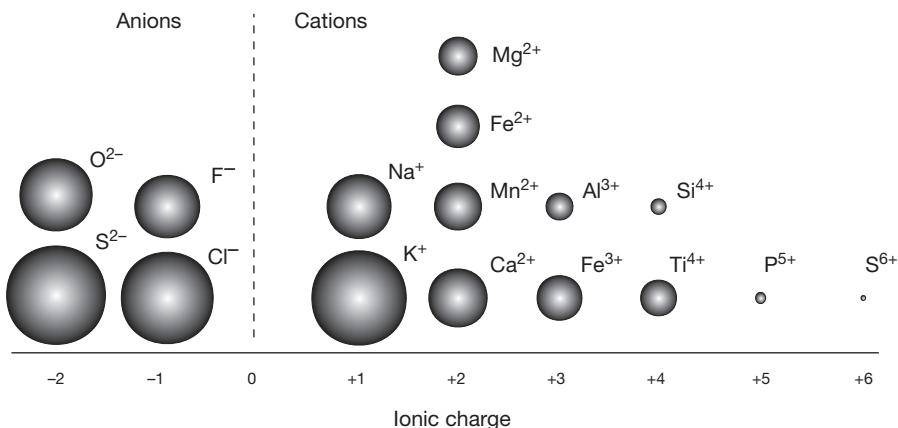
We can best see the relationship between cation radius and charge by looking at elements that exist in more than one valence state. Table 3 gives ionic radii for manganese ions, and Table 4 shows similar data for vanadium. As expected, the radii decrease with charge, reflecting the greater pull nucleus protons have on outer electrons.

The radii of  $\text{Na}^+$  given in Tables 1 and 2 are different because Table 1 refers to alkali oxides, whereas Table 2 contains average values for many different types of crystals. This distinction reminds us that the concept of ionic radius is an approximation because the effective radius of an ion depends on several things. Most significantly, radii are only constant if bond types are constant. For example, the average ionic radius of  $\text{Mg}^{2+}$  is 0.88Å, while its covalent radius is 1.36Å and its metallic radius is 1.60Å. Additionally, bond length varies with atomic structure and the number of anions surrounding a cation. A further complication may arise because in some structures ions become **polarized** (elongated) in one direction and no longer act as spheres. A final ambiguity arises because we must assume a value for the radius of  $\text{O}^{2-}$  to calculate radii for other elements. Depending on the kind of bonding and several other things,  $\text{O}^{2-}$  may have an effective radius between 1.27Å and 1.34Å, but the values in this text's tables are based on an assumed radius of 1.32Å. The inside back cover has a complete list of ionic radii based on this value.

**TABLE 2** Average Radii of Ions from One Row in the Periodic Table (see inside front cover)

Ion	$\text{Na}^+$	$\text{Mg}^{2+}$	$\text{Al}^{3+}$	$\text{Si}^{4+}$	$\text{P}^{5+}$	$\text{S}^{6+}$	$\text{S}^{2-}$	$\text{Cl}^-$	$\text{Ar}^0$
<b>Atomic Number</b>	11	12	13	14	15	16	16	17	18
<b>Ion Radius (Å)</b>	1.18	0.79	0.55	0.41	0.25	0.20	1.72	1.70	—

## Atomic Structure



**FIGURE 2** The relative sizes and ionic charges of common cations and anions in minerals.

## COORDINATION NUMBER

Most minerals, except native elements such as gold or copper, contain anions or anionic groups. Especially common are  $O^{2-}$ ,  $S^{2-}$ ,  $(OH)^-$ , and  $(CO_3)^{2-}$ . The large size of oxygen and other anions (and anionic groups) compared with most common cations (Figure 2) means that we can often think of crystal structures as large anions with small cations in **interstices** (spaces) between them. The anions are packed in a repetitive structure, with the cations at regular intervals throughout. The number of anions to which some particular cation bonds is the cation's **coordination number** (C.N.).  $Si^{4+}$ , for example, nearly always bonds to four  $O^{2-}$  in minerals, and therefore has a C.N. of 4. So we say it is "in 4-fold coordination."

The size of interstices between anions depends on how the anions are packed. In two dimensions, anions can fit together in symmetrical patterns to form hexagonal or square patterns (see Figure 5). In three dimensions, other possibilities including tetrahedral and cubic arrangements can exist. Figure 3 shows some ways that groups of identical anions may pack around a single cation. Since only one cation and one kind of anion are involved, all bond distances are the same. We give coordination arrangements geometrical names depending on the shape of the polyhedron created by connecting the centers of the anions (Figure 3). We call some 2-fold coordination *linear* because the ions form a line. We call 3-fold coordination *triangular* because the anions form a triangle. We call some 4-fold coordination *tetrahedral* because the four anions form tetrahedra. We call the 6-fold coordination, shown in Figure 3c, *octahedral* because the anions outline an octahedron (an eight-sided geometric shape). We call the 8-fold coordination, shown in

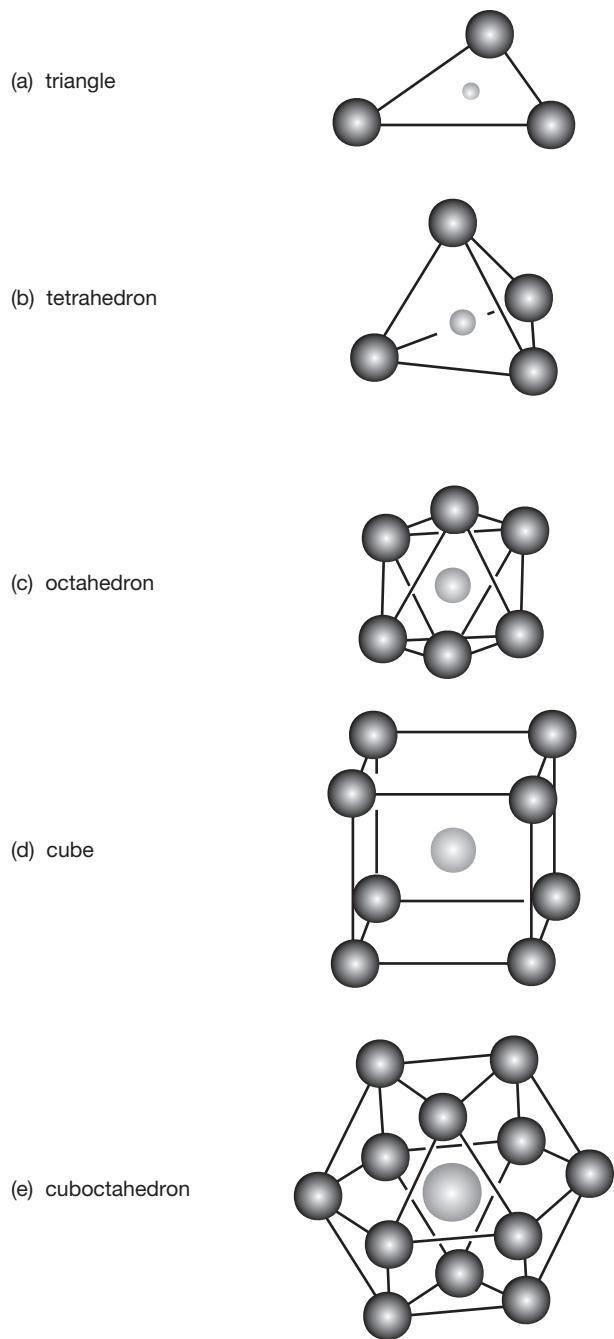
Figure 3d, *cubic* because connecting the centers of the anions produces a cube. (Fortunately, we never call cubic coordination *hexahedral* even though a cube has six faces.) We call the 12-fold coordination, shown in Figure 3e, *dodecahedral* because the coordinating polyhedron has twelve vertices. The coordination polyhedra shown in Figure 3 are all regular, meaning the cation-to-anion distance is the same for all anions. As C.N. increases, the space inside the polyhedron increases and larger cations can be accommodated. So, large cations have greater C.N.s than small cations. Cations sometimes occupy distorted sites or sites with unusual coordinations not represented by the drawings in Figure 3. Atoms in minerals typically have C.N. of 3, 4, 6, or 8, but 5-fold, 7-fold, 9-fold, and 10-fold coordination are possible. The atoms in some native metals are in 12-fold coordination. Most common elements have different coordinations in different minerals.

Figure 4 shows a typical ball-and-stick model for kaolinite. This model is convenient and easy to examine, but incorrect in detail since balls of similar size, separated by large distances, represent all atoms, anions, or cations. More accurate models of crystal structures could reflect variations in ionic radii. In principle we could construct very exact models, using balls of correctly proportioned sizes. In practice it is not often done because regular ball-and-stick models are easier to make and examine.

## CLOSEST PACKING

### Packing in Two Dimensions

In some crystals, anions pack together in highly regular repetitive patterns. As an analogy, consider a collection of equal-sized marbles. We may arrange the marbles so rows line up and repeat at



**FIGURE 3** Packing of ions and coordination polyhedra: (a) a cation in triangular coordination; (b) a cation in tetrahedral (4-fold) coordination; (c) a cation in octahedral (6-fold coordination); (d) a cation in cubic (8-fold) coordination; (e) a cation in dodecahedral (12-fold) coordination.

regular spacing characterized by translational symmetry. Figure 5 shows two alternative ways that marbles (shown as circles) can pack together in two dimensions. In Figure 5a groups of three marbles are arranged so that connecting their centers yields an equilateral triangle. On a slightly

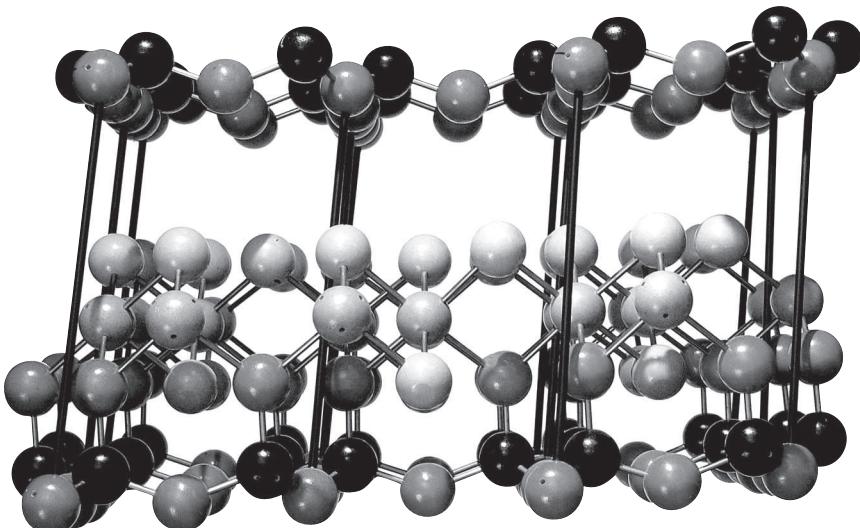
larger scale, each marble is surrounded by six others, and connecting their centers makes a hexagon. The total pattern has 2-fold, 3-fold, and 6-fold rotational symmetry, as well as translational symmetry and mirror planes. Figure 5b shows an alternative arrangement of marbles in two dimensions. This arrangement has 2-fold and 4-fold axes of symmetry, but not 3-fold. The symmetries of the two patterns in Figure 5 are equivalent to the symmetries of a hexanet and a square net.

We call the arrangement of marbles in Figure 5a **hexagonal packing**. We call the pattern in Figure 5b **tetragonal packing** because of the obvious 4-fold symmetry. In hexagonal packing the marbles are closer together than in tetragonal packing. Because no other two-dimensional arrangement allows marbles to be closer together, we say the hexagonal arrangement is **closest packed**. Each marble touches six others, the maximum possible. In the tetragonal arrangement each marble only touches four others.

### Packing in Three Dimensions

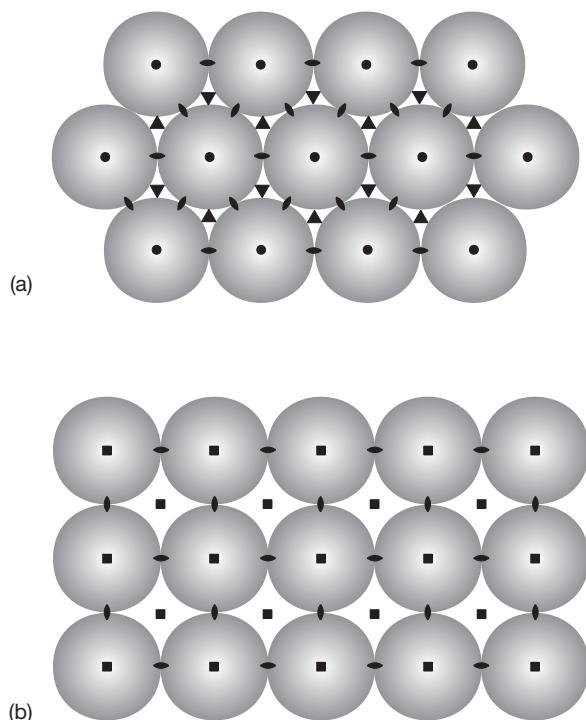
In three dimensions, marbles (or anions) can be closest packed in two ways. Both are equivalent to piling hexagonal packed sheets one above another. Three adjacent marbles in a hexagonal closest-packed sheet make a triangle. If we put another marble on top of them, it slips into the low spot above the center of the triangle, resulting in a tetrahedral structure composed of four marbles (Figure 6a-c). All four marbles touch each other, so the arrangement is closest packed. Alternatively, we could put three marbles on top of the first three, as shown in Figure 6d-f. This arrangement of marbles, too, is closest packed. Each marble is in contact with three in the adjacent layer, but the second layer contains no marble directly above the center of the triangle in the first layer.

Now consider an entire layer of hexagonal packed marbles. If we put another hexagonal packed layer on top, its marbles naturally fall into gaps produced by groups of three in the bottom layer, so the marbles in the second layer will not be directly above those in the first (Figure 7). If we now place a third layer on top of the second, marbles will fill gaps as before. However, marbles in the third layer may or may not be directly above those in the first layer (Figure 8). If they are, we call the structure **hexagonal closest packed**. If they are not, we call it **cubic closest**



**FIGURE 4** Photograph of a ball-and-stick model of kaolinite. The white marbles represent Al, the black marbles Si, and the gray marbles are O and (OH).

**packed** (see Box 1 and Figure 9). Although it may not be immediately obvious, if we add a fourth layer, its marbles must lie directly above those of one of the other layers. Hexagonal closest packed (HCP) structures are often described as having ABABAB layering because alternate layers are directly above each. Cubic closest packed (CCP) structures have an ABCABCABC packing

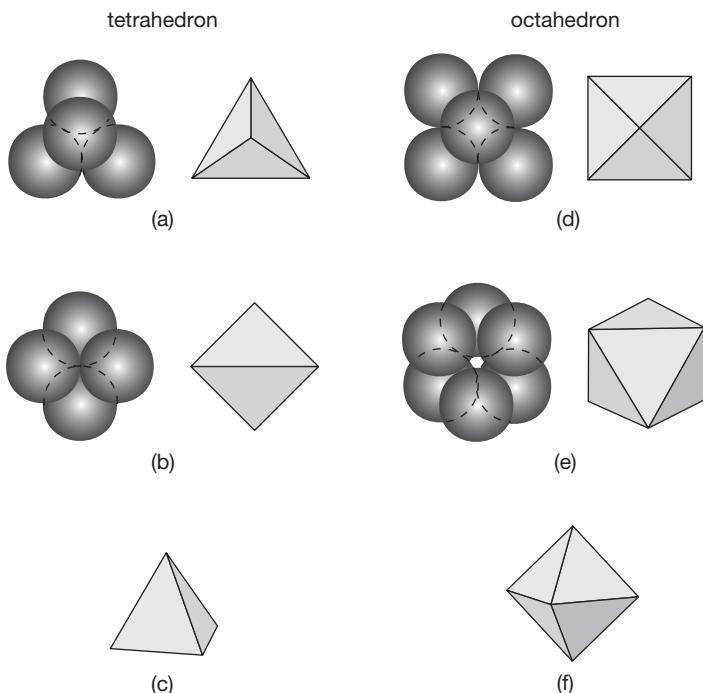


**FIGURE 5** Circles arranged in hexagonal and tetragonal patterns: (a) hexagonal packing; (b) tetragonal packing; rotational axes of symmetry have been shown using conventional symbols; mirror planes of symmetry have been omitted for clarity.

sequence; it takes three layers before they repeat. In both HCP and CCP, every marble (or anion) is in contact with 12 others.

### Exceptions to Closest Packing

Johannes Kepler first broached the idea of atoms as touching spheres in 1611. William Barlow described the systematics of closest-packed structures more than 250 years later in 1883. For a long time, all structures were thought to have simple repetitive closest packing. It was not long after the Braggs's X-ray studies led to the first crystal structure determination that scientists found exceptions. Anions in closest-packed structures are arranged so that only tetrahedral and octahedral sites exist between them (Figure 6). We can use closest packing to describe metals, sulfides, halides, some oxides, and other structures in which all cations are in tetrahedral or octahedral coordination. Sphalerite ( $\text{ZnS}$ ), halite ( $\text{NaCl}$ ), and native metals gold, silver, platinum, and copper are all examples of cubic closest-packed minerals. Wurtzite ( $\text{ZnS}$ ), magnesium metal, and zinc metal are hexagonal closest packed. Other mineral structures are, however, not truly closest packed. In general, dense minerals with few large cations are most closely packed. Today we know that some minerals have complicated structures with mixed stacking sequences, and that many minerals have polyhedral frameworks that are not closest packed at all. Minerals containing alkali or alkaline earth elements cannot be closest packed because alkalis and alkaline earths are too large to fit in tetrahedral or octahedral sites. The closest-packed model also fails for other minerals, such as fluorite,  $\text{CaF}_2$ , in which small anions are between large cations, and for metals that have a body-centered cubic structure in which each atom contacts eight others.



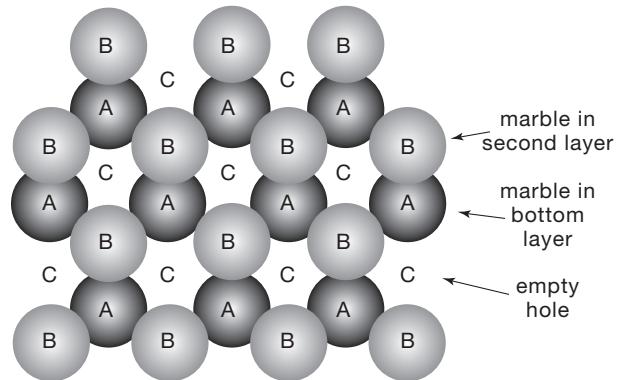
**FIGURE 6** Tetrahedron and octahedron formed by closest packing spheres and polyhedral created when the centers of the spheres are connected: (a), (b), and (c) show different views of a tetrahedral arrangement. (d), (e), and (f) show different views of an octahedral arrangement. The top eight drawings look down on apices, edges or faces, and so the overall geometric distribution of spheres is somewhat hidden. The bottom two drawings, viewed at an oblique angle, show the shape and symmetry of the polyhedral more clearly.

## PAULING'S RULES

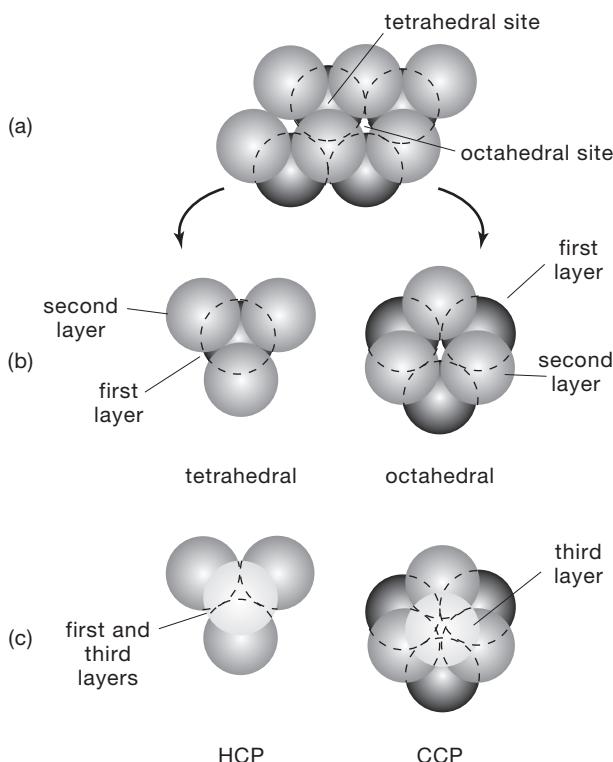
In 1929, Linus Pauling (see Box 3) summarized five general rules that apply to ionic structures. The rules, now called **Pauling's rules**, provide a convenient framework for examining some details of ionic structures.

### Pauling's First Rule

Pauling's first rule, sometimes called the *Radius Ratio Principle*, states that the distance between cations and anions can be calculated from their effective



**FIGURE 7** Stacking of two layers of marbles in hexagonal arrangements (for clarity, the size of the circles has been reduced so that both layers can be seen). The bottom layer is designated by the letter A and the top layer by the letter B. Open spaces, designated by C, might contain marbles in a third layer. Alternatively, marbles in a third layer could be placed directly above A-marbles in the first layer.

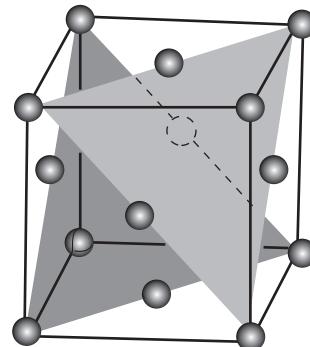
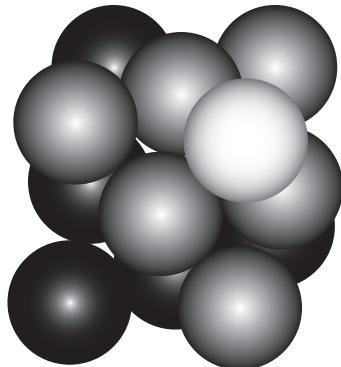


**FIGURE 8** Cubic and hexagonal closest packing. (a) One closest-packed layer on top of another. (b) View of tetrahedral and octahedral sites between closest-packed layers. (c) In hexagonal closest packing (HCP), a third layer is directly above the first. In cubic closest packing (CCP), marbles in a third layer are not above marbles in either of the first two layers.

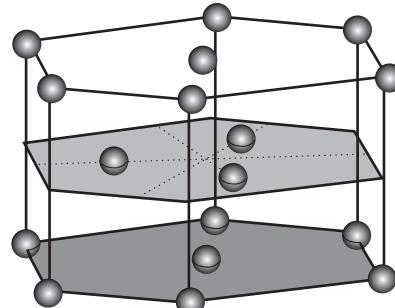
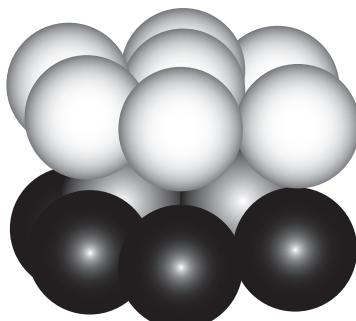
## BOX 1

### Why Are They Called Hexagonal Closest Packed (HCP) and Cubic Closest Packed (CCP)?

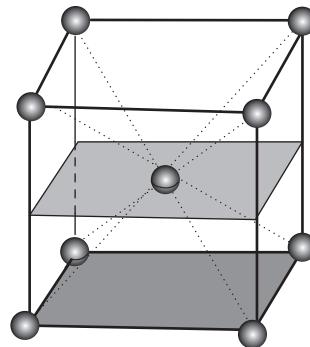
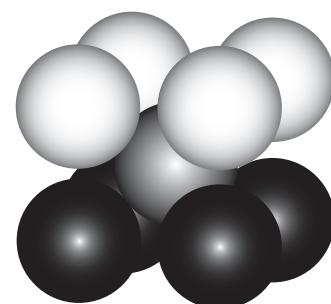
In closest-packed structures, each atom is surrounded by 12 others. Standard unit cells are usually chosen: For HCP, atoms from three layers combine to form a unit cell with the shape of a hexagonal prism; for CCP, atoms from four layers combine to form a unit cell with the shape of a cube. The difference between the two is that HCP involves ABABAB stacking, while CCP involves ABCABC stacking. The sphere and ball-and-stick views in Figure 9 show both unit cells and, for comparison, a body-centered cubic unit cell (not closest packed) in which all atoms contact eight neighbors. Metals, alloys, and minerals of all three structures are known.



(a) cubic closest packing



(b) hexagonal closest packing



(c) body-centered cube

**FIGURE 9** Atoms packed together as spheres and as balls connected by sticks (in a and b, different closest-packed layers are shown with different shades of gray): (a) cubic closest packing; (b) hexagonal closest packing; (c) a body-centered cubic arrangement of atoms (not closest packed). Although the closest packing model is a convenient concept, with the exception of some native metals, minerals do not in general have atoms in closest-packed arrangements. Gold, silver and platinum are examples of native metals with cubic closest packing. Magnesium and zinc are examples of native metals with hexagonal closest packing. Native iron has atoms with a body-centered cubic arrangement.

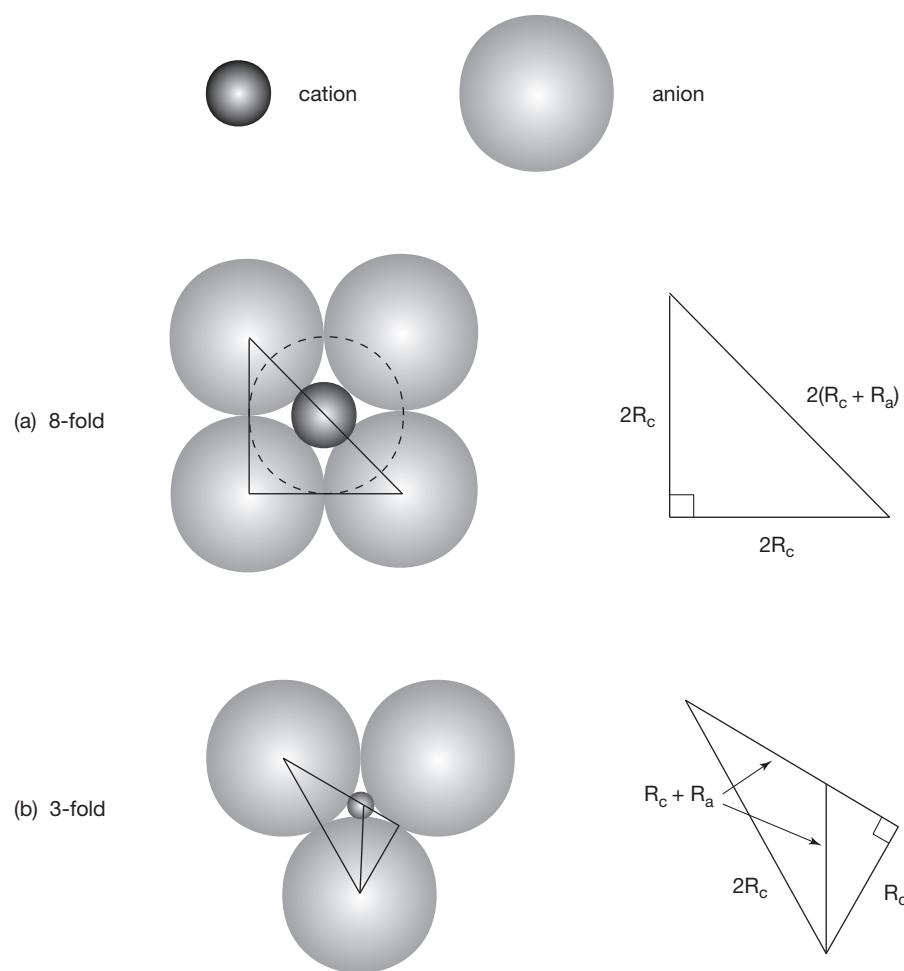
ionic radii, and cation coordination depends on the relative radii of the cation and surrounding anions. In essence, this rule says that very small cations will bond to only a few anions, while very large cations may bond to many anions. In other words, as the radius of the cation increases, so too will the C.N. Figure 10a shows the limiting case when a cation just fits into the opening between four touching anions. If additional anions are directly above and below the cation, the cation is in perfect octahedral coordination (compare with Figure 6d). Application of the Pythagorean theorem to the right triangle shown in Figure 10a reveals the ratio of cation radius to anion radius ( $R_c/R_a$ ) to be 0.414. Figure 10b shows how we can use geometry to calculate  $R_c/R_a$  for cations in perfect triangular coordination;  $R_c/R_a$  is 0.155. We can make similar, though more complicated, calculations for cations in tetrahedral (4-fold), cubic (8-fold), or dodecahedral (12-fold) coordination (Table 5). As C.N. increases, space between anions increases, and the size of the cation that fits increases. Pauling argued, therefore,

that as  $R_c/R_a$  increases, cations will move from 2- or 3-fold to higher coordinations in atomic structures. He further argued that stretching a polyhedron to hold a cation slightly larger than ideal might be possible. However, it was unlikely, he argued, that a polyhedron would be stable if cations were smaller than ideal. In nature, the upper limits given for various coordinations are sometimes stretched; the lower ones are rarely violated.

As an example of application of Pauling's first rule, let's take another look at halite. The radii of  $\text{Na}^+$  and  $\text{Cl}^-$  are  $1.10\text{\AA}$  and  $1.72\text{\AA}$ . The radius ratio,  $R_c/R_a$ , is  $1.10/1.72 = 0.64$ . Thus we can expect the cation  $\text{Na}^+$  to be in octahedral (6-fold) coordination, consistent with the model shown in Figure 1a. If  $\text{Na}^+$  is in 6-fold coordination,  $\text{Cl}^-$  must be as well, since the structure contains an equal number of both.

### **Pauling's Second Rule**

Pauling's second rule, sometimes called the *Electrostatic Valency Principle*, says that we can calculate the



**FIGURE 10** Two examples of how geometry can be used to calculate the limits on cation size in different coordinations:  
(a) octahedral coordination  
(additional cations above and below the anion are shown with dashed lines); (b) triangular coordination.

## BOX 2

## Pauling's Rules

**Rule 1. Radius Ratio Principle:** Cation-anion distances are equal to the sum of their effective ionic radii, and cation coordination numbers are determined by the ratio of cation to anion radii.

**Rule 2. Electrostatic Valency Principle:** The strength of an ionic bond is equal to ionic charge divided by coordination number.

**Rule 3.** Sharing of edges or faces by coordinating polyhedra is inherently unstable.

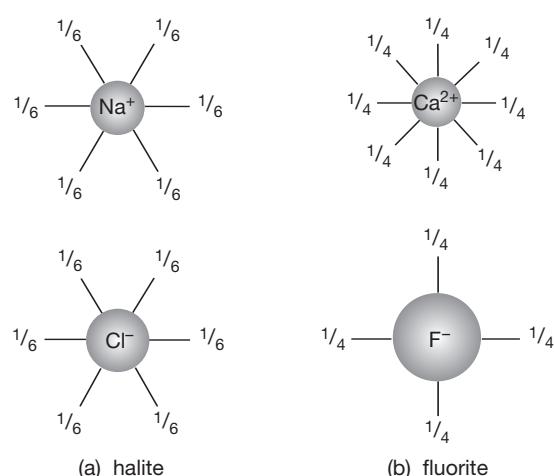
**Rule 4.** Cations of high valence and small coordination number tend not to share anions with other cations.

**Rule 5. Principle of Parsimony:** The number of different components in a crystal tends to be small.

**TABLE 5**  $R_c/R_a$  and Coordination of Cations

$R_c/R_a$	Expected Coordination of Cation	C.N.
<0.15	2-fold coordination	2
0.15	ideal triangular coordination	3
0.15–0.22	triangular coordination	
0.22	ideal tetrahedral coordination	4
0.22–0.41	tetrahedral coordination	
0.41	ideal octahedral coordination	6
0.41–0.73	octahedral coordination	
0.73	ideal cubic coordination	8
0.73–1.0	cubic coordination	
1.0	ideal dodecahedral coordination	12
>1.0	dodecahedral coordination	

strength of a bond (its electrostatic valence) by dividing an ion's valence by its C.N. Consequently, the sum of all bonds to an ion must be equal to the charge on the ion. In halite, six anions bond to each  $\text{Na}^+$  and the strength of each bond is  $\frac{1}{6}$ , total charge/number of bonds (Figure 11a). The strength of each bond around  $\text{Cl}^-$  is  $\frac{1}{6}$  as well. Six bonds of charge  $\frac{1}{6}$  add up to 1, the charge on each ion.



**FIGURE 11** Pauling's second rule: (a) bond strengths in halite ( $\text{NaCl}$ ); (b) bond strengths in fluorite ( $\text{CaF}_2$ ).

We can use Pauling's first two rules to analyze a more complicated mineral, fluorite ( $\text{CaF}_2$ ), in which Ca-F bonds are the only bonds present (Figure 11b). The radii of  $\text{Ca}^{2+}$  and  $\text{F}^-$  are  $1.12\text{\AA}$  and  $1.31\text{\AA}$ .  $R_c/R_a$  is 0.85 and, as predicted by Rule 1,  $\text{Ca}^{2+}$  is in 8-fold (cubic) coordination (Table 5). Each bond has a strength of  $\frac{2}{8}$  (total charge  $\div$  number of bonds) =  $\frac{1}{4}$ . Since each  $\text{F}^-$  has a total charge of  $-1$ , it must be bonded to four  $\text{Ca}^{2+}$  to satisfy Rule 2, so  $\text{F}^-$  is in tetrahedral coordination.

Although Pauling's first two rules are useful guides to crystal structures, they have shortcomings. First, ionic radii vary with C.N. and valence, among other things. Sometimes radius-ratio calculations may be ambiguous because they require choosing a C.N. before we may make calculations. Second, bonds in minerals are rarely completely ionic, and ionic radius varies somewhat with the nature of the bond. Third, in cases where  $R_c/R_a$  is near a limiting value, we cannot be certain whether the higher or lower C.N. will prevail. Fourth, some coordination polyhedra, especially for high C.N.s, may be irregular in shape.

Halite and fluorite are relatively simple minerals; they each contain one cation and one anion and, therefore, one kind of bond. Most minerals contain more than two elements and may have many kinds of bonds. Spinel,  $\text{MgAl}_2\text{O}_4$ , contains Mg-O and Al-O bonds. X-ray studies reveal that  $\text{Mg}^{2+}$  is in tetrahedral coordination and  $\text{Al}^{3+}$  is in octahedral coordination. Consequently, the strength of the bonds around  $\text{Mg}^{2+}$  is  $2 \div 4 = \frac{1}{2}$ , and the strength of the bonds around  $\text{Al}^{3+}$  is  $3 \div 6 = \frac{1}{2}$ . Compounds such as spinel, in which all bonds have the same strength, are termed **isodesmic**.

Sulfates such as anhydrite,  $\text{CaSO}_4$ , are examples of **anisodesmic** compounds. In sulfates,  $\text{S}^{6+}$  is in 4-fold coordination with  $\text{O}^{2-}$ . The strength of a sulfur-oxygen (S-O) bond is therefore  $6 \div 4 = 1\frac{1}{2}$ . Because the strength of an S-O bond is greater than half the charge on a coordinating oxygen, oxygen

## BOX 3

## Who Was Linus Pauling?

Linus Carl Pauling was a prolific American chemist and, in his later years, a peace and health activist. His success as a scientist stemmed from his ability to cross traditional discipline boundaries, an uncanny ability to identify key questions, and courage to put forth new, although sometimes incorrect, ideas. Born in Portland, Oregon, on February 28, 1901, Pauling received a B.S. in chemical engineering from Oregon State University in 1922 and a Ph.D. from California Institute of Technology (Cal Tech) in 1925. For several years he was a postdoctoral fellow in Europe, where he worked with such renowned scientists as Niels Bohr, Erwin Schrödinger, and Sir William Henry Bragg. He returned to the United States and began his career as a professor of chemistry at Cal Tech in 1927. In 1963 he left Cal Tech to join the Center for the Study of Democratic Institutions at Santa Barbara, where he spent his time working for world peace. In the late 1960s he worked for a brief period of time at the University of California–Santa Barbara before moving to Stanford University. He died in Big Sur, California, on August 29, 1994, at the age of 93.

Pauling's chemical studies covered many fields, including both organic and inorganic chemistry. One of the first to interpret crystal structures using quantum mechanics, he was also one of the pioneers of X-ray diffraction. His studies of chemical bonding resulted in the publication of his book *The Nature of the Chemical Bond and the Structure of Molecules and Crystals* in 1939. In the 1930s and 1940s, Pauling turned his attention to molecular chemistry, producing significant papers concerning blood, proteins, and sickle cell anemia. In 1954 he was awarded the Nobel Prize in Chemistry "for research into the nature of the chemical bond and its

application to the elucidation of the structure of complex substances." During his later years, Pauling received acclaim for his investigations of vitamin C. His vitamin C studies resulted in many publications including the books *Cancer and Vitamin C* and *Vitamin C and the Common Cold*, published in the 1970s.

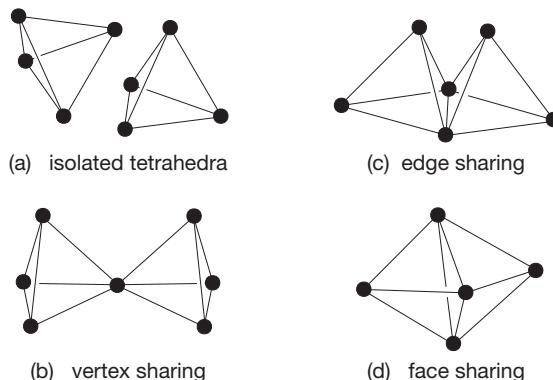
With the advent of nuclear weapons, Pauling became concerned about potential world destruction. In 1958 he published *No More War!*, and during the same year he delivered a petition urging the end of nuclear testing signed by more than 11,000 scientists to the United Nations. In 1962 he was awarded the Nobel Peace Prize, making him one of only a few individuals ever to win two Nobel prizes. During his long career he received many other honors, including the Mineralogical Society of America's Roebling Medal in 1967.



**FIGURE 12** Linus Pauling.

is bonded to  $\text{S}^{6+}$  more tightly than to other cations. Consequently,  $(\text{SO}_4)^{2-}$  complexes are tight units within the crystal structure. All sulfates, carbonates, nitrates, and other anisodesmic compounds have tightly bonded complexes. So, we often think of  $(\text{SO}_4)^{2-}$ ,  $(\text{CO}_3)^{2-}$ , and  $(\text{NO}_3)^-$  as single anionic units within crystals.

Silicate minerals belong to a special group of compounds called **mesodesmic** compounds. If a bond distribution is mesodesmic, cation-anion bond strength equals exactly half the charge on the anion. In silicates,  $\text{Si}^{4+}$  is in tetrahedral coordination and each Si-O bond has a strength of 1, exactly half the charge of  $\text{O}^{2-}$ . Consequently, the oxygen may coordinate to another cation just as strongly as to its coordinating  $\text{Si}^{4+}$ . In some silicates, the "other" cation is another  $\text{Si}^{4+}$ , so two silica tetrahedra may share an oxygen. This is why silica tetrahedra can polymerize to form pairs,



**FIGURE 13** Sharing of oxygen by  $\text{SiO}_4$  tetrahedra:  
 (a) no sharing (isolated); (b) vertex sharing; (c) edge sharing;  
 (d) face sharing. For clarity, the  $\text{Si}^{4+}$  ions at the centers of the tetrahedra have been omitted. Many minerals, including olivine, have isolated silica tetrahedra; (a) In pyroxenes, amphiboles and some other minerals, tetrahedra share one oxygen (b), but edge sharing (c) is less common, and face sharing (d) extremely rare.

chains, sheets, or networks. It also helps explain why many silicate minerals are quite hard.

### **Pauling's Third Rule**

Pauling's third rule is that coordinating polyhedra become less stable when they share edges and are extremely unstable if they share faces. In all crystal structures, anions bond to more than one cation, which holds structures together. Rule 3 states that it is unlikely that two cations will share *two* anions (polyhedral edge) and extremely unlikely that they will share *three* (polyhedral face). Instability results because if polyhedra share edges or faces, cations in the centers of the polyhedra are too close together and will repel. The

instability is especially important for cations of high charge, high C.N., or in cases when  $R_c/R_a$  is near limiting values. Figure 13 shows several ways silica tetrahedra might be associated in an atomic structure. In Figure 13a, tetrahedra do not share any common oxygen. In 13b, pairs of tetrahedra share one oxygen, called a **bridging oxygen**. In Figure 13c, adjacent tetrahedra share an edge (two oxygen). In Figure 13d, they share a face (three oxygen). We can see that as the structure progresses from Figure 13a to 13d,  $\text{Si}^{4+}$  in the centers of the tetrahedra get closer together. Yet the  $\text{Si}^{4+}$  are all positively charged, so we expect them to repel each other. This is the essence of Pauling's third rule. This discussion of Pauling's third rule is focused on tetrahedra. The

**TABLE 6 Ionic Radii and Typical Coordination Number with Oxygen**

Ion	Ionic Radius (Å)	Typical C.N. with Oxygen	Examples in Minerals	
			C.N.	Minerals and Formulas
$\text{K}^+$	1.59–1.68	8–12 (cubic or dodecahedral)	9	nepheline, $(\text{Na},\text{K})\text{AlSiO}_4$ ; orthoclase, $\text{KAlSi}_3\text{O}_8$
			12	leucite, $\text{KAlSi}_2\text{O}_6$ ; muscovite, $\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$
$\text{Na}^+$	1.10–1.24	6–8 (octahedral or cubic)	6	pectolite, $\text{NaCa}_2(\text{SiO}_3)_3\text{H}$ ; albite, $\text{NaAlSi}_3\text{O}_8$
			7	sodalite, $\text{Na}_3\text{Al}_3\text{Si}_3\text{O}_{12}\cdot\text{NaCl}$
			8	nepheline, $(\text{Na},\text{K})\text{AlSiO}_4$
$\text{Ca}^{2+}$	1.08–1.20	6–8 (octahedral or cubic)	6	wollastonite, $\text{CaSiO}_3$ ; pectolite, $\text{NaCa}_2(\text{SiO}_3)_3\text{H}$
			7	plagioclase, $(\text{Ca},\text{Na})(\text{Al},\text{Si})_4\text{O}_8$ ; titanite, $\text{CaTiSiO}_5$
			8	diopside, $\text{CaMgSi}_2\text{O}_6$ ; garnet, $(\text{Mg},\text{Fe},\text{Ca},\text{Mn})_3\text{Al}_2\text{Si}_3\text{O}_{12}$
$\text{Mn}^{2+}$	0.83–1.01	6–8 (octahedral or cubic)	6	rhodonite, $\text{MnSiO}_3$
			8	garnet, $(\text{Mg},\text{Fe},\text{Ca},\text{Mn})_3\text{Al}_2\text{Si}_3\text{O}_{12}$
$\text{Mg}^{2+}$	0.80–0.97	6–8 (octrahedral or cubic)	6	diopside, $\text{CaMgSi}_2\text{O}_6$ ; olivine, $(\text{Mg},\text{Fe})_2\text{SiO}_4$
			8	garnet, $(\text{Mg},\text{Fe},\text{Ca},\text{Mn})_3\text{Al}_2\text{Si}_3\text{O}_{12}$
$\text{Fe}^{2+}$	0.71–0.77	6–8 (octahedral or cubic)	4	staurolite, $\text{Fe}_2\text{Al}_9\text{Si}_4\text{O}_{23}(\text{OH})$
			6	biotite, $\text{K}(\text{Mg},\text{Fe})_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ ; olivine, $(\text{Mg},\text{Fe})_2\text{SiO}_4$
			8	garnet, $(\text{Ca},\text{Mn},\text{Fe},\text{Mg})_3\text{Al}_2\text{Si}_3\text{O}_{12}$
$\text{Ti}^{4+}$	0.69	6 (octahedral)	6	titanite, $\text{CaTiSiO}_5$
$\text{Fe}^{3+}$	0.57–0.68	4–6 (tetrahedral or octahedral)	6	epidote, $\text{Ca}_2(\text{Al},\text{Fe})_3\text{Si}_3\text{O}_{12}(\text{OH})$
$\text{Al}^{3+}$	0.47–0.61	4–6 (tetrahedral or octahedral)	4	muscovite, $\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ ; orthoclase, $\text{KAlSi}_3\text{O}_8$
			5	andalusite, $\text{Al}_2\text{SiO}_5$
			6	muscovite, $\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ ; beryl, $\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$
$\text{Si}^{4+}$	0.34–0.48	4 (tetrahedral)	4	quartz, $\text{SiO}_2$ ; tremolite, $\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$
			6	stishovite, $\text{SiO}_2$
$\text{P}^{5+}$	0.025	4 (tetrahedral)	4	apatite, $\text{Ca}_5(\text{PO}_4)_3(\text{OH},\text{F},\text{Cl})$
$\text{C}^{+4}$	—	3 (triangular)	3	calcite, $\text{CaCO}_3$ ; malachite, $\text{Cu}_2(\text{CO}_3)(\text{OH})_2$

same principles apply to octahedra and other polyhedra, but because they are larger than tetrahedra, sharing of anions is more common.

### **Pauling's Fourth Rule**

Pauling's fourth rule is an extension of his third, stating that small cations with high charges do not share anions easily with other cations. This is another consequence of the fact that highly charged cations will repel each other. For example, all silicate minerals contain  $\text{Si}^{4+}$  tetrahedra. Yet in all the many known silicate minerals, none contains  $(\text{SiO}_4)^{4-}$  polyhedra that shares edges or faces because that would bring  $\text{Si}^{4+}$  cations too close together.

### **Pauling's Fifth Rule**

We call Pauling's last rule the **principle of parsimony**. It states that atomic structures tend to be composed of only a few distinct components. This means that atomic structures tend to be simple and ordered. They normally have few types of bonds and only a few types of cation or anion sites. While a mix of ions on a particular site is possible, the mix is limited and controlled.

## **OXYGEN AND OTHER COMMON ELEMENTS**

Oxygen is the most abundant element in Earth's crust, accounting for about 60 wt %. It is not surprising, then, that  $\text{O}^{2-}$  is the most common anion in minerals. The ionic radius of oxygen varies from about 1.27 Å to 1.34 Å, depending on its C.N. The abundant crustal cations include  $\text{Si}^{4+}$ ,  $\text{Al}^{3+}$ ,  $\text{Fe}^{2+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{Na}^+$ ,  $\text{Ca}^{2+}$ , and  $\text{K}^+$ . Table 6 lists  $R_c/R_a$  values for the common cations and  $\text{O}^{2-}$ . A range of radius values has been considered for each cation because cation radius varies slightly with structure and coordination. The predicted C.N.s in Table 6 are consistent with most known mineral structures. Small cations such as  $\text{C}^{4+}$  and  $\text{B}^{3+}$  can have triangular coordination.  $\text{Si}^{4+}$  is nearly exclusively tetrahedral, while  $\text{Al}^{3+}$  may be either tetrahedral or octahedral. Although radius ratios predict only 6-fold coordination for  $\text{Fe}^{3+}$ , in nature  $\text{Fe}^{3+}$  can be either tetrahedral or octahedral. Other elements can be in octahedral coordination as well. The alkalis and the alkaline earths are the only elements that normally can be in cubic or dodecahedral coordination. When contradictions between nature and Table 6 occur, it is usually for cations in highly irregularly shaped sites. For example, the aluminum in andalusite is in both 5-fold and 6-fold coordination, some magnesium in anthophyllite is

in 7-fold coordination, and the potassium in microcline is in 10-fold coordination. We do not include 5-fold and 7-fold coordination in Tables 5 and 6 because no regular polyhedra have five or seven vertices, so application of Pauling's first rule is problematic.

Sometimes we wish to show cation coordination in a mineral formula. Traditionally, this has been done using superscript Roman numerals. For example, we may write andalusite's formula as  $\text{Al}^{\text{IV}}\text{Al}^{\text{VI}}\text{SiO}_5$  to remind us of the unusual aluminum coordination. We may write magnetite's as  $\text{Fe}^{\text{IV}}\text{Fe}^{\text{VI}}_2\text{O}_4$  to show that iron occupies two differently coordinated sites. Some chemists today use Arabic numerals in square brackets instead of Roman numerals.

## **SILICATE STRUCTURES IN GENERAL**

Here we take another look at silicate structures in light of Pauling's rules and other crystal-chemical principles. Because oxygen and silicon are the two most abundant elements in the Earth's crust, and because the  $(\text{SiO}_4)$  tetrahedron is such a stable complex, silicate minerals are extremely stable and abundant in crustal rocks and sediments. They dominate igneous and metamorphic rocks, as well as many sedimentary rocks. An individual  $\text{SiO}_4$  tetrahedron has a charge of -4. Because minerals must be charge balanced, silicon tetrahedra must share oxygen ions, or must be bonded to other cations. The sharing of oxygen between tetrahedra is a form of **polymerization**. Quartz and tridymite ( $\text{SiO}_2$ ), for example, are highly **polymerized**. In most of the  $\text{SiO}_2$  minerals, two  $(\text{SiO}_4)^{4-}$  tetrahedra share each oxygen atom. The strength of each Si-O bond is 1; each  $\text{Si}^{4+}$  bonds to four oxygen, and each  $\text{O}^{2-}$  to two silicon, so charge balance is maintained and the overall formula is  $\text{SiO}_2$ .

Polymerization is absent in some silicates, such as olivine,  $(\text{Mg},\text{Fe})_2\text{SiO}_4$ . Instead, cations link individual silica tetrahedra. In many silicates, a combination of oxygen sharing between silicon tetrahedra, and the presence of additional cations leads to charge balance. The more oxygen sharing, the fewer additional cations needed. In still other silicates,  $\text{Al}^{3+}$  replaces some tetrahedral  $\text{Si}^{4+}$ . Consequently, more additional cations must be present to maintain charge balance. In albite, for example,  $\text{Al}^{3+}$  replaces one-fourth of the tetrahedral  $\text{Si}^{4+}$ .  $\text{Na}^+$  ions between tetrahedra maintain charge balance. Albite's formula is  $\text{NaAlSi}_3\text{O}_8$ , which we may write  $\text{Na}(\text{AlSi}_3)\text{O}_8$  to emphasize that both  $\text{Al}^{3+}$  and  $\text{Si}^{4+}$

occupy the same structural sites. In anorthite, another feldspar, Al<sup>3+</sup> replaces half the Si<sup>4+</sup>, resulting in the formula Ca(Al<sub>2</sub>Si<sub>2</sub>)O<sub>8</sub>. Besides feldspars, tetrahedral aluminum is common in micas, amphiboles, and, to a lesser extent, in pyroxenes.

The orderly way silica (or alumina) tetrahedra polymerize leads naturally to the division of silicate minerals into the subclasses shown in Table 7. We call silicates such as olivine, in which tetrahedra share no O<sup>2-</sup>, **isolated tetrahedral silicates** (also called **nesosilicates** or **orthosilicates**). Silicates in which pairs of tetrahedra share oxygen are **paired tetrahedral silicates (sorosilicates)**. If two oxygen on each tetrahedron link to other tetrahedra, we get **single-chain silicates (inosilicates)** or **ring silicates (cyclosilicates)**. If some oxygen are shared between two tetrahedra, and some between three, we get **double-chain silicates** (also considered inosilicates). If three oxygen on each tetrahedron link to other tetrahedra to form tetrahedral planes, we get **sheet silicates** (also called **layer silicates** or **phyllosilicates**), and if all oxygen are shared between tetrahedra we get **framework silicates** (also called **network silicates** or **tectosilicates**). The ratio of Si:O, then, indicates silicate subclass because different ratios result from different amounts of oxygen sharing (Table 7). In minerals containing tetrahedral aluminum, the ratio of (Al<sup>IV+</sup>:Si<sup>IV</sup>):O, which we can abbreviate T:O, reflects the silicate subclass. If the only tetrahedral cation is silicon, isolated tetrahedral silicates are often characterized by SiO<sub>4</sub> in their formulas, paired tetrahedral silicates by Si<sub>2</sub>O<sub>7</sub>, single-chain silicates by SiO<sub>3</sub> or Si<sub>2</sub>O<sub>6</sub>, ring silicates by Si<sub>6</sub>O<sub>18</sub>, double-chain silicates by Si<sub>4</sub>O<sub>11</sub>, sheet silicates by Si<sub>2</sub>O<sub>5</sub> or Si<sub>4</sub>O<sub>10</sub>, and framework silicates by SiO<sub>2</sub>.

The chemistries of silicates correlate, in a general way, with the subclass to which they belong (Table 7). This correlation reflects silicon:oxygen ratios, and it also reflects the way in which silica polymerization controls atomic structures. There are many variables, but we can make some generalizations. Isolated tetrahedral silicates and chain silicates include minerals rich in Fe<sup>2+</sup> and Mg<sup>2+</sup>, but framework silicates do not. The three-dimensional polymerization of framework silicates generally lacks sufficient anionic charge and the small crystallographic sites necessary for small highly charged cations. For opposite reasons, Na<sup>+</sup> and K<sup>+</sup> enjoy highly polymerized structures, which have large sites that easily accommodate monovalent cations.

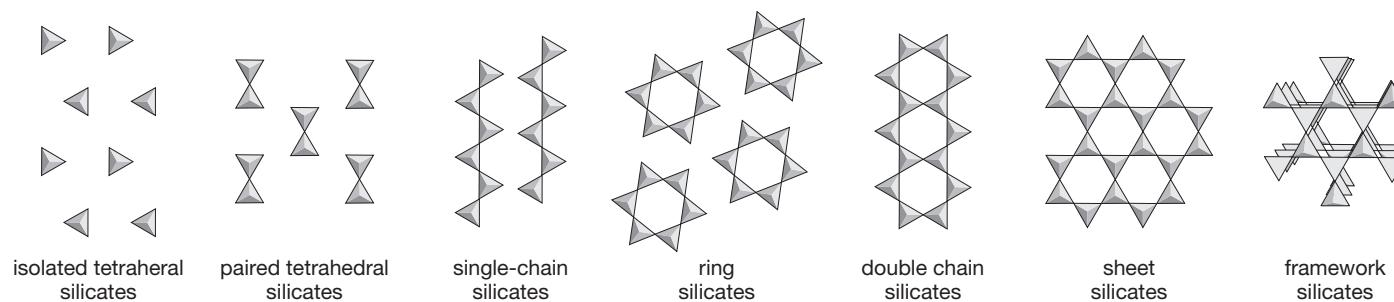
Bowen's reaction series compares the melting temperatures of most common igneous minerals. Quartz has the lowest melting temperature, K-feldspar the second lowest, followed by muscovite, biotite, amphiboles, pyroxenes, and finally olivine. Bowen's reaction series is based on melting temperatures determined by laboratory experiments, but it mirrors the degree to which silicate minerals are polymerized (which is also a reflection of how much silica they contain). Quartz, feldspars, and other framework silicates are highly polymerized, and they melt at the lowest temperatures. Muscovite, biotite, and other sheet silicates are less polymerized, and melt at higher temperatures. Amphiboles (double chain silicates) and pyroxenes (single chain silicates) are still less polymerized, and melt at even higher temperatures. Olivine and other isolated tetrahedral silicates are not polymerized at all, and melt at the highest temperatures. Why does the polymerization affect melting temperatures? The answer lies not so much with the nature of the minerals, but with the nature of the melt they create. Magmas, just like minerals, become polymerized when silicon and oxygen form complexes in the melt. Magmas richest in silicon and oxygen are more polymerized, and have lower Gibbs free energy. In a sense, magmas that are highly polymerized form at lower temperatures than those that are less polymerized because fewer bonds need to be broken to create the melt. So, silica-rich magmas, and silica-rich minerals, melt at lower temperatures than those that are silica-poor.

The order in which silicate minerals weather is opposite the order in which they melt. Those minerals that melt at lowest temperature are most resistant to weathering. This phenomenon, too, is partly a result of the amount of silica in the different silicate minerals. Minerals rich in silica are more tightly bonded (and thus more resistant to weathering) because they contain more (SiO<sub>4</sub>)<sup>4-</sup> complexes and because the valence of ionic bonds is generally greater than in minerals poorer in silica. Because of stronger bonds, they are less easily attacked by water and other weathering agents.

Silicate crystal structures may be complex. Many silicates contain anions or anionic groups other than O<sup>2-</sup>. Muscovite, for example, contains (OH)<sup>-</sup> and has the formula KAl<sub>2</sub>(AlSi<sub>3</sub>O<sub>10</sub>)(OH)<sub>2</sub>. Other silicates, such as kyanite, and titanite, CaTi(SiO<sub>4</sub>)O, contain O<sup>2-</sup> ions unassociated with the (SiO<sub>4</sub>)<sup>4-</sup> tetrahedra. In muscovite and many other minerals, aluminum is in both tetrahedral and octahedral coordination. Still other silicates do not fit neatly into a subclass. Zoisite, Ca<sub>2</sub>Al<sub>3</sub>O(SiO<sub>4</sub>)(Si<sub>2</sub>O<sub>7</sub>)(OH), contains both isolated tetrahedra and paired tetrahedra. Some mineralogy texts and reference books separate elements and

**TABLE 7** Silicate Structures

Silicate Subclass	Example Minerals	Mineral Formula	Cation Coordination	Si:O or (Si,Al <sup>IV</sup> ):O	Number of Oxygen Shared by Tetrahedra
isolated tetrahedral silicates	olivine almandine	(Mg,Fe) <sub>2</sub> SiO <sub>4</sub> Fe <sub>3</sub> Al <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>	Fe <sup>VI</sup> ,Mg <sup>VI</sup> , Si <sup>IV</sup> Fe <sup>VIII</sup> ,Al <sup>VI</sup> , Si <sup>IV</sup> Si <sup>IV</sup>	1:4	0
paired tetrahedral silicates	lawsonite åkermanite	CaAl <sub>2</sub> (Si <sub>2</sub> O <sub>7</sub> )(OH) <sub>2</sub> · H <sub>2</sub> O Ca <sub>2</sub> MgSi <sub>2</sub> O <sub>7</sub>	Ca <sup>VIII</sup> ,Al <sup>VI</sup> , Si <sup>IV</sup> Ca <sup>VIII</sup> ,Mg <sup>IV</sup> ,Si <sup>IV</sup>	2:7 (1:3.5)	1
single-chain silicates	diopside wollastonite	CaMgSi <sub>2</sub> O <sub>6</sub> CaSiO <sub>3</sub>	Ca <sup>VIII</sup> ,Mg <sup>VI</sup> ,Si <sup>IV</sup> Ca <sup>VI</sup> ,Si <sup>IV</sup>	2:6 or 1:3	2
ring silicates	tourmaline beryl	(Na,Ca)(Fe,Mg,Al,Li) <sub>3</sub> Al <sub>6</sub> (BO <sub>3</sub> ) <sub>3</sub> Si <sub>6</sub> O <sub>18</sub> (OH) <sub>4</sub> Be <sub>3</sub> Al <sub>2</sub> Si <sub>6</sub> O <sub>18</sub>	Na <sup>VI</sup> ,Ca <sup>VI</sup> ,Li <sup>VI</sup> ,Fe <sup>VI</sup> ,Mg <sup>VI</sup> ,Al <sup>VI</sup> ,B <sup>III</sup> ,Si <sup>IV</sup> Be <sup>IV</sup> ,Al <sup>VI</sup> ,Si <sup>IV</sup>	1:3	2
double-chain silicates	anthophyllite tremolite	(Mg,Fe) <sub>7</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub> Ca <sub>2</sub> Mg <sub>5</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	Mg <sup>VI-VII</sup> ,Si <sup>IV</sup> Ca <sup>VIII</sup> ,Mg <sup>VI</sup> ,Si <sup>IV</sup>	4:11 (1:2.75)	2 or 3
sheet silicates	talc phlogopite kaolinite	Mg <sub>3</sub> Si <sub>4</sub> O <sub>10</sub> OH <sub>2</sub> KMg <sub>3</sub> (AlSi <sub>3</sub> O <sub>10</sub> )(OH) <sub>2</sub> Al <sub>2</sub> Si <sub>2</sub> O <sub>5</sub> (OH) <sub>4</sub>	Mg <sup>VI</sup> ,Si <sup>IV</sup> K <sup>VI</sup> ,Mg <sup>VI</sup> ,Al <sup>IV</sup> ,Si <sup>IV</sup>	4:10 (1:2.5)	3
framework silicates	quartz microcline	SiO <sub>2</sub> KAlSi <sub>3</sub> O <sub>8</sub>	Si <sup>IV</sup> K <sup>X</sup> ,Al <sup>IV</sup> ,Si <sup>IV</sup>	1:2	4



include extra parentheses in mineral formulas (as has been done in this paragraph) to emphasize the nature of the atomic arrangement, but often we omit such niceties for brevity. In shorter form, we can write muscovite's formula as  $KAl_3Si_3O_{10}(OH)_2$ ; kyanite's becomes  $Al_2SiO_5$ ; titanite's becomes  $CaTiSiO_5$ ; and zoisite's becomes  $Ca_2Al_3Si_3O_{12}(OH)$ . While being shorter and, perhaps, easier to write, these formulas give little hint of crystal structure.

## ELEMENTAL SUBSTITUTIONS IN SILICATES

While quartz is usually  $>99.9\% SiO_2$ , most minerals have variable chemistries due to elemental substitutions. Consistent with Pauling's rules, the nature and extent of substitutions depend primarily on ionic size and charge and on the nature of atomic bonding in a mineral's structure. Because silicate minerals are dominantly ionic, the nature of bonding is relatively constant; size and ionic charge control most substitutions. Figure 2 shows the relative sizes and charges of the most common elements in silicate minerals. Elements of similar size and charge may occupy similar sites in crystal structures without causing distortion or charge imbalance. For example,  $Ca^{2+}$ ,  $Mn^{2+}$ ,  $Fe^{2+}$ , and  $Mg^{2+}$  substitute for each other in many silicates (and other minerals), including garnets and pyroxenes.

The extent to which elements may substitute for each other is often limited. Natural garnets may have any composition described by the formula  $(Ca, Mn, Fe, Mg)_3Al_2Si_3O_{12}$ . In contrast, the substitution of  $Ca^{2+}$  for  $Mn^{2+}$ ,  $Fe^{2+}$ , or  $Mg^{2+}$  in pyroxene is limited at all but the highest temperatures, due to the large size of  $Ca^{2+}$  compared with the other ions. Consequently, there is a miscibility gap between orthopyroxene and clinopyroxene, and a similar gap exists in the Ca-Mn-Fe-Mg carbonate system.

Similarity in size and charge allows  $K^+$  and  $Na^+$  to substitute for each other in feldspars, amphiboles, and other minerals.  $Fe^{3+}$  and  $Al^{3+}$  replace each other in minerals such as garnet and spinel. These are both examples of **simple substitutions**. In a simple substitution the substituting ion has the same charge as the one it replaces. Sometimes simple substitutions are described using equations such as  $Fe^{2+} = Mg^{2+}$  or  $Fe^{3+} = Al^{3+}$ . Other elemental substitutions are more complex. For example,  $Ca^{2+}$  may replace  $Na^+$  in feldspar. To maintain charge balance,  $Al^{3+}$  replaces  $Si^{4+}$  at the same time, and we describe the **coupled substitution** as  $Ca^{2+}Al^{3+} = Na^+Si^{4+}$  or

just  $CaAl = NaSi$ . No common substitutions involve ions with charge difference greater than 1.

Anions, too, may substitute for each other in minerals. In some micas and amphiboles, for example,  $F^-$  or  $Cl^-$  may replace  $(OH)^-$ . More complex substitutions in micas involve the replacement of  $(OH)^-$  by  $O^{2-}$ , which requires some compensatory substitution to maintain charge balance. In scapolite and a few other minerals,  $(CO_3)^{2-}$  or  $(SO_4)^{2-}$  may replace  $Cl^-$ . To add further complexity, in some minerals substitutions involve vacancies. For example, in hornblende,  $\square Si = KAl$  is a common substitution. The  $\square$  symbol indicates a vacancy. Some of the more common and most important elemental substitutions are tabulated in Table 8.

While the elemental substitutions listed in Table 8 occur in many minerals, including many nonsilicates, they do not necessarily occur in all. For example, there is only very minor substitution of  $Fe^{3+}$  for  $Al^{3+}$  in corundum, even though complete solid solution exists between andradite ( $Ca_3Fe_2Si_3O_{12}$ ) and grossular ( $Ca_3Al_2Si_3O_{12}$ ). Similarly, periclase is always close to end member  $MgO$ , rarely forming significant solid solution with  $FeO$  or with  $MnO$ . Nonetheless, the substitutions listed in Table 8 are common, occur in more than one mineral class, and explain most of the mineral end members. Elemental substitutions, including the nature and extent of solvi, are about the same in pyroxenes, amphiboles, and

**TABLE 8** Some Typical Elemental Substitutions in Silicates

Substitution	Example Minerals
$Na^+ = K^+ = Li^+$	alkali feldspar, hornblende, micas
$Ca^{2+} = Mg^{2+} = Fe^{2+} = Mn^{2+}$	pyroxene, amphiboles, micas, garnet, carbonates
$F^- = Cl^- = OH^-$	amphiboles, micas, apatite
$Fe^{3+} = Al^{3+}$	garnet, spinels
$Ca^{2+}Al^{3+} = Na^+Si^{4+}$	plagioclase, hornblende
$\square Si^{4+} = K^+Al^{3+}$	hornblende
$O^{2-} = (OH)^-$	biotite, titanite

carbonates. Major substitutions for both are  $\text{Ca}^{+2} = \text{Mg}^{+2} = \text{Fe}^{2+} = \text{Mn}^{2+}$ .

## STRUCTURES OF THE BASIC SILICATE SUBCLASSES

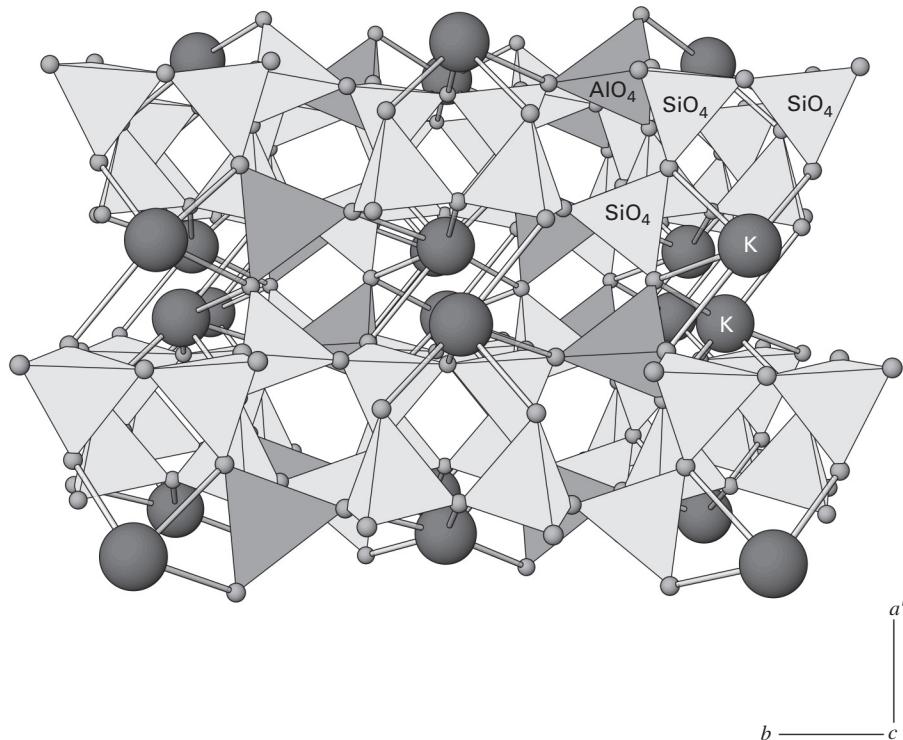
### Framework Silicates

Framework silicates consist of a three-dimensional polymerized network of Si or (Al,Si) tetrahedra. Quartz is the most common framework silicate. In quartz and the other  $\text{SiO}_2$  polymorphs (except stishovite), oxygen links each silicon tetrahedron to four others. Each  $\text{SiO}_2$  polymorph has a different arrangement of tetrahedra; some contain 4-, 6-, or 8-membered loops, and some contain channels. In some framework silicates, Al replaces some Si. Three-dimensional polymerization leaves large holes, cages, loops, or channels that can hold large cations such as  $\text{K}^+$ ,  $\text{Na}^+$ , or  $\text{Ca}^{2+}$ . Figure 14 shows such a mineral, orthoclase. In orthoclase and other feldspars, the sites occupied by  $\text{K}^+$ ,  $\text{Na}^+$ , or  $\text{Ca}^{2+}$  are distorted; coordination is 6 to 9, depending on the feldspar. In other framework silicates, including some feldspathoids (for example, analcime) and zeolites, the openings between silica tetrahedra are large enough to hold molecular water. Framework silicates are often twinned. Quartz is typically

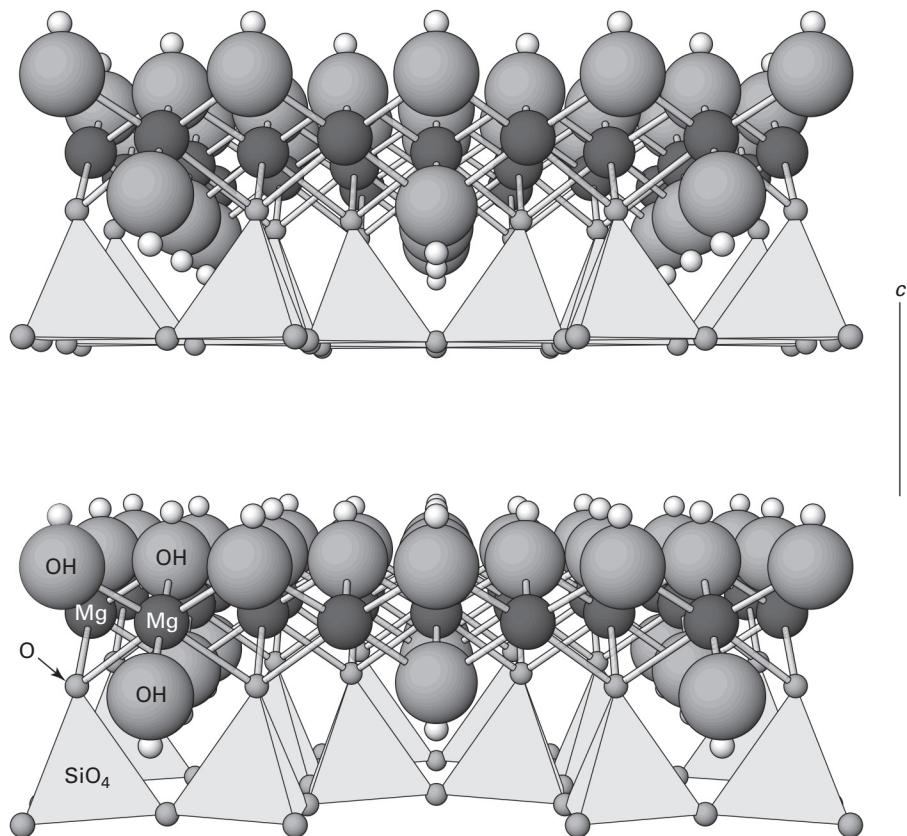
twinned according to the **Dauphiné** or **Brazil** laws, although we cannot normally see the twins with the naked eye. Feldspars and other framework silicates twin by many different laws.

### Sheet Silicates

In sheet silicates, sheet-like tetrahedral and octahedral layers combine to produce a planar structure. The tetrahedral layers are stacked with other layers containing octahedrally coordinated cations, and sometimes with layers containing alkalis. We call the octahedral layers **gibbsite layers** if they contain  $\text{Al}^{3+}$  and **brucite layers** if they contain  $\text{Mg}^{2+}$  or  $\text{Fe}^{2+}$  because the structures of the layers resemble these minerals. Some sheet silicates contain three divalent octahedral cations for every four tetrahedra; others contain two trivalent octahedral cations instead. So, we call muscovite,  $\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ , and other aluminous sheet silicates **dioctahedral**. Biotite,  $\text{K}(\text{Mg},\text{Fe})_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ , and other Mg-Fe sheet silicates are **trioctahedral**. Figure 15 shows the atomic structure of serpentine, a dioctahedral sheet silicate. Units composed of one tetrahedral layer and one dioctahedral layer stack on top of each other but are slightly offset.



**FIGURE 14** Atomic arrangement in orthoclase: The large spheres represent  $\text{K}^+$ ; the tetrahedra are  $(\text{AlO}_4)^{5-}$  and  $(\text{SiO}_4)^{4-}$  groups. This view is down the  $c$ -axis.



**FIGURE 15** Atomic arrangement in serpentine: The tetrahedra are  $(\text{SiO}_4)^{4-}$ ; the spheres represent  $\text{O}^{2-}$ ,  $\text{OH}^-$ , and  $\text{Mg}^{2+}$ . The orientation of the  $c$ -axis is shown.

Tetrahedral (T) and octahedral (O) layers may stack in various ways. In kaolinite and serpentine they alternate. In pyrophyllite, talc, and micas, tetrahedral layers surround octahedral layers to produce T-O-T sandwiches.  $\text{K}^+$ , and more rarely  $\text{Na}^+$  or  $\text{Ca}^{2+}$ , occupy sites between the sandwiches in micas. In chlorites (Figure 16), additional octahedral layers separate the sandwiches, and in other sheet silicates the stacking may be more complex. Clay minerals, in particular, have complex layered structures involving interlayer  $\text{H}_2\text{O}$ . Micas have several different polymorphs, which are related by the way in which octahedral and tetrahedral layers are stacked with respect to each other. They also commonly twin, but the subtle distinctions between polymorphs and the twinning are difficult to detect without detailed X-ray or transmission electron microscope studies.

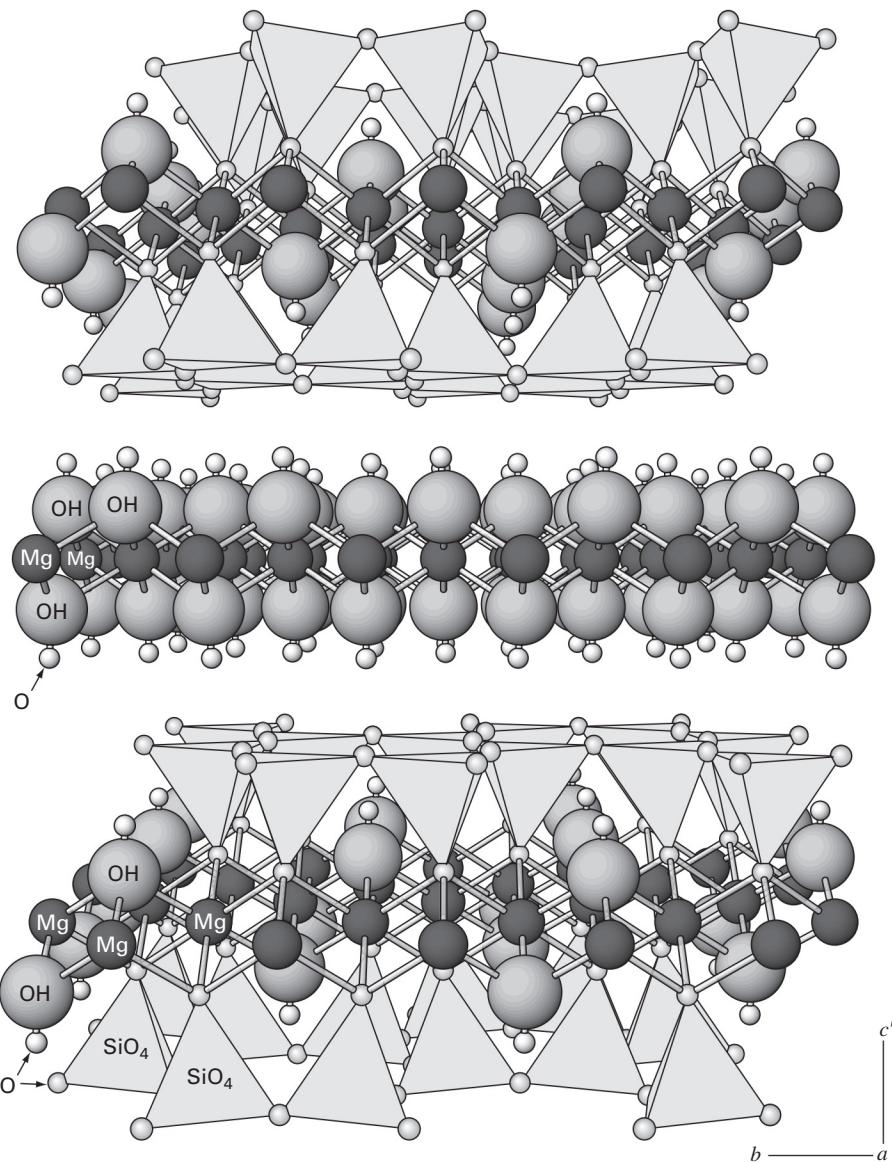
### Chain Silicates

The chain silicates, including the single-chain silicates (pyroxenes and pyroxenoids) and the double-chain silicates (amphiboles), all have similar structures based on chains of silica tetrahedra. The chains, which run parallel to the  $c$  axis, alternate

with bands of octahedrally coordinated cations (Figure 17). Tetrahedra in adjacent chains point in opposite directions. Two or three oxygen in each tetrahedron are shared with adjacent tetrahedra. The other two provide links to the octahedral cations. In pyroxenes and pyroxenoids, four octahedral sites are found between pairs of chains. Seven octahedral sites characterize amphiboles. In both pyroxenes and amphiboles, two octahedral sites are larger than the others and may contain  $\text{Ca}^{2+}$  or  $\text{Na}^+$ . Any of the octahedral sites may contain  $\text{Mg}^{2+}$  or  $\text{Fe}^{2+}$ , and some may contain  $\text{Al}^{3+}$ .  $\text{K}^+$  is present in a large interlayer site in hornblende and some other amphiboles. Twinning, both simple and complex, is common in many pyroxenes and amphiboles.

### Ring Silicates

Tourmaline is the only common mineral in which all tetrahedra are linked to form independent rings (Figure 18). Other minerals, including beryl,  $\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$ , and cordierite,  $(\text{Mg},\text{Fe})_2\text{Al}_4\text{Si}_5\text{O}_{18}$ , contain rings, but they also contain tetrahedra joined in other ways. In tourmaline, 6-membered tetrahedral rings are connected to octahedral  $\text{Fe}^{2+}$ ,



**FIGURE 16** Atomic arrangement in chlorite: The tetrahedra are  $(\text{SiO}_4)^4-$ ; the spheres represent  $\text{O}^{2-}$ ,  $\text{OH}^-$ , and  $\text{Mg}^{2+}$ . This drawing shows two “talc” layers with a “brucite” layer between. This view is down the  $a$ -axis.

$\text{Mg}^{2+}$ , or  $\text{Al}^{3+}$ , and to triangular  $(\text{BO}_3)^-$  groups.  $\text{Ca}^{2+}$ ,  $\text{Na}^+$ , and  $\text{K}^+$  occupy large sites centered in the tetrahedral rings and coordinated to the borate groups and silica tetrahedra.

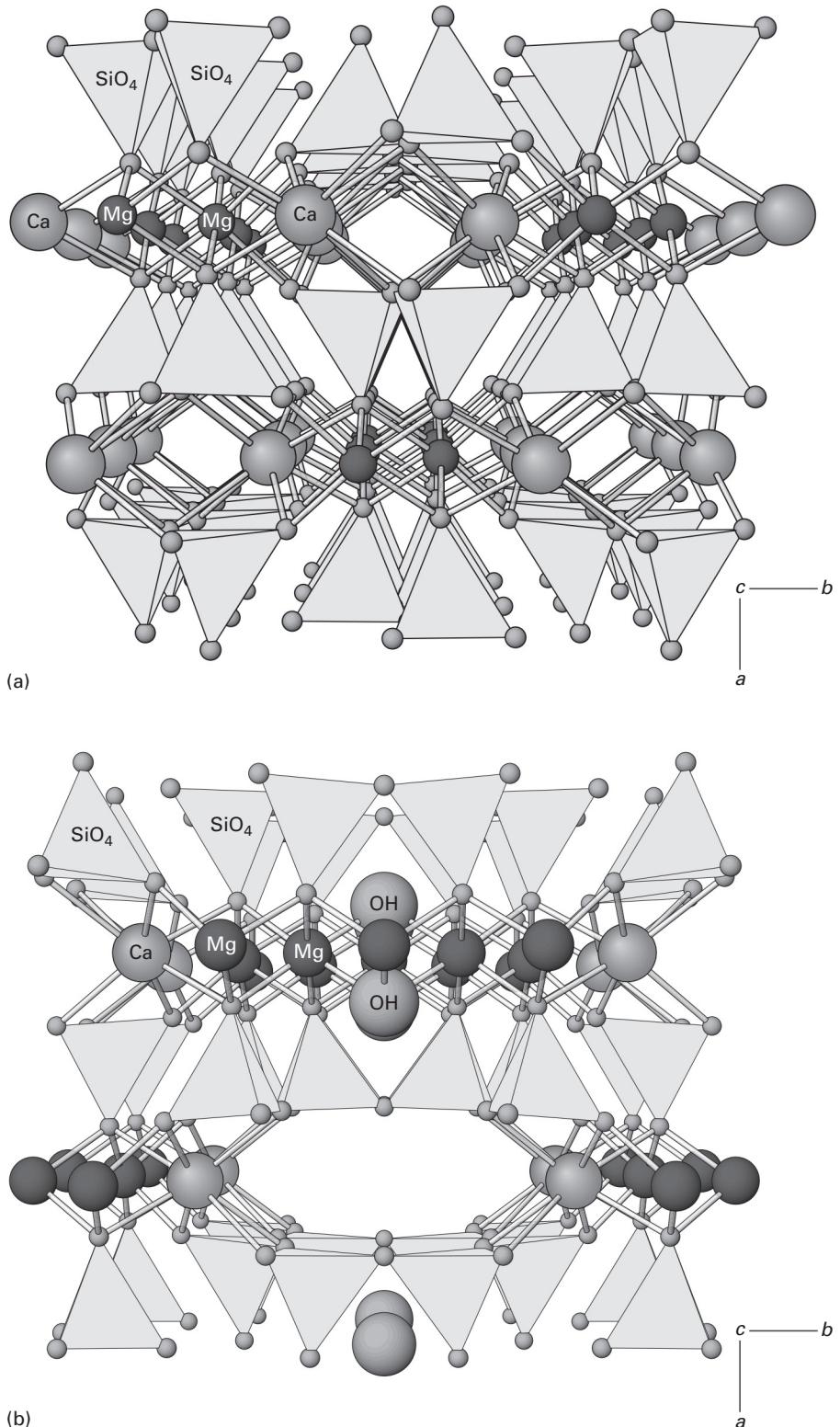
### Paired Tetrahedral Silicates

Lawsonite, a rare mineral found in blueschists, and the melilites åkermanite and gehlenite (also rare) are perhaps the best examples of paired tetrahedral silicates (Figure 19). The paired silicon tetrahedra result in  $\text{Si}_2\text{O}_7$  groups. Other minerals contain some paired and some unpaired tetrahedra. Vesuvianite and epidote, for example, contain both  $\text{SiO}_4$  and  $\text{Si}_2\text{O}_7$  groups and are often grouped with lawsonite and the melilites. In lawsonite,  $\text{Al}^{3+}$  links pairs of silica tetrahedra. In vesuvianite and

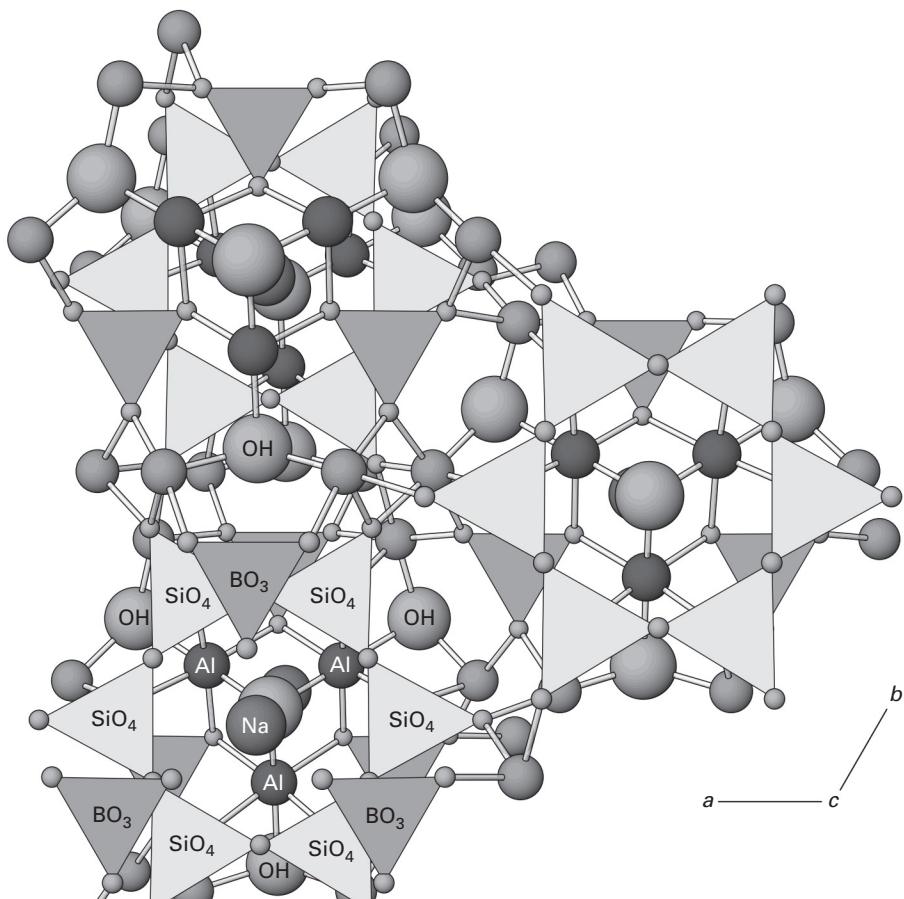
the melilites, octahedral  $\text{Al}^{3+}$ ,  $\text{Fe}^{2+}$ , or  $\text{Mg}^{2+}$  links tetrahedral groups, and  $\text{Ca}^{2+}$  occupies large sites between layers of octahedra.

### Isolated Tetrahedral Silicates

Mineralogists often call isolated tetrahedral silicates **island silicates** because tetrahedra do not share oxygen. Olivine,  $(\text{Mg}, \text{Fe})_2\text{SiO}_4$ , and garnet,  $(\text{Ca}, \text{Mn}, \text{Fe}, \text{Mg})_3\text{Al}_2\text{Si}_3\text{O}_{12}$ , are examples. In olivine, divalent octahedral cations occupying two slightly different sites link independent silica tetrahedra (Figure 20). The larger site contains  $\text{Ca}^{2+}$  in monticellite,  $\text{CaMgSiO}_4$ , which may be considered a calcic olivine. In the garnet structure, isolated tetrahedra share oxygen with two kinds of cationic sites: an octahedral site and a



**FIGURE 17** Atomic arrangement in (a) diopside (pyroxene) and (b) tremolite (amphibole). The tetrahedra are  $(\text{SiO}_4)^{4-}$  with small spheres at the corners. The larger spheres represent  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ , and  $(\text{OH})^-$  in tremolite. Both views are down the *c*-axis, so we are looking down the chains of tetrahedra.



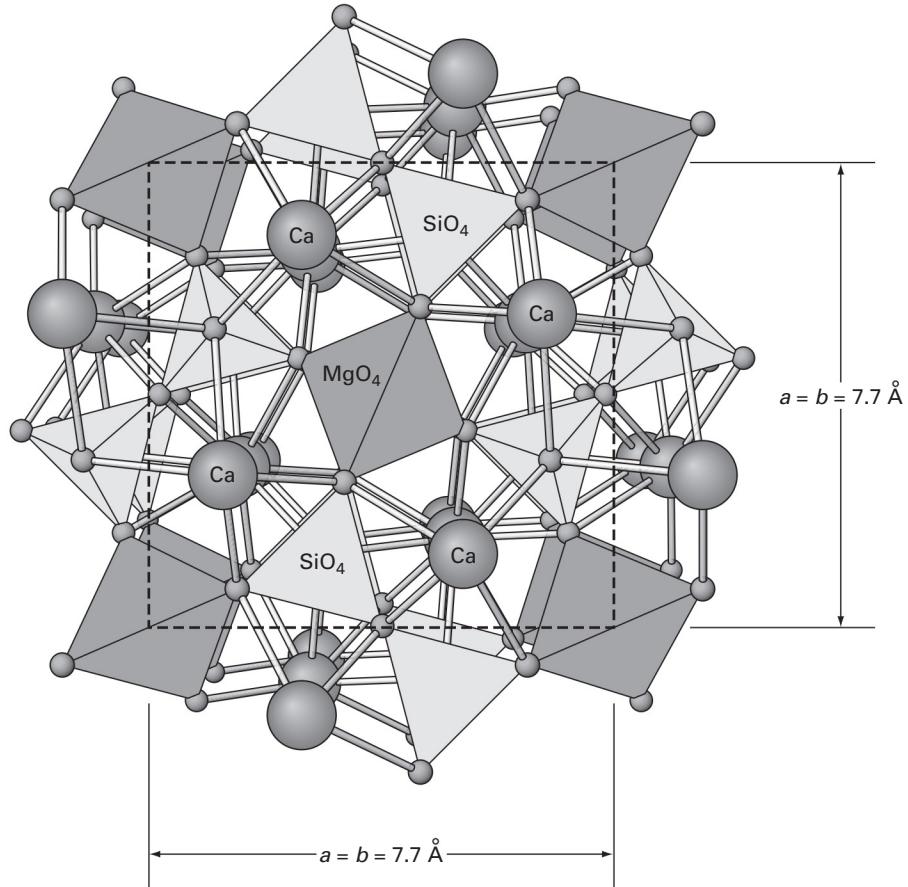
**FIGURE 18** Atomic arrangement in tourmaline: The smallest spheres are O<sup>2-</sup>. The largest spheres are OH<sup>-</sup> and Na<sup>+</sup> (or Ca<sup>2+</sup>). The medium-sized spheres are Al<sup>3+</sup> (or Li<sup>+</sup>, Fe<sup>2+</sup>, Mg<sup>2+</sup>). This view is looking down the c-axis.

highly distorted site with 8-fold coordination. The octahedral site usually contains Ca<sup>2+</sup>, Mg<sup>2+</sup>, or Fe<sup>2+</sup>.

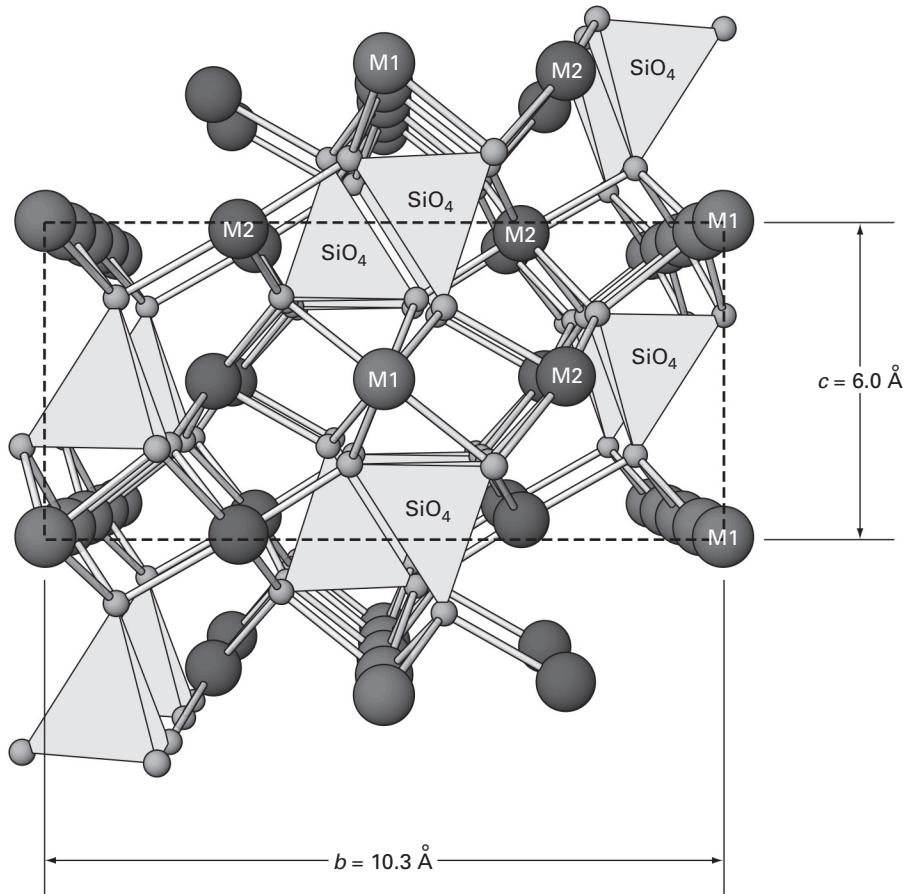
## STRUCTURES AND CHEMISTRY OF NONSILICATES

Having discussed silicate structures, we could go on and discuss other mineral groups. However, unless we wanted to go into great detail, such a discussion would not be particularly fruitful, for several reasons. First, in our preceding discussion of silicate structures, we ignored or glossed over some complications that become apparent when we examine the finer details of crystal structures. Second, because silicate structures are largely ionic, they are simpler and more regular than those of most other mineral groups. Third, for many mineral groups we cannot

make meaningful generalizations or categorize structures in a useful way. For example, the sulfide minerals involve structures that are covalent or metallic, or both. Sulfur may have any of a number of valences, and sulfide structures involve many different coordination polyhedra, layers, clusters, and other complex structural units. Generalizations made about structure types will inevitably be too detailed or not detailed enough for different purposes. Instead of worrying about the details of structure and chemistry of all mineral groups, we note that the same principles that apply to silicates also apply to other minerals. To find the details, we must go to mineralogical literature. Some excellent references are the five-volume series *Rock Forming Minerals* by Deer, Howie, and Zussman (Longman, 1972–1977) and the *Reviews in Mineralogy* series (Mineralogical Society of America, 1974–2009).



**FIGURE 19** Atomic arrangement in åkermanite,  $\text{Ca}_2\text{MgSi}_2\text{O}_7$ , a rare mineral that is a member of the melilite group. The tetrahedra are  $(\text{SiO}_4)^{4-}$  and  $(\text{MgO}_4)^{6-}$ . The  $(\text{MgO}_4)^{6-}$  do not look like tetrahedra because they are viewed edge-on. The spheres are  $\text{Ca}^{2+}$ . Melilites are tetragonal; the dashed lines outline a unit cell.



**FIGURE 20** Atomic arrangement in forsterite,  $\text{Mg}_2\text{SiO}_4$ : The tetrahedra are  $(\text{SiO}_4)^{4-}$  and the larger spheres are  $\text{Mg}^{2+}$  in two sites (M1 and M2). Forsterite and other olivines are orthorhombic; the dashed lines outline a unit cell.

## Questions for Thought

Some of the following questions have no specific correct answers; they are intended to promote thought and discussion.

1. Crystals are not all ionic, but we have concentrated on ionic crystals in this text. Why?
2. What are the factors that control the ability of an element to substitute for another one in a mineral?
3.  $\text{Ca}^{2+}$  and  $\text{Fe}^{2+}$  mix freely in garnet, so we have solid solutions between grossular ( $\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ ) and almandine ( $\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ ). On the other hand,  $\text{Ca}^{2+}$  and  $\text{Fe}^{2+}$  do not mix freely in carbonates. Only limited solid solution is possible between calcite ( $\text{CaCO}_3$ ) and siderite ( $\text{FeCO}_3$ ), and an intermediate compound called *ankerite* is stable. What is ankerite? Why is there only limited substitution of  $\text{Ca}^{2+}$  for  $\text{Fe}^{2+}$  in carbonates?
4. Silicate complexes,  $(\text{SiO}_4)^{4-}$ , polymerize to form chains, sheets, or networks. Carbonate complexes,  $(\text{CO}_3)^{2-}$ , do not. Why?
5. Why are silicates, especially alkali aluminosilicates, so abundant in the Earth's crust?
6. We divide silicates into subgroups, such as sheet silicates, based on the way silica tetrahedra polymerize. Can all silicates be classified unambiguously into one of the groups?
7. Titanium can be found in biotite, amphibole, and a few other common minerals, but typically most of the titanium in rocks is in titanium-rich minerals such as ilmenite ( $\text{FeTiO}_3$ ) or rutile ( $\text{TiO}_2$ ). Why?
8. Consider the crystal structures of pyroxenes. Why do many mineralogists prefer to write the formula of enstatite as  $\text{Mg}_2\text{Si}_2\text{O}_6$  rather than  $\text{MgSiO}_3$ ?

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# Descriptions of Minerals

Geologists and mineralogists have described more than 3,000 minerals; most are exceedingly rare, so it is unnecessary and impractical to try to describe them all in this text. The most common minerals are listed here, as well as those of the greatest economic importance. Other species are listed if they have unique structures or chemistries, or demonstrate principles or properties not well represented by the common or economic minerals. Still others are included if they are useful indicators of geological environments and processes or if they can be used for practical purposes, such as age determinations. There are descriptions of about 200 minerals, which is more than sufficient for most purposes. Intended for students of mineralogy, emphasis has been placed on those properties that best aid in practical mineral identification: hand specimen characteristics and, to a lesser extent, occurrences, associations, and optical properties. The mineral descriptions contain only brief discussions of atomic structure and crystal chemistry.

The descriptions are arranged in order based on a classification scheme. A brief tabulation of mineral species introduces each of the classes, subclasses, or groups listed in bold type below.

## I. Silicate Class

Framework silicate subclass  
silica group  
feldspar group  
feldspathoid group  
scapolite series  
zeolite group  
other framework silicates

Sheet silicate subclass  
serpentine group  
clay mineral group  
mica group  
chlorite group  
other sheet silicates

Chain silicate subclass  
pyroxene group  
amphibole group  
pyroxenoid group

Ring silicate subclass

Isolated tetrahedral silicate subclass  
garnet group  
olivine group  
humite group  
aluminosilicate group  
other isolated tetrahedral silicates

Paired tetrahedral silicate subclass  
lawsonite group  
epidote group

## II. Native Element Class

metals  
semimetals  
nonmetals

## III. Sulfide Class

tetrahedral sulfide group  
octahedral sulfide group  
other sulfides

## IV. Halide Class

**V. Oxide Class**

tetrahedral and octahedral  
oxide group  
spinels and other oxides with  
mixed or unusual coordination

**VI. Hydroxide Class****VII. Carbonate and Nitrate Class**

calcite group  
dolomite group  
aragonite group  
other carbonates  
nitrate group

**VIII. Borate Class**

anhydrous borate group  
hydrous borate group

**IX. Sulfate Class**

anhydrous sulfate group  
hydrous sulfate group

**X. Tungstate, Molybdate, and Chromate Class**

tungstate group  
molybdate group  
chromate group

**XI. Phosphate, Arsenate, and Vanadate Class**

phosphate group  
vanadate group  
arsenate group

**I. SILICATES****FRAMEWORK SILICATES****Silica Group Minerals**

quartz	$\text{SiO}_2$
cristobalite	$\text{SiO}_2$
tridymite	$\text{SiO}_2$
coesite	$\text{SiO}_2$
stishovite	$\text{SiO}_2$

The silica group minerals have composition  $\text{SiO}_2$ , and all except stishovite have structures based on  $\text{SiO}_4$  tetrahedra linked at their vertices by "bridging" oxygen. Quartz, tridymite, and cristobalite have high-temperature and low-temperature polymorphs; coesite and stishovite do not. Scientists have synthesized several additional  $\text{SiO}_2$  polymorphs in the laboratory. Although mineralogists have described many polymorphs, only common quartz, properly called *low quartz*, exists in substantial amounts; it is the second most abundant mineral in Earth's crust.

The different polymorphs vary in the way  $\text{SiO}_4$  tetrahedra join to form a three-dimensional framework. Consequently, they vary in symmetry: High quartz is hexagonal, low quartz is trigonal, low tridymite is orthorhombic, low cristobalite is tetragonal, and coesite is monoclinic.

Structural variations among the  $\text{SiO}_2$  polymorphs reflect the different conditions under which they form. Low quartz is the only stable  $\text{SiO}_2$  polymorph under normal Earth surface conditions, but some rocks contain metastable stishovite, coesite, cristobalite, or tridymite.

**Quartz ( $\alpha$ -quartz)***Origin of Name*

From German, *quartz*, of unknown origin.

*Hand Specimen Identification*

Hardness, lack of cleavage, conchoidal fracture, and vitreous luster usually serve to identify quartz. When euhedral, its pseudohexagonal prismatic habit can be distinctive. Quartz is sometimes confused with calcite, beryl, cordierite, or feldspars. Plates 2.1 through 2.8 show color pictures of quartz. Figures 1, 2 and 3 contain additional photographs and drawings.

*Physical Properties*

hardness	7
specific gravity	2.65
cleavage/fracture	no cleavage or parting; brittle/conchoidal fracture
luster/transparency	vitreous/transparent



**FIGURE 1** Prismatic quartz crystals from Huaron, Peru.

color	colorless, white, milky; less commonly purple, pink, yellow, brown, or black
streak	white

#### *Optical Properties*

In thin section, quartz is distinguished by low relief, low birefringence (maximum interference colors are gray), lack of color, lack of cleavage, lack of visible twinning, lack of alteration, usually anhedral character, and undulatory extinction. Uniaxial (+);  $\omega = 1.544$ ,  $\epsilon = 1.553$ ,  $\delta = 0.009$ . Plates 5.5, 5.6, 5.7, and 5.8 show quartz in thin section.

#### *Crystallography*

Hexagonal (rhombohedral),  $a = 4.913$ ,  $c = 5.405$ ,  $Z = 3$ ; space group  $R\bar{3}_12$  or  $R\bar{3}_22$ ; point group 32.

#### *Habit*

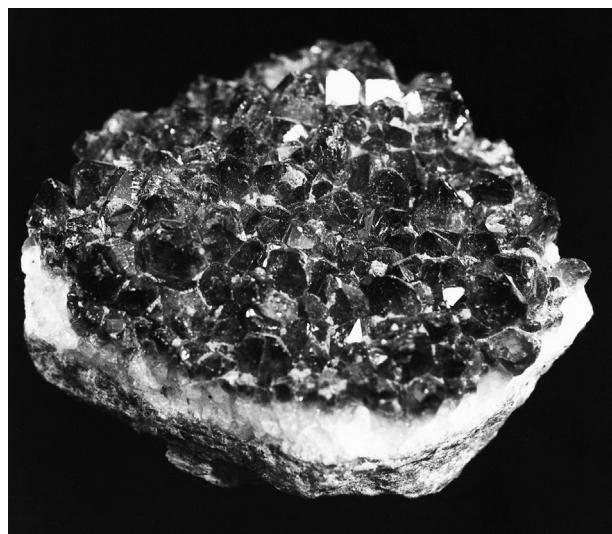
Crystals are prismatic or massive. They belong to class 32, but may appear to have 6-fold symmetry. Common crystals are six-sided prisms terminated by rhombohedrons, sometimes appearing to be hexagonal dipyramids (Figures 1, 2 and 3). Prism faces often show horizontal growth striations. Rare forms include trapezohedra. Most, if not all, quartz is twinned. Two kinds of twins, Dauphiné and Brazil, are common, but normally cannot be seen with the naked eye.

#### *Structure and Composition*

Quartz is always essentially pure  $\text{SiO}_2$  but may contain trace amounts of other elements. It consists of a three-dimensional framework of  $\text{SiO}_4$  tetrahedra, with all oxygens shared by two tetrahedra. At 1 atm, upon heating to  $573^\circ\text{C}$ , ( $1,063^\circ\text{F}$ ) minor changes in bond angles cause low quartz to change into high quartz ( $\beta$ -quartz) with crystal symmetry 622; it reverts to low quartz when cooled.



**FIGURE 2** Quartz crystals from Minas Gerais, Brazil (left), and Middleville, New York (right).



**FIGURE 3** Citrine, a yellow to brown variety of quartz.

#### *Occurrence and Associations*

Quartz is a common and essential ingredient in many sedimentary, metamorphic, and igneous rocks. It dominates in sandstone and quartzite and occurs in all silicic metamorphic and igneous rocks. It also dominates in beach sands, many soils, and other sediments.

#### *Varieties*

Coarsely crystalline varieties of quartz include citrine (yellow to orange; Figure 3), amethyst (purple), rose quartz (pink), smoky quartz (yellow-brown to black), and milky quartz (milky white). Fibrous microcrystalline varieties include many types of chalcedony, such as carnelian (red), sard (brown), chrysoprase (apple green), agate (banded or variegated), and onyx (white and gray bands). Jasper (iron red), chert (light gray), and flint (dull dark color) are granular microcrystalline varieties of quartz.

#### *Related Minerals*

More than a half dozen  $\text{SiO}_2$  polymorphs exist, the principal ones being low quartz ( $\alpha$ -quartz); high quartz ( $\beta$ -quartz); coesite; stishovite; low and high cristobalite; and low, middle, and high tridymite. Low quartz is the only common one. Opal is an amorphous variety of  $\text{SiO}_2$  that contains some  $\text{H}_2\text{O}$ .

## Cristobalite

## $\text{SiO}_2$

#### *Origin of Name*

Named after occurrence at Cerro San Cristóbal, Mexico.

#### *Hand Specimen Identification*

Cristobalite is difficult to identify in hand specimen. X-ray or optical techniques are required. Cristobalite is sometimes confused with zeolites in hand specimen.

It may appear as white "snowflakes" in obsidian.

#### *Physical Properties*

hardness	6½
specific gravity	2.33
cleavage/fracture	none/conchoidal
luster/transparency	vitreous/translucent to transparent
color	colorless
streak	white

#### *Optical Properties*

Crystal habit, low birefringence, and moderate negative relief characterize cristobalite in thin section. Low cristobalite: uniaxial (-),  $\omega = 1.489$ ,  $\epsilon = 1.482$ ,  $\delta = 0.007$ .

#### *Crystallography*

Low cristobalite is tetragonal,  $a = 4.97$ ,  $c = 6.93$ ,  $Z = 4$ ; space group  $P4_32_12$ ; point group 422. High cristobalite is cubic,  $a = 7.13$ ,  $Z = 8$ ; space group  $F\bar{4}_1/d\bar{3}2/m$ ; point group  $4/m\bar{3}2/m$ .

#### *Habit*

Cubic, octahedral, or coarse aggregates typify cristobalite. Although low cristobalite crystals belong to crystal class 422, they often appear as small octahedra or globby aggregates.

#### *Structure and Composition*

Cristobalite, always nearly pure  $\text{SiO}_2$ , may contain minor amounts of  $\text{Al}^{3+}$  and alkalis. As with quartz, the structure is based on a three-dimensional framework of  $\text{SiO}_4$  tetrahedra. The difference between cristobalite, quartz, and other  $\text{SiO}_2$  polymorphs is the way in which the tetrahedra are linked. Mineralogists have described two cristobalite polymorphs: low cristobalite ( $\alpha$ -cristobalite) is tetragonal, high cristobalite ( $\beta$ -cristobalite) is cubic.

#### *Occurrence and Associations*

Cristobalite is only found in high-temperature silicic extrusive igneous rocks. Rapid cooling may keep it from changing into the more stable, low quartz. Typically it occurs as small spherical grains or aggregates in vugs, as misty inclusions in volcanic glass, or as principal components in fine-grained ground mass. It is associated with other high-temperature minerals including sanidine and tridymite.

#### *Related Minerals*

$\text{SiO}_2$  polymorphs include quartz, cristobalite, tridymite, coesite, and stishovite.

## **Tridymite (low tridymite)**

**$\text{SiO}_2$**

#### *Origin of Name*

From Greek for "threefold," a reference to its habit of forming compound crystals of three individuals or triangular wedge-shaped crystals.

#### *Hand Specimen Identification*

Tridymite is usually sufficiently fine grained that X-ray or optical measurements are needed for identification. It is sometimes confused with zeolites. Figure 4 shows a scanning electron microscope image of hexagonal tridymite crystals.

#### *Physical Properties*

hardness	6 to 7
specific gravity	2.28
cleavage/fracture	none/conchoidal
luster/transparency	vitreous/transparent to translucent
color	colorless
streak	white

#### *Optical Properties*

In thin section, tridymite can be distinguished by its low birefringence, low refractive index (RI), moderate relief, and typical habit often showing wedge-shaped twins. Low tridymite: biaxial (+);  $\alpha = 1.478$ ,  $\beta = 1.479$ ,  $\gamma = 1.481$ ,  $\delta = 0.003$ ,  $2V = 70^\circ$ .

#### *Crystallography*

Low tridymite is orthorhombic,  $a = 9.9$ ,  $b = 17.1$ ,  $c = 16.3$ ,  $Z = 64$ ; space group  $P222$ ; point group 222.

#### *Habit*

Characteristic habit includes wedge-shaped crystals in vesicles or on the walls of cavities of volcanic rocks. Crystals belong to crystal class 222, but often appear as twinned pseudomorphs after high tridymite ( $6/m2/m2/m$ ).

#### *Structure and Composition*

Tridymite may contain minute amounts of  $\text{Al}^{3+}$  and alkalis. Its structure consists of sheets of  $\text{SiO}_4$  tetrahedra joined together by bridging oxygens. Three tridymite polymorphs are known (low, middle, and high tridymite).

#### *Occurrence and Associations*

Tridymite is found in high-temperature silicic igneous rocks, where it commonly associates with other high-temperature minerals, including sanidine and cristobalite. It is also found in some stony meteorites and lunar basalts.

#### *Related Minerals*

$\text{SiO}_2$  polymorphs include quartz, cristobalite, tridymite, coesite, and stishovite.

**Coesite****SiO<sub>2</sub>***Origin of Name*

Named after L. Coes, who first described it in detail.

*Hand Specimen Identification*

Coesite cannot be identified in hand specimen.

*Physical Properties*

hardness	7 to 8
specific gravity	2.93
cleavage/fracture	none/conchoidal
luster/transparency	vitreous/transparent
color	colorless
streak	white

*Optical Properties*

Biaxial (+),  $\alpha = 1.59$ ,  $\beta = 1.60$ ,  $\gamma = 1.60$ ,  $\delta = 0.01$ ,  $2V = 64^\circ$ .

*Crystallography*

Monoclinic,  $a = 7.17$ ,  $b = 12.33$ ,  $c = 7.17$ ,  $\beta = 120.0^\circ$ ,  $Z = 16$ ; space group  $C2/c$ ; point group  $2/m$ .

*Habit*

Crystals are usually thin tabs, invisible without a microscope.

*Structure and Composition*

Coesite's structure consists of a very dense three-dimensional network of SiO<sub>4</sub> tetrahedra. In some ways, the structure is similar to that of feldspars.

*Occurrence and Associations*

Coesite, a rare high-pressure polymorph of SiO<sub>2</sub>, is known only from meteor impact craters and some rare xenoliths and other rocks of deep crust or mantle origin.

*Related Minerals*

SiO<sub>2</sub> polymorphs include quartz, cristobalite, tridymite, coesite, and stishovite.

**Stishovite****SiO<sub>2</sub>***Origin of Name*

Named after S. M. Stishov, an early investigator of high-pressure SiO<sub>2</sub> polymorphs.

*Hand Specimen Identification*

Stishovite only exists as tiny grains in rocks near meteorite impact craters.

*Physical Properties*

hardness	7 to 8
specific gravity	4.30
cleavage/fracture	{110}/conchoidal
luster/transparency	vitreous/transparent
color	colorless
streak	white

*Optical Properties*

Uniaxial (+),  $\omega = 1.799$ ,  $\epsilon = 1.826$ ,  $\delta = 0.027$ .

*Crystallography*

Tetragonal,  $a = 4.18$ ,  $c = 2.66$ ,  $Z = 2$ ; space group  $P4_2/m2_1/n2/m$ ; point group  $4/m2/m2/m$ .

*Habit*

Stishovite has a prismatic habit.

*Structure and Composition*

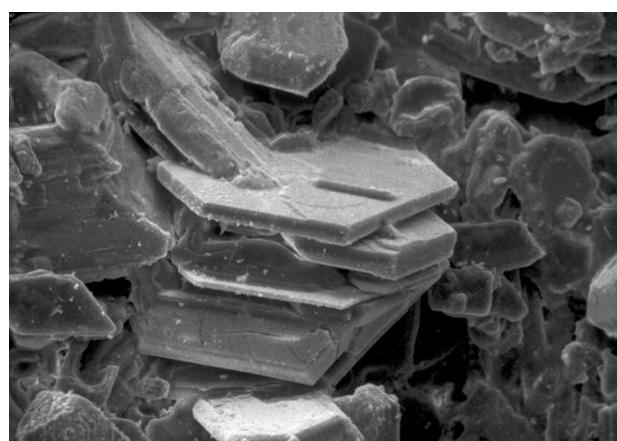
Stishovite is always nearly pure SiO<sub>2</sub>. The structure is extremely dense and resembles the structure of rutile. Si<sup>4+</sup> is in octahedral coordination, in contrast with the other SiO<sub>2</sub> polymorphs.

*Occurrence and Associations*

Stishovite, a rare, high-pressure polymorph of SiO<sub>2</sub>, is known only from meteor impact craters.

*Related Minerals*

SiO<sub>2</sub> polymorphs include quartz, cristobalite, tridymite, coesite, and stishovite.



**FIGURE 4** Tridymite crystals imaged with a scanning electron microscope.

**Feldspar Group Minerals****Alkali Feldspar Series**

orthoclase	KAlSi <sub>3</sub> O <sub>8</sub>
sanidine	(K,Na)AlSi <sub>3</sub> O <sub>8</sub>
microcline	KAlSi <sub>3</sub> O <sub>8</sub>
albite	NaAlSi <sub>3</sub> O <sub>8</sub>

**Plagioclase Feldspar Series**

albite	NaAlSi <sub>3</sub> O <sub>8</sub>
anorthite	CaAl <sub>2</sub> Si <sub>2</sub> O <sub>8</sub>

Feldspars are the most abundant minerals in the Earth's crust. Their compositions can be described with the general formula  $(\text{Ca}, \text{Na}, \text{K})(\text{Si}, \text{Al})_4\text{O}_8$ . Feldspar structures are based on  $\text{SiO}_4$  and  $\text{AlO}_4$  tetrahedra linked to form a three-dimensional framework. They form two series that share one end member: the alkali feldspar series (orthoclase-albite) and the plagioclase feldspar (albite-anorthite) series.

The three KAlSi<sub>3</sub>O<sub>8</sub> polymorphs differ in the way  $\text{SiO}_4$  and  $\text{AlO}_4$  tetrahedra are distributed in their structures. Sanidine, the high-temperature polymorph, is most disordered; microcline, the low-temperature polymorph, is most ordered. Orthoclase has intermediate and somewhat variable ordering. Albite and anorthite also exhibit variable ordering, depending on temperature.

Ordering complicates phase relations among the feldspars. At high temperatures alkali feldspars form complete solid solutions between monalbite (a high-temperature albite polymorph) and sanidine. Intermediate compositions are often termed *anorthoclase*. At intermediate and low temperatures, however, anorthoclase is unstable because a solvus limits solid solutions between orthoclase/microcline and albite.

At high temperatures plagioclase feldspar may have any composition between albite and anorthite. At low temperatures variable ordering and several small solvi lead to complications. Most alkali feldspars contain minor Ca, and most plagioclase feldspars contain small amounts of K. The extent to which the two series can mix is limited and varies with temperature.

Feldspars commonly form simple or polysynthetic twins, or both. Both contact and penetration twins are possible. Sometimes twinning is visible with the naked eye, but often must be seen with a microscope. Twin laws include Carlsbad, Baveno, Mannebach, albite, and pericline.

**Orthoclase****KAlSi<sub>3</sub>O<sub>8</sub>***Origin of Name*

From the Greek word *orthos* (right angle) and *klasis* (to break), referring to this mineral's perpendicular cleavages.

*Hand Specimen Identification*

The luster, hardness, and color of orthoclase are similar to other feldspars, but (in contrast with plagioclase) orthoclase is frequently pink or flesh colored, has cleavage planes that meet at 90°, and does not show twin striations. Association with other felsic minerals also helps identification. Distinguishing orthoclase from its polymorphs, microcline and sanidine, can be very difficult without X-ray or optical data. It is sometimes confused with calcite or corundum but can be distinguished by its hardness. Plate 1.5 is a color photo of twinned orthoclase crystals.

*Physical Properties*

hardness	6
specific gravity	2.56
cleavage/fracture	90° cleavage angle; perfect (001), good (010), poor {110}/uneven
luster/transparency	pearly, vitreous/translucent
color	white, pink, turbid
streak	white

*Optical Properties*

In thin section, orthoclase has low birefringence, moderate relief, and resemblance to quartz. However, it has negative relief, is biaxial, and is often clouded by fine-grained alteration. It is distinguished from sanidine by  $2V$  and from microcline by its lack of plaid twinning. Biaxial,  $\alpha = 1.521$ ,  $\beta = 1.525$ ,  $\gamma = 1.528$ ,  $\delta = 0.007$ ,  $2V = 60^\circ$  to  $65^\circ$ .

*Crystallography*

Monoclinic,  $a = 8.56$ ,  $b = 12.99$ ,  $c = 7.19$ ,  $\beta = 116.01^\circ$ ,  $Z = 4$ ; space group  $C2/m$ ; point group  $2/m$ .

*Habit*

Crystals are prismatic, stubby to elongate, and may be flattened or doubly terminated. Penetration twins and contact twins are common.

*Structure and Composition*

The structure of orthoclase consists of a three-dimensional framework of  $\text{SiO}_4$  and  $\text{AlO}_4$  tetrahedra.  $\text{K}^+$  ions occupy available holes between the tetrahedra. Most orthoclase contains some Na replacing K; complete solid solution between

orthoclase and albite ( $\text{NaAlSi}_3\text{O}_8$ ) is possible only at high temperature. Some orthoclase contains small amounts of CaAl replacing NaSi.

#### *Occurrence and Associations*

Orthoclase is common in many kinds of silicic igneous rocks, sediments such as arkoses, and a variety of metamorphic rocks. Quartz and micas are typically associated minerals.

#### *Related Minerals*

The principal K-feldspar polymorphs are sanidine (high-temperature form), orthoclase (moderate-temperature form), and microcline (low-temperature form). They differ in the way  $\text{SiO}_4$  and  $\text{AlO}_4$  tetrahedra are arranged in their structure. Several other related minerals are known: Adularia is a colorless, transparent form of K-feldspar that forms prismatic crystals. If it shows opalescence, we call it *moonstone*. Perthite is a form of K-feldspar containing exsolved patches or lamellae of albitic feldspar (refer to Plate 6.7).

## **Sanidine**

### **(K,Na)AlSi<sub>3</sub>O<sub>8</sub>**

#### *Origin of Name*

From the Greek word *sanis* (tablet) and *idios* (appearance), referring to this mineral's typical habit.

#### *Hand Specimen Identification*

Sanidine may be difficult to tell from other feldspars, but its restricted occurrence in felsic volcanic rocks and associations are helpful diagnostic tools. Certain identification requires X-ray analysis or thin sections. Plagioclase and microcline have different kinds of twins than sanidine, and sanidine never shows twin lamellae.

#### *Physical Properties*

hardness	6
specific gravity	2.56
cleavage/fracture	perfect (001), good (010)
luster/transparency	vitreous/transparent to translucent
color	white, variable
streak	white

#### *Optical Properties*

Sanidine is similar to orthoclase but with greater  $2V$ . Carlsbad twins may divide crystals into halves. Manebach and Baveno twins may also be present. Biaxial (-),  $\alpha = 1.521$ ,  $\beta = 1.525$ ,  $\gamma = 1.528$ ,  $\delta = 0.007$ ,  $2V$  varies depending on structure.

#### *Crystallography*

Monoclinic,  $a = 8.56$ ,  $b = 13.03$ ,  $c = 7.17$ ,  $\beta = 116.58^\circ$ ,  $Z = 4$ ; space group  $C2/m$ ; point group  $2/m$ .

#### *Habit*

Crystals are prismatic, may be tabular or elongate, and often have a square cross section. Carlsbad twins are common.

#### *Structure and Composition*

Similar to orthoclase, the structure of sanidine consists of a three-dimensional framework of  $\text{SiO}_4$  and  $\text{AlO}_4$  tetrahedra. In sanidine the two kinds of tetrahedra are randomly distributed in the structure, while in orthoclase they are partially ordered.  $\text{K}^+$  ions occupy available holes between the tetrahedra. Na may replace K; complete solid solution between sanidine and albite ( $\text{NaAlSi}_3\text{O}_8$ ) is possible at high temperature.

#### *Occurrence and Associations*

Sanidine occurs in silicic igneous rocks but is restricted to rocks that have cooled quickly. If cooling is slow, orthoclase will be present instead. Typical occurrences are as phenocrysts in rocks such as trachyte or rhyolite.

#### *Related Minerals*

Related minerals include the other  $\text{KAlSi}_3\text{O}_8$  polymorphs, orthoclase and microcline, and the plagioclase feldspar series.

## **Microcline**

### **KAlSi<sub>3</sub>O<sub>8</sub>**

#### *Origin of Name*

From the Greek word *micros* (small) and *klinein* (to lean), referring to this mineral's cleavage angles being close to  $90^\circ$ .

#### *Hand Specimen Identification*

Hardness, luster, cleavage, habit, and association help identify microcline, but it is easily confused with other feldspars, especially orthoclase, its polymorph (see **orthoclase**). Distinctive "microcline" twinning or a bluish green color are diagnostic but may not be present or visible see Figure 5. X-ray or optical measurements are needed for certain identification.

#### *Physical Properties*

hardness	6
specific gravity	2.56
cleavage/fracture	perfect (001), good (010)
luster/transparency	pearly, vitreous/translucent
color	white, green, salmon-pink
streak	white

#### *Optical Properties*

Microcline's "tartan plaid" twinning (a combination of albite and pericline twinning) is its most diagnostic

characteristic in thin section. Plagioclase may show two sets of twins at about  $90^\circ$ , but in plagioclase the twins have sharp parallel boundaries, while in microcline they pinch and swell. Biaxial (-),  $\alpha = 1.518$ ,  $\beta = 1.524$ ,  $\gamma = 1.528$ ,  $\delta = 0.010$ ,  $2V = 77^\circ - 84^\circ$ .

#### *Crystallography*

Triclinic,  $a = 8.58$ ,  $b = 12.96$ ,  $c = 7.21$ ,  $\alpha = 89.7^\circ$ ,  $\beta = 115.97^\circ$ ,  $\gamma = 90.87^\circ$ ,  $Z = 4$ ; space group  $P\bar{1}$ ; point group 1.

#### *Habit*

Prismatic, stubby to elongate crystals are typical. It is also common as cleavable masses or irregular grains. Twins, both contact and penetration, may be present. Combinations of polysynthetic albite and pericline twinning result in the “tartan plaid” appearance, normally only visible under a microscope.

#### *Structure and Composition*

The structure of microcline is similar to orthoclase and sanidine, but the  $\text{SiO}_4$  and  $\text{AlO}_4$  tetrahedra are more regularly ordered, leading to less symmetry. Ordering decreases with increasing temperature of formation: Low microcline has complete tetrahedral ordering. Intermediate and high microcline are less well ordered. A solvus limits solid solutions between microcline and albite,  $\text{NaAlSi}_3\text{O}_8$ , at low temperatures.

#### *Occurrence and Associations*

Microcline is common in many kinds of silicic igneous rocks, sediments such as arkoses, and a variety of metamorphic rocks. It easily forms from sanidine or orthoclase as rocks cool from high

temperatures. Quartz and micas are typically associated minerals.

#### *Varieties*

When colored a deep green, microcline is given the name *amazonite* shown in Figure 5 (refer also to Plate 8.3).

#### *Related Minerals*

Related minerals include the other  $\text{KAlSi}_3\text{O}_8$  polymorphs, orthoclase, microcline, adularia, and perthite (see **orthoclase**), and the plagioclase feldspar series.

## Albite

## $\text{NaAlSi}_3\text{O}_8$

#### *Origin of Name*

From the Latin word *albus*, meaning “white.”

#### *Hand Specimen Identification*

Cleavage, hardness, luster, association, and fine polysynthetic twinning help identify albite and other plagioclase feldspars. If not twinned, it may be difficult to tell from K-feldspar. Distinguishing albite from other plagioclase feldspars cannot be done precisely without detailed X-ray or optical data. Plate 6.8 shows rare euhedral albite.

#### *Physical Properties*

hardness	6
specific gravity	2.62
cleavage/fracture	perfect (001), good (010), poor {110}/uneven
luster/transparency	pearly, vitreous/translucent
color	white, gray, green
streak	white

#### *Optical Properties*

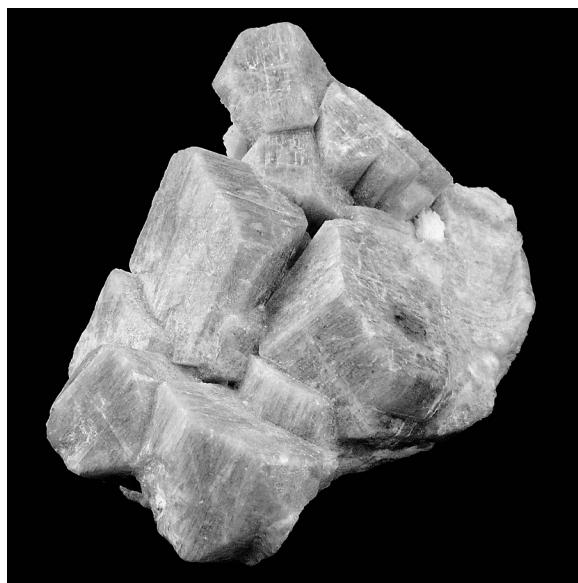
In thin section, plagioclase shows no color, has low relief, and exhibits gray interference colors. It is similar to K-feldspar and superficially similar to quartz. However, cleavage, biaxial character, and “zebra stripes” caused by polysynthetic twinning usually serve to identify it. Biaxial (+),  $\alpha = 1.527$ ,  $\beta = 1.531$ ,  $\gamma = 1.538$ ,  $\delta = 0.011$ ,  $2V = 77^\circ$ . Plates 5.7 and 5.8 show plagioclase in thin section.

#### *Crystallography*

Triclinic,  $a = 8.14$ ,  $b = 12.79$ ,  $c = 7.16$ ,  $\alpha = 93.17^\circ$ ,  $\beta = 115.85^\circ$ ,  $\gamma = 87.65^\circ$ ,  $Z = 4$ ; space group  $P\bar{1}$ ; point group 1.

#### *Habit*

Masses or subhedral grains are common. Rare euhedral crystals are prismatic, tabular, or bladed. Most crystals are twinned according to the



**FIGURE 5** Amazonite, a variety of microcline, from Teller Co., Colorado.

pericline law, and some are twinned by the albite law. Albite twins give plagioclase the characteristic polysynthetic twinning that is often visible as fine striations in hand specimen and as stripes in thin section.

#### *Structure and Composition*

Albite is an end member of both the plagioclase feldspar and the alkali felspar series. As with K-feldspar, ordering of  $\text{AlO}_4$  and  $\text{SiO}_4$  tetrahedra decreases with increasing temperature, leading to minor changes in structure. Low albite's structure is similar to that of low microcline; high albite's structure is more disordered. At very high temperature a completely disordered albite, called *monalbite* because it is monoclinic, is stable. At all but the lowest temperatures, complete solid solution exists between albite and the other plagioclase end member, anorthite,  $\text{CaAl}_2\text{Si}_2\text{O}_8$ . Albite, and other plagioclase feldspars, also form limited solid solutions with orthoclase,  $\text{KAlSi}_3\text{O}_8$ .

#### *Occurrence and Associations*

The most abundant mineral of the Earth's crust, plagioclase feldspars are found in a wide variety of igneous, metamorphic, and, less commonly, sedimentary rocks. Most are intermediate between albite and anorthite, but compositions approaching end members are known. Albite, defined as plagioclase with greater than 90%  $\text{NaAlSi}_3\text{O}_8$ , is found in silicic igneous rocks such as granite, syenite, trachyte, or rhyolite, where it associates with quartz and orthoclase.

#### *Varieties*

Clevelandite is a form of albite, typified by curved plates, found in pegmatites. Opalescent varieties of albite or other plagioclase feldspars are called *moonstone*.

#### *Related Minerals*

Albite is closely related to the other, more calcic plagioclase feldspars, and to the other alkali feldspars (orthoclase, sanidine, and microcline).

---

## Anorthite

## $\text{CaAl}_2\text{Si}_2\text{O}_8$

#### *Origin of Name*

From the Greek word meaning "oblique," in reference to anorthite's crystal shape.

#### *Hand Specimen Identification*

Cleavage, hardness, luster, and association help identify anorthite, but it can be extremely difficult to tell from other feldspars.

Several kinds of twinning are common (see albite). Albite twins, if present, may be difficult to see in hand specimen.

#### *Physical Properties*

hardness	6 to $6\frac{1}{2}$
specific gravity	2.76
cleavage/fracture	perfect (001), good (010), poor {110}/uneven
luster/transparency	pearly, vitreous/translucent
color	white, gray
streak	white

#### *Optical Properties*

In thin section, anorthite is similar to other plagioclase feldspars. Biaxial (-),  $\alpha = 1.577$ ,  $\beta = 1.585$ ,  $\gamma = 1.590$ ,  $\delta = 0.013$ ,  $2V = 78^\circ$ .

#### *Crystallography*

Triclinic,  $a = 8.17$ ,  $b = 12.88$ ,  $c = 14.16$ ,  $\alpha = 93.33^\circ$ ,  $\beta = 115.60^\circ$ ,  $\gamma = 91.22^\circ$ ,  $Z = 8$ ; space group  $P\bar{1}$ ; point group  $\bar{1}$ .

#### *Habit*

Anorthite is common as cleavable masses or irregular grains. Euhedral crystals are rare. They may be prismatic, tabular, or bladed and are frequently twinned according to the same laws as albite. When present, albite twins give calcic plagioclase characteristic polysynthetic twinning, but the width of the twins is usually greater than is common for albitic plagioclase.

#### *Structure and Composition*

Anorthite is the calcic end member of the plagioclase feldspar series, but the name is also used for any plagioclase containing  $> 90\%$   $\text{CaAl}_2\text{Si}_2\text{O}_8$ . Its structure is similar to those of albite and orthoclase. As with the other feldspars, the ordering of  $\text{AlO}_4$  and  $\text{SiO}_4$  tetrahedra decreases with increasing temperature, leading to minor changes in structure. Complete solid solution with albite,  $\text{NaAlSi}_3\text{O}_8$ , is possible at all but very low temperatures. Minor solid solution with orthoclase,  $\text{KAlSi}_3\text{O}_8$ , is common.

#### *Occurrence and Associations*

Anorthite, found primarily in mafic igneous rocks, is rarer than other plagioclase feldspars. In igneous rocks, it associates with amphibole, pyroxene, or olivine. It is occasionally found in metamorphosed carbonates.

#### *Related Minerals*

Anorthite is closely related to the other, more sodic plagioclase feldspars, and to the potassic feldspars (orthoclase, sanidine, and microcline).

**Feldspathoid Group Minerals**

analcime	$\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$
leucite	$\text{KAlSi}_2\text{O}_6$
nepheline	$(\text{Na},\text{K})\text{AlSiO}_4$

Feldspathoid minerals are similar to feldspars in many ways, but they contain more Al and less Si. They have structures based on three-dimensional frameworks of  $\text{AlO}_4$  and  $\text{SiO}_4$  tetrahedra; alkalis occupy holes between the tetrahedra. Al:Si ratios vary from 1:1 in nepheline,  $\text{NaAlSiO}_4$ , to 1:4 in the rare feldspathoid petalite,  $\text{LiAlSi}_4\text{O}_{10}$ . Feldspathoids are closely related to zeolites; the distinction between the two groups is hazy. The major difference is that zeolite structures contain large cavities or open channels and usually contain  $\text{H}_2\text{O}$ .

The most important feldspathoids are leucite, nepheline, and analcime, although analcime is often considered a zeolite because it contains molecular  $\text{H}_2\text{O}$ . Sodalite,  $\text{Na}_3\text{Al}_3\text{Si}_3\text{O}_{12} \cdot \text{NaCl}$ , and haüyne,  $\text{Na}_3\text{CaAl}_3\text{Si}_3\text{O}_{12} (\text{SO}_4)$ , are sometimes grouped with the feldspathoids but have a cage structure more similar to that of zeolites.

**Analcime** **$\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$** *Origin of Name*

From the Greek word *analkimos* (weak), referring to its weak pyroelectric character.

*Hand Specimen Identification*

Crystal habit (if euhedral) and association help identify analcime, but it may be difficult to tell from leucite. Because of its typical form, it is occasionally confused with garnet.

*Physical Properties*

hardness	5 to $5\frac{1}{2}$
specific gravity	2.26
cleavage/fracture	poor cubic {100}/uneven
luster/transparency	vitreous/transparent to translucent
color	white, gray, pink
streak	white

*Optical Properties*

In thin section, analcime is colorless and exhibits low negative relief and low birefringence. It may be confused with leucite, which has higher indices of refraction, or with sodalite, which is usually slightly bluish. Isotropic,  $n = 1.482$ .

*Crystallography*

Cubic,  $a = 13.71$ ,  $Z = 16$ ; space group  $I\bar{4}_1/a\bar{3}2/d$ ; point group  $4/m\bar{3}2/m$ .

*Habit*

Analcime typically forms distinct euhedral crystals. Trapezohedrons and cubes are common forms, often in combination. Massive and granular aggregates are also known.

*Structure and Composition*

The framework structure of analcime consists of  $\text{AlO}_4$  and  $\text{SiO}_4$  groups joined to make rings of four, six, or eight tetrahedra. Rings align, producing channels that hold  $\text{H}_2\text{O}$  molecules. The channels can hold additional absorbed ions or groups.  $\text{Na}^+$  ions occupy nonchannel sites between rings. Minor substitution of K or Cs for Ca and of Al for Si are common. Analcime forms a limited solid solution with pollucite,  $(\text{Cs},\text{Na})_2(\text{AlSi}_2\text{O}_6)_2 \cdot \text{H}_2\text{O}$ .

*Occurrence and Associations*

Analcime is found in cavities in basalt and as a primary mineral in alkalic igneous rocks such as Na-rich basalt or syenite. In cavities, it is associated with zeolites, calcite, or prehnite.

*Related Minerals*

Analcime is similar in structure to zeolites such as wairakite,  $\text{Ca}(\text{Al}_2\text{Si}_4\text{O}_{12}) \cdot 2\text{H}_2\text{O}$ , and to leucite,  $\text{KAlSi}_2\text{O}_6$ .

**Leucite** **$\text{KAlSi}_2\text{O}_6$** *Origin of Name*

From the Greek word *leukos*, meaning “white,” in reference to leucite’s color.

*Hand Specimen Identification*

Occurrence in Si-poor, K-rich volcanic rocks, crystal habit and pseudocubic form (if euhedral), and color help identify leucite. It may be confused with analcime, but leucite typically forms as a matrix mineral whereas analcime forms in cavities.

*Physical Properties*

hardness	$5\frac{1}{2}$ to 6
specific gravity	2.48
cleavage/fracture	poor {100}, poor (001)/conchoidal
luster/transparency	vitreous/transparent to translucent
color	white, gray
streak	white

*Optical Properties*

Low relief, gray interference colors, and lamellar or concentric twins help identify leucite. Uniaxial (+),  $\omega = 1.508$ ,  $\epsilon = 1.509$ ,  $\delta = 0.001$ .

*Crystallography*

Tetragonal,  $a = 13.04$ ,  $c = 13.85$ ,  $Z = 16$ ; space group  $I\bar{4}_1/a$ ; point group  $4/m$ .

*Habit*

Although tetragonal at low temperatures, leucite normally has the form of its high-temperature cubic polymorph. Trapezohedral crystals are typical. Polysynthetic twinning may give faces fine striations.

*Structure and Composition*

Leucite's structure consists of a framework of 4-, 6-, and 8-membered rings of  $\text{AlO}_4$  and  $\text{SiO}_4$  tetrahedra.  $\text{K}^+$  ions occupy half the available sites between the rings. Leucite is generally close to end member composition, although small amounts of Fe, Na, and other alkalis may be present.

*Occurrence and Associations*

Leucite is a rare mineral found in Si-poor, K-rich volcanic rocks. It is never found with quartz.

*Related Minerals*

Leucite is isostructural with pollucite,  $(\text{Cs}, \text{Na})_2(\text{AlSi}_2\text{O}_6)_2 \cdot \text{H}_2\text{O}$ . Chemically, it is closely related to orthoclase,  $\text{KAlSi}_3\text{O}_8$ ; kaliophilite,  $\text{KAlSiO}_4$ ; and to analcime,  $\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$ . A cubic polymorph of leucite exists above  $605^\circ\text{C}$  ( $1,120^\circ\text{F}$ ).

**Nepheline****(Na,K)AlSiO<sub>4</sub>***Origin of Name*

From the Greek word *nephele*, meaning "cloud," because crystals turn cloudy when immersed in acid.

*Hand Specimen Identification*

Occurrence in alkaline igneous rocks, lack of cleavage, and greasy luster help identify nepheline. It may be confused with feldspar or quartz but is softer. Occasionally it is confused with apatite.

*Physical Properties*

hardness	$5\frac{1}{2}$ to 6
specific gravity	2.60
cleavage/fracture	poor {100}, poor (001)/sub-conchoidal
luster/transparency	vitreous, greasy/transparent to translucent
color	colorless, turbid
streak	white

*Optical Properties*

Low birefringence and relief and common alteration identify nepheline. It is distinguished from

the feldspars by its uniaxial nature and from quartz by its optic sign. Uniaxial (-),  $\omega = 1.540$ ,  $\epsilon = 1.536$ ,  $\delta = 0.004$ .

*Crystallography*

Hexagonal,  $a = 10.01$ ,  $c = 8.41$ ,  $Z = 8$ ; space group  $P\bar{6}_3$ ; point group 6.

*Habit*

Massive, compact, and embedded grains are common. Crystals are short and prismatic with six or twelve sides.

*Structure and Composition*

The structure of nepheline derives from that of tridymite: Every other Si is replaced by Al, and Na occupies large sites between Al and Si tetrahedra. All natural nepheline contains some K substituting for Na, but a solvus exists between nepheline and kalsilite,  $\text{KAlSiO}_4$ , at temperatures below  $1,000^\circ\text{C}$  ( $1,830^\circ\text{F}$ ). Exsolution, similar to perthite (see orthoclase), is common.

*Occurrence and Associations*

Nepheline is characteristic of some Si-poor igneous rocks, such as syenite. It is found with feldspars, apatite, cancrinite, sodalite, zircon, and biotite.

*Related Minerals*

Nepheline is isostructural with tridymite. It has a high-temperature polymorph above  $900^\circ\text{C}$  ( $1,650^\circ\text{F}$ ). It forms a solid solution with kalsilite,  $\text{KAlSiO}_4$ , and is chemically related to kaliophilite,  $\text{KAlSiO}_4$ . Cancrinite,  $(\text{Na}_3\text{Ca}_2)_2\text{CO}_3(\text{Si}_3\text{Al}_3\text{O}_{12}) \cdot 2\text{H}_2\text{O}$ , is similar to nepheline in many ways and occurs in the same type of rocks.

**Scapolite Series Minerals**

marialite	$\text{Na}_4(\text{AlSi}_3\text{O}_8)_3\text{Cl}$
meionite	$\text{Ca}_4(\text{Al}_2\text{Si}_2\text{O}_8)_3(\text{CO}_3, \text{SO}_4)$

Scapolites are metamorphic minerals with formulas related to the feldspars, but with structures more closely related to nepheline. The two principal end members are marialite,  $\text{Na}_4(\text{AlSi}_3\text{O}_8)_3\text{Cl}$ , equivalent in composition to albite plus halite; and meionite,  $\text{Ca}_4(\text{Al}_2\text{Si}_2\text{O}_8)_3(\text{CO}_3, \text{SO}_4)$ , equivalent in composition to anorthite plus calcite/anhydrite. Complete solid solution between the two end members is possible; F and OH may replace Cl and  $\text{CO}_3$ .

## **Scapolite Solid solutions of marialite, $\text{Na}_4(\text{AlSi}_3\text{O}_8)_3\text{Cl}$ , and meionite, $\text{Ca}_4(\text{Al}_2\text{Si}_2\text{O}_8)_3(\text{CO}_3,\text{SO}_4)$**

### *Origin of Name*

From the Greek word *skapos*, meaning “stalk,” in reference to its common, woody appearance.

### *Hand Specimen Identification*

The scapolites are characterized by prismatic crystals with square cross sections and  $45^\circ$  cleavage. Massive samples often have a distinct woody or fibrous appearance. Scapolite may be confused with feldspar.

### *Physical Properties*

hardness	5 to 6
specific gravity	2.55
cleavage/fracture	good {100}, poor {110}/conchoidal
luster/transparency	vitreous/transparent to translucent
color	colorless, variable
streak	white

### *Optical Properties*

Scapolite may appear similar to feldspars but is uniaxial and has different cleavage. Uniaxial ( $-$ ),  $\omega = 1.540$ ,  $\epsilon = 1.536$ ,  $\delta = 0.004$ .

### *Crystallography*

Tetragonal,  $a = 12.11$ ,  $c = 7.56$ ,  $Z = 2$ ; space group  $I\bar{4}m$ ; point group  $4/m$ .

### *Habit*

Crystals are typically tetragonal prisms, often woody looking. Massive varieties are common.

### *Structure and Composition*

The structure, closely related to that of nepheline, consists of  $\text{AlO}_4$  and  $\text{SiO}_4$  joined in a three-dimensional framework. The structure contains two types of holes for anions and anionic groups: One holds Na and Ca; the other Cl or  $\text{CO}_3$ .  $\text{CaAl}$  substitutes for  $\text{NaSi}$  freely;  $\text{SO}_4$  and F may substitute for Cl and  $\text{CO}_3$ . The two important end members are marialite,  $\text{Na}_4(\text{AlSi}_3\text{O}_8)_3\text{Cl}$ , and meionite,  $\text{Ca}_4(\text{Al}_2\text{Si}_2\text{O}_8)_3(\text{CO}_3,\text{SO}_4)$ . Natural scapolites have intermediate compositions. Chemically, scapolites are equivalent to plagioclase feldspar plus  $\text{CaCO}_3$ ,  $\text{NaCl}$ , or  $\text{CaSO}_4$ . Minor K, OH, and F may be present.

### *Occurrence and Associations*

Most scapolite occurrences are in calcic metamorphic rocks: marbles, marls or mafic gneisses, and amphibolites. Rare occurrences are reported from igneous rocks. Associated minerals include plagioclase, clinopyroxene, hornblende, apatite, garnet, and sphene.

### **Zeolite Group Minerals**

natrolite	$\text{Na}_2\text{Al}_2\text{Si}_3\text{O}_{10} \cdot 2\text{H}_2\text{O}$
chabazite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 6\text{H}_2\text{O}$
heulandite	$\text{CaAl}_2\text{Si}_7\text{O}_{18} \cdot 6\text{H}_2\text{O}$
stilbite	$\text{CaAl}_2\text{Si}_7\text{O}_{18} \cdot 7\text{H}_2\text{O}$
sodalite	$\text{Na}_3\text{Al}_3\text{Si}_3\text{O}_{12} \cdot \text{NaCl}$

Zeolites are a large and important group of minerals. Only five are considered in detail here, but more than 40 natural species are known, and many equivalent phases have been synthesized. All are framework silicates, containing a three-dimensional network of  $\text{SiO}_4$  and  $\text{AlO}_4$  tetrahedra linked to form channels, cages, rings, or loops. Alkalies or alkaline earths occupy large sites in the structures. Some zeolites have 4-, 6-, 8-, or 10-member tetrahedral rings. Others contain complex polyhedra resulting in cagelike openings. Unlike other framework silicates, zeolites contain large open cavities and channels in their structures that permit cations and  $\text{H}_2\text{O}$  molecules to pass in and out without disruption. Consequently, zeolites are used as molecular sieves in water softeners and other industrial applications.

Crystal symmetry and morphology vary between species. Different zeolites are cubic, tetragonal, orthorhombic, hexagonal, or monoclinic, and habits may be fibrous, tabular or platy, prismatic, or equant. Figure 6 shows two examples: chabazite and stilbite. Although sodalite is sometimes grouped with the feldspathoids, it is here grouped with the zeolites because it has a cagelike structure with 4- and 6-member silica rings.

## **Natrolite**



### *Origin of Name*

From the Greek word *natron*, meaning “soda.”

### *Hand Specimen Identification*

The many different zeolites have similar occurrences and may be hard to distinguish. Natrolite typically occurs as white radiating needles or as radial aggregates. Its perfect prismatic cleavage and uneven fracture and association also aid identification. Natrolite may be confused with aragonite or pectolite.

### *Physical Properties*

hardness	5 to $5\frac{1}{2}$
specific gravity	2.23
cleavage/fracture	perfect prismatic {110}/uneven
luster/transparency	vitreous/transparent to translucent
color	colorless, gray
streak	white

*Optical Properties*

Natrolite may be difficult to distinguish from other zeolites. It has two perfect cleavages, is of parallel extinction, is length slow, and has a moderate  $2V$ . Biaxial (+),  $\alpha = 1.48$ ,  $\beta = 1.48$ ,  $\gamma = 1.49$ ,  $\delta = 0.012$ ,  $2V = 38^\circ$  to  $62^\circ$ .

*Crystallography*

Orthorhombic,  $a = 18.30$ ,  $b = 18.63$ ,  $c = 6.60$ ; space group  $Fd2d$ ; point group  $mm2$ .

*Habit*

Acicular crystals, often radiating, are typical. Crystals may show vertical striations. Radiating rounded masses are also common. Less commonly, it is fibrous, massive, or granular.

*Structure and Composition*

Natrolite and all zeolites are framework structures built of  $\text{AlO}_4$  and  $\text{SiO}_4$  tetrahedra. The tetrahedra are linked to form chains, cages, rings, or loops. In

contrast with some other framework silicates, the zeolite structure contains many large holes and channels, which hold weakly bonded  $\text{H}_2\text{O}$ . Slightly smaller holes contain Na, Ca, or K. In natrolite, scolecite, and some other zeolites, the tetrahedral framework has a strong linear fabric parallel to the c-axis. Crystal habit is therefore fibrous or acicular. Natrolite always contains minor amounts of Ca and K and has variable  $\text{H}_2\text{O}$  content.

*Occurrence and Associations*

Natrolite and most other zeolites are secondary minerals that form in cracks or on cavity walls in mafic igneous rocks. It is found with calcite and other zeolites.

*Related Minerals*

Scolecite,  $\text{CaAl}_2\text{Si}_3\text{O}_{10} \cdot 3\text{H}_2\text{O}$ , and thomsonite,  $\text{NaCa}_2\text{Al}_5\text{Si}_5\text{O}_{20} \cdot 6\text{H}_2\text{O}$ , are closely related to natrolite.

**Chabazite***Origin of Name*

From the Greek word *chabazios*, meaning "hail."

*Hand Specimen Identification*

Form, color, and association help identify chabazite but it may be difficult to distinguish from other zeolites. Crystals are transparent to translucent pseudocubic rhombs, similar to calcite. Chabazite is distinguished from calcite by its poorer cleavage and lack of reaction to HCl. Figure 6a shows chabazite crystals on basalt.

*Physical Properties*

hardness	4 to 5
specific gravity	2.1
cleavage/fracture	poor rhombohedral {101}/uneven
luster/transparency	vitreous/transparent to translucent
color	colorless, red
streak	white

*Optical Properties*

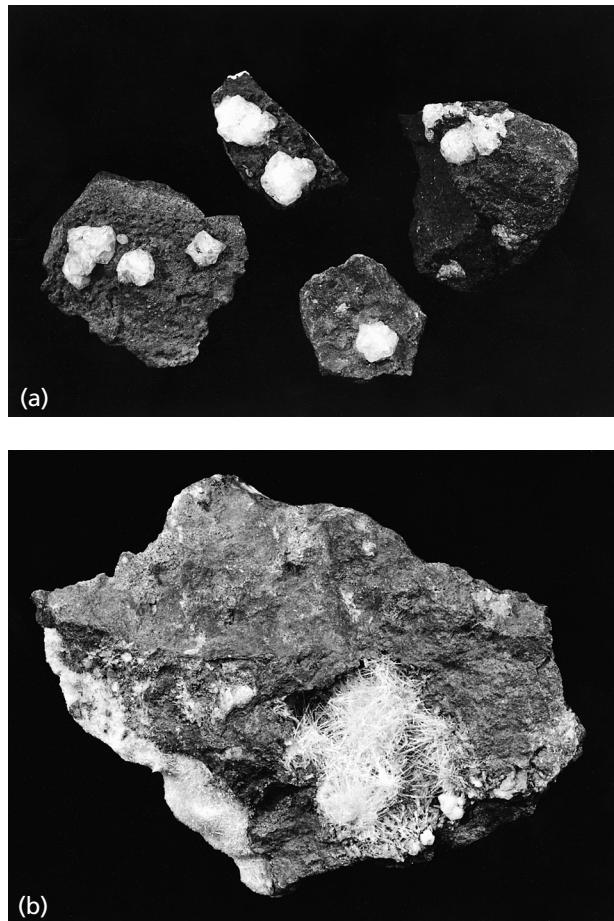
Uniaxial (-),  $\omega = 1.484$ ,  $\epsilon = 1.481$ ,  $\delta = 0.003$ .

*Crystallography*

Trigonal,  $a = 13.17$ ,  $c = 15.06$ ,  $Z = 6$ ; space group  $R\bar{3}2/m$ ; point group  $\bar{3}2/m$ .

*Habit*

Chabazite usually forms simple rhombohedral crystals that may, at first glance, appear cubic. Some crystals are more complicated, showing more than one rhombohedral form or exhibiting penetration twins.



**FIGURE 6** (a) Chabazite,  $\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 6\text{H}_2\text{O}$ , is one of the more common zeolites. Here it is shown as euhedral crystals on basalt from Melbourne, Australia. (b) Stilbite,  $\text{CaAl}_2\text{Si}_7\text{O}_{18} \cdot 7\text{H}_2\text{O}$ , is another relatively common zeolite. This specimen containing stilbite needles is from Golden, Colorado.

***Structure and Composition***

Chabazite is similar in structure to natrolite and other zeolites. Tetrahedra form large cagelike openings, which can hold a variety of loosely bonded ions and molecules. The large openings allow diffusion of some small molecules through the structure. Considerable substitution of Na and K for Ca is common.

***Occurrence and Associations***

Chabazite is a secondary mineral that forms in cracks or on cavity walls in mafic igneous rocks and as an alteration product in silicic igneous rocks. It is found with calcite and with other zeolites.

***Related Minerals***

Several other rare zeolites have structures similar to chabazite's.

**Heulandite*****Origin of Name***

Named for H. Heuland, a British mineralogist.

***Hand Specimen Identification***

Heulandite may be difficult to distinguish from other zeolites, but crystal habit, perfect one direction of cleavage, and luster aid identification.

***Physical Properties***

hardness	3½ to 4
specific gravity	2.15
cleavage/fracture	one perfect (010)/subconchoidal
luster/transparency	vitreous/transparent to translucent
color	white, variable
streak	white

***Optical Properties***

Biaxial (+),  $\alpha = 1.49$ ,  $\beta = 1.50$ ,  $\gamma = 1.50$ ,  $\delta = 0.005$ ,  $2V = 35^\circ$ .

***Crystallography***

Monoclinic,  $a = 17.73$ ,  $b = 17.82$ ,  $c = 7.43$ ,  $\beta = 116.3^\circ$ ,  $Z = 4$ ; space group  $Cm$ ; point group  $m$ .

***Habit***

Crystals are typically platy with a diamond or modified diamond shape.

***Structure and Composition***

The structure of heulandite is similar to that of other zeolites, except that tetrahedra are linked in 6-member rings that align to give a more planar structure than most others. End member calcic heulandite, called *mordenite*, is rare. Considerable solid solution towards clinoptilolite,  $(\text{Na},\text{K})\text{Si}_7\text{Al}_2\text{O}_{18} \cdot 6\text{H}_2\text{O}$ , is typical.

***Occurrence and Associations***

Heulandite is one of the more common zeolites. It is a secondary mineral, found with calcite and with other zeolites, that forms in cracks or on cavity walls in mafic igneous rocks, and in some metamorphic rocks.

***Related Minerals***

Other zeolites, including clinoptilolite,  $(\text{Na},\text{K})\text{Si}_7\text{Al}_2\text{O}_{18} \cdot 6\text{H}_2\text{O}$ , and stilbite,  $\text{CaAl}_2\text{Si}_7\text{O}_{18} \cdot 7\text{H}_2\text{O}$ , have structures similar to heulandite's.

**Stilbite*****Origin of Name***

From the Greek word *stilbein*, meaning "to shine," referring to this mineral's luster.

***Hand Specimen Identification***

Sheaflike aggregates of twinned crystals, one excellent cleavage, pearly luster, color, and association identify stilbite. See Figure 6b.

***Physical Properties***

hardness	3½ to 4
specific gravity	2.15
cleavage/fracture	perfect (010)/subconchoidal
luster/transparency	pearly/transparent to translucent
color	gray
streak	gray

***Optical Properties***

Cruciform twins and parallel or near-parallel extinction help identify stilbite in thin section. Biaxial (-),  $\alpha = 1.49$ ,  $\beta = 1.50$ ,  $\gamma = 1.50$ ,  $\delta = 0.010$ ,  $2V = 30^\circ$  to  $50^\circ$ .

***Crystallography***

Monoclinic,  $a = 13.64$ ,  $b = 18.24$ ,  $c = 11.27$ ,  $\beta = 129.16^\circ$ ,  $Z = 8$ ; space group  $C2/m$ ; point group  $2/m$ .

***Habit***

Simple crystals are extremely rare. Aggregates of twinned crystals, having the appearance of sheaves of grain, are common. Sometimes aggregates appear fibrous. More rarely, stilbite forms crystals displaying cruciform twinning.

***Structure and Composition***

Stilbite's structure is similar to heulandite's. Considerable substitution of Na and K for Ca is common.

***Occurrence and Associations***

Stilbite is one of the more common zeolites. It is a secondary mineral, found with calcite and with other zeolites, that forms in cracks or on cavity walls in igneous rocks and in some schists associated with hydrothermal ore bodies.

**Related Minerals**

Stilbite is grouped with heulandite,  $\text{CaAl}_2\text{Si}_7\text{O}_{18} \cdot 6\text{H}_2\text{O}$ , and several others because of its chemical and structural similarity.

**Sodalite***Origin of Name*

This mineral's name refers to its sodium content.

*Hand Specimen Identification*

Color (if blue) and association are usually diagnostic for sodalite. If not blue, identification may require chemical tests to tell it from zeolites or analcime. It is sometimes confused with lazulite but has different associations.

*Physical Properties*

hardness	$5\frac{1}{2}$ to 6
specific gravity	2.3
cleavage/fracture	six poor {110} at $60^\circ$ angles/conchoidal
luster/transparency	vitreous/transparent to translucent
color	blue, white
streak	white

*Optical Properties*

In thin section, sodalite is distinguished by being isotropic and having a low index of refraction and, sometimes, a hexagonal outline. Isotropic,  $n = 1.485$ .

*Crystallography*

Cubic,  $a = 8.87$ ,  $Z = 2$ ; space group  $P\bar{4}3m$ ; point group  $\bar{4}3m$ .

*Habit*

Often massive or in embedded grains, sodalite forms rare dodecahedral crystals.

*Structure and Composition*

The structure of sodalite is similar to many zeolites, containing 4- and 6-member tetrahedral rings but, unlike true zeolites, it contains no molecular water that can be driven off easily. The Al and Si tetrahedral rings are linked to form a framework with cagelike openings that hold Cl and sometimes S or  $\text{SO}_4$ . Sodalite is usually close to end member composition. Small amounts of K or Ca may also be present.

*Occurrence and Associations*

Sodalite is associated with nepheline,  $(\text{Na},\text{K})\text{AlSiO}_4$ , cancrinite,  $(\text{Na}_3\text{Ca})_2(\text{Al}_3\text{Si}_3\text{O}_{12})\text{CO}_3 \cdot 2\text{H}_2\text{O}$ , leucite,  $\text{KAlSi}_2\text{O}_6$ , and with feldspars in Si-poor, alkali-rich igneous rocks.

*Varieties*

Hackmanite is a sulfurous form of sodalite.

*Related Minerals*

Sodalite is structurally and chemically related to other zeolites and to cancrinite,  $(\text{Na}_3\text{Ca}_2)_2(\text{Al}_3\text{Si}_3\text{O}_{12})\text{CO}_3 \cdot 2\text{H}_2\text{O}$ .

**Other Framework Silicates**

beryl	$\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$
cordierite	$(\text{Mg},\text{Fe})_2\text{Al}_4\text{Si}_5\text{O}_{18}$

Beryl and cordierite, which contain 6-membered tetrahedral rings, are sometimes considered to be ring silicates. They are, however, more properly classified as framework silicates because they have an overall three-dimensional framework of connecting tetrahedra. Open channels in their structures almost always contain some  $\text{H}_2\text{O}$ .

**Beryl***Origin of Name*

From the Greek word *beryllos*, meaning "a blue-green gem."

*Hand Specimen Identification*

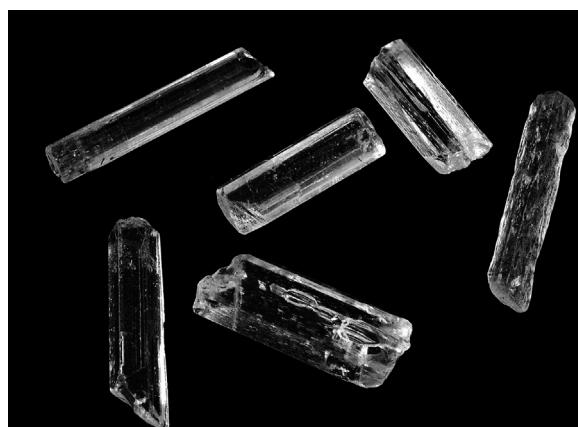
Association, sometimes hexagonal crystal shape, very poor cleavage, color (if blue), and hardness identify beryl. See Figure 7.

*Physical Properties*

hardness	$7\frac{1}{2}$ to 8
specific gravity	2.7 to 2.9
cleavage/fracture	poor {001}/even
luster/transparency	vitreous/transparent to translucent
color	blue, colorless, variable
streak	white

*Optical Properties*

In thin section, beryl may appear similar to quartz, apatite, or topaz, but quartz is (+), apatite has higher relief, and topaz is biaxial. Uniaxial (-),  $\omega = 1.568$ ,  $\epsilon = 1.562$ ,  $\delta = 0.006$ .



**FIGURE 7** Prismatic beryl crystals, from Minas Gerais, Brazil: These 4 cm long crystals are light blue and nearly clear.

***Crystallography***

Hexagonal,  $a = 9.23$ ,  $c = 9.19$ ,  $Z = 2$ ; space group  $P6/m2/c2/c$ ; point group  $6/m2/m2/m$ .

***Habit***

Beryl typically forms hexagonal prisms. When present, terminating faces are pinacoids or, more rarely, pyramids. Single crystals (Figure 7) are common; columnar aggregates are less so.

***Structure and Composition***

6-membered tetrahedral rings form sheets that are linked by tetrahedral Be and octahedral Al. Some classification schemes group beryl with true ring silicates such as tourmaline, but in beryl the framework structure is not completely planar; there is much cross linking. Small amounts of Na, Rb, and Li may substitute for Be; minor  $H_2O$  and  $CO_2$  may occupy spaces within the rings.

***Occurrence and Associations***

Beryl is found in granitic rocks, notably in pegmatites. It may also be found in schists and in rare ore deposits.

***Varieties***

Beryl can be many different colors due to small amounts of trace elements: emerald is vivid green; aquamarine is pale greenish blue (Plates 3.3 and 8.5); morganite is rose colored; heliodor is gold.

***Related Minerals***

Cordierite,  $(Mg,Fe)_2Al_4Si_5O_{18}$ , is similar in structure to beryl. Euclidean,  $BeAlSiO_4(OH)$ , is another of the rare beryllium silicates.

***Cordierite*** **$(Mg,Fe)_2Al_4Si_5O_{18}$** ***Origin of Name***

Named after P. L. A. Cordier (1777–1861), the French mineralogist who first described the mineral.

***Hand Specimen Identification***

Prismatic cleavage, color, and association aid identification, but if it is not blue, this mineral is often difficult to distinguish without a microscope. It may be easily confused with quartz in hand specimen and with plagioclase in thin section.

***Physical Properties***

hardness	7 to $7\frac{1}{2}$
specific gravity	2.5 to 2.8
cleavage/fracture	fair prismatic (010), poor (100)/conchoidal
luster/transparency	vitreous/transparent to translucent
color	indigo to gray-blue
streak	white

***Optical Properties***

In thin section, cordierite may be clear or pale blue-violet. Lamellar twinning is common. Pleochroic halos around zircon inclusions are diagnostic. Cordierite often alters to a fine-grained mass called *pinnite*. It may be confused with quartz, feldspar, or nepheline. Biaxial (+ or -),  $\alpha = 1.54$ ,  $\beta = 1.55$ ,  $\gamma = 1.56$ ,  $\delta = 0.02$ ,  $2V = 65^\circ$  to  $105^\circ$ .

***Crystallography***

Orthorhombic,  $a = 17.13$ ,  $b = 9.80$ ,  $c = 9.35$ ,  $Z = 4$ ; space group  $C2/c2/c2/m$ ; point group  $2/m2/m2/m$ .

***Habit***

Rare, euhedral crystals are short and prismatic and may appear pseudohexagonal. Twins are common. Cordierite is more typically granular, massive, or compact.

***Structure and Composition***

Cordierite, like beryl, consists of 6-membered tetrahedral rings joined in a three-dimensional framework.  $Mg^{2+}$ ,  $Fe^{2+}$ , and  $Al^{3+}$  link the rings to each other. Hollow channels, sometimes occupied by  $H_2O$  or alkalis, run parallel to the c-axis. Fe:Mg ratio is variable.

***Occurrence and Associations***

Cordierite is found as a product of contact or regional metamorphism in high-grade metamorphosed aluminous rocks. Rare occurrences in igneous rocks have been reported. Associated minerals include garnet, sillimanite, spinel, plagioclase, anthophyllite, and orthopyroxene.

***Varieties***

A high-temperature polymorph of cordierite, indialite, is isostructural with beryl.

***Related Minerals***

Cordierite is structurally similar to beryl, and is chemically and structurally similar to osumilite,  $(K,Na)(Fe,Mg)_2(Al,Fe)_3(Si,Al)_{12}O_{30} \cdot H_2O$ .

**SHEET SILICATES****Serpentine Group Minerals**

antigorite	$Mg_6Si_4O_{10}(OH)_8$
chrysotile	$Mg_6Si_4O_{10}(OH)_8$
lizardite	$Mg_6Si_4O_{10}(OH)_8$

Antigorite, chrysotile, and lizardite comprise the serpentine group. Antigorite and lizardite are typically massive and fine grained; chrysotile is fibrous and is one of the few asbestos minerals. Most of the world's asbestos is chrysotile; crocidolite and amosite, both amphibole varieties, account for the rest. Chrysotile and lizardite are true polymorphs, but antigorite has a slightly different composition not reflected in its formula. Figure 8 shows typical massive serpentine.

**Antigorite****Mg<sub>6</sub>Si<sub>4</sub>O<sub>10</sub>(OH)<sub>8</sub>***Origin of Name*

Named after Valle Antigorio, Italy, the first reported locality in which this mineral was found.

*Hand Specimen Identification*

Green color, greasy luster, lack of cleavage, and association identify antigorite. Chrysotile is a more fibrous variety of serpentine.

*Physical Properties*

hardness	3 to 4
specific gravity	2.6
cleavage/fracture	perfect (001)/flexible
luster/transparency	resinous, silky/translucent
color	green, yellow-green
streak	white

*Optical Properties*

In thin section, serpentine typically has a netlike pattern and exhibits wavy extinction. Very low birefringence results in anomalous interference colors. It may be confused with chlorite or brucite. Biaxial (-),  $\alpha = 1.56$ ,  $\beta = 1.57$ ,  $\gamma = 1.57$ ,  $\delta = 0.007$ ,  $2V = 20^\circ$  to  $60^\circ$ .

*Crystallography*

Monoclinic,  $a = 5.32$ ,  $b = 9.50$ ,  $c = 14.9$ ,  $\beta = 101.9^\circ$ ,  $Z = 4$ ; space group  $C2/m$ ; point group  $2/m$ .

*Habit*

Antigorite is commonly fine grained, massive, or platy, in contrast with fibrous chrysotile.

*Structure and Composition*

The layered structure consists of paired sheets of SiO<sub>4</sub> tetrahedra and Mg(O,OH)<sub>6</sub> octahedra stacked on top of each other. Antigorite has a slightly different composition from that indicated by its formula because the ratio of brucite layers to tetrahedral layers is slightly greater than 1. Because atoms in the tetrahedral and octahedral layers have slightly mismatched spacings, layers curve slightly. In antigorite the sheets curve in both directions, alternating on a fine scale, so the overall structure retains sheetlike properties. Small amounts of Ni, Mn, Al, Ti, and Fe typically substitute for Mg.

*Occurrence and Associations*

Antigorite is a common secondary mineral in mafic and ultramafic igneous rocks. It is also found in some marbles. In some serpentinites it is the only mineral present. Associated minerals include magnesium silicates, carbonates, hydroxides, and oxides, as well as olivine, pyroxene, amphibole, magnesite, spinel, chromite, magnetite, brucite, and talc.

*Varieties*

Garnierite is a Ni-rich variety of serpentine associated with Ni-peridotites.

*Related Minerals*

Antigorite is closely related to lizardite and chrysotile (common asbestos). Greenalite, Fe<sub>3</sub>Si<sub>2</sub>O<sub>5</sub>(OH)<sub>4</sub>, the Fe equivalent of serpentine, has a different structure.

**Chrysotile****Mg<sub>6</sub>Si<sub>4</sub>O<sub>10</sub>(OH)<sub>8</sub>***Origin of Name*

From the Greek word *chrysos* and *tilos*, meaning “golden” and “fiber.”

*Hand Specimen Identification*

Fiberlike, asbestiform appearance is diagnostic (Figure 8). Chrysotile may be distinguished from most fibrous amphiboles by its greenish white color; compare Plates 3.4 and 3.7.

*Physical Properties*

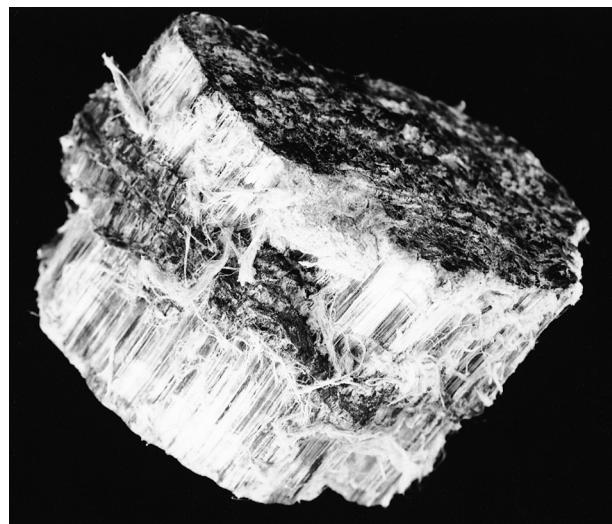
hardness	3 to 5
specific gravity	2.5 to 2.6
cleavage/fracture	none/uneven
luster/transparency	greasy, waxy/translucent
color	variable white, greenish white
streak	white

*Crystallography*

Monoclinic,  $a = 5.34$ ,  $b = 9.25$ ,  $c = 14.65$ ,  $\beta = 93^\circ$ ,  $Z = 8$ ; or orthorhombic, depending on polymorph.

*Habit*

Fibrous, asbestiform habit typifies chrysotile (Figure 8).



**FIGURE 8** Chrysotile, Mg<sub>6</sub>Si<sub>4</sub>O<sub>10</sub>(OH)<sub>8</sub> from Waldheim, Germany. Chrysotile is the asbestiform variety of serpentine.

***Structure and Composition***

Composition and structure are similar to those of antigorite, except that the mismatch in spacing of the octahedral and tetrahedral layers causes them to curl in one direction only, forming fibers.

***Occurrence and Associations***

Occurrence and associations are the same as for antigorite. In many serpentine samples, chrysotile layers are separated by a fine-grained platy polymorph called *lizardite*.

***Related Minerals***

Chrysotile has two polymorphs, lizardite and antigorite. Greenalite,  $\text{Fe}_3\text{Si}_2\text{O}_5(\text{OH})_4$ , the Fe equivalent of serpentine, has a different structure. Amosite and crocidolite, varieties of amphibole, are also asbestosiform.

**Clay Mineral Group**

montmorillonite	$(\text{Ca},\text{Na})_{0.2-0.4}(\text{Al},\text{Mg},\text{Fe})_2(\text{Si},\text{Al})_4\text{O}_{10}(\text{OH})_2 \cdot n\text{H}_2\text{O}$
illite	micalike clay mineral
kaolinite	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$
pyrophyllite	$\text{Al}_2\text{Si}_4\text{O}_{10}(\text{OH})_2$
talc	$\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$

To a petrologist, the term *clay* refers to a kind of rock or sediment, usually made of a number of minerals referred to as *clay minerals*. To a mineralogist, clays are a group of sheet silicates with related atomic structures. Most are hydrated aluminum or magnesium silicates that form as products of weathering. Clay mineral compositions are highly variable, in part due to poor crystallinity and mixed structures. The most common clay minerals are kaolinite, illite, and montmorillonite. Montmorillonite is the most common clay in bentonite, altered volcanic ash. *Smectite* is a general term for a number of clay minerals similar to montmorillonite.

Clay minerals fall into three main subgroups: smectite, illite, and kaolinite. For many clays, crystal structure and chemistry are variable or poorly determined. Illite and smectite are basically "three-layer" structures, while kaolinite clays are "two-layer" structures. Illite group clays, including illite, are transitional from smectites to true micas.

Similar in structure to serpentine, kaolinite is composed of alternating layers of Al octahedra and Si tetrahedra. Other clays have more complex structures. Illite is close to mica in structure but lacks essential alkalis. Pyrophyllite and talc, sometimes grouped with serpentine or considered to belong to a separate group, are here grouped with the other clay minerals because of similar chemistry.

**Montmorillonite*****Origin of Name***

From its original discovery at Montmorillon, near Limoges, France.

***Hand Specimen Identification***

Clays are difficult to tell apart without detailed X-ray study. When massive, they are unctuous and earthy if wet, and appear as soft, very fine-grained aggregates if dry.

***Physical Properties***

hardness	1 to $1\frac{1}{2}$
specific gravity	2.0 to 2.7
cleavage/fracture	perfect {001} rarely visible/irregular
luster/transparency	dull/sometimes translucent
color	white, gray, variable
streak	none

***Optical Properties***

Optical properties are highly variable due to variable chemistry and crystallinity.

***Crystallography***

Monoclinic,  $a = 5.17$ ,  $b = 8.94$ ,  $c = 15.20$ ,  $\beta = 99.9$ ,  $Z = 2$ ; point group  $2/m$ ; space group  $C2/m$ .

***Habit***

Earthy masses are typical.

***Structure and Composition***

The structure is based on groups of three layers: Single sheets of  $(\text{Al},\text{Mg})(\text{O},\text{OH})_6$  octahedra are sandwiched between two sheets of  $\text{SiO}_4$  tetrahedra. Montmorillonite is a member of the smectite group and forms solid solutions with beidellite,  $(\text{Na},\text{Ca})\text{Al}_2(\text{Si},\text{Al})_4\text{O}_{10}(\text{OH})_2 \cdot n\text{H}_2\text{O}$ . Other minor solid solutions are common, and the amount of  $\text{H}_2\text{O}$  is variable.

***Occurrence and Associations***

Clays are secondary minerals, often residual, formed by alteration of Al-rich silicates.

**Kaolinite*****Origin of Name***

From the Chinese word *Kao-ling*, the name of the hill that was the first source of kaolinite sent to Europe for ceramics.

***Hand Specimen Identification***

Claylike properties, including softness, habit, feel, and earthy smell, help identify kaolinite, but without

X-ray data it cannot be distinguished from other light-colored clays.

#### *Physical Properties*

hardness	2 to 2½
specific gravity	2.6
cleavage/fracture	perfect (001) but rarely seen
luster/transparency	dull/sometimes translucent
color	white
streak	white

#### *Optical Properties*

Optical identification of kaolinite is very difficult. Biaxial (-),  $\alpha = 1.556$ ,  $\beta = 1.563$ ,  $\gamma = 1.565$ ,  $\delta = 0.007$ ,  $2V = 40^\circ$ .

#### *Crystallography*

Triclinic,  $a = 5.15$ ,  $b = 8.92$ ,  $c = 7.38$ ,  $\alpha = 91.8^\circ$ ,  $\beta = 104.8^\circ$ ,  $\gamma = 90.0^\circ$ ,  $Z = 2$ ; space group  $P\bar{1}$ ; point group  $\bar{1}$ .

#### *Habit*

Kaolinite is usually massive or a fine-grained aggregate; rare platy, pseudohexagonal crystals have been found.

#### *Structure and Composition*

Kaolinite has a two-layer structure: Layers of  $\text{Al}(\text{O},\text{OH})_6$  octahedra alternate with sheets of  $\text{SiO}_4$  tetrahedra. Several minor substitutions are possible: Alkalies or alkaline earths may be present, as well as excess  $\text{H}_2\text{O}$ .

#### *Occurrence and Associations*

Kaolinite is a common secondary mineral, forming after aluminous silicates. It is a rock-forming mineral, a component of soils, and replaces feldspar in rocks undergoing weathering. Associated minerals include quartz and other minerals resistant to alteration.

#### *Related Minerals*

In composition and structure, kaolinite is equivalent to an aluminous serpentine. It has two polymorphs, dickite and nacrite.

## Pyrophyllite

## $\text{Al}_2\text{Si}_4\text{O}_{10}(\text{OH})_2$

#### *Origin of Name*

From the Greek word *pyro* and *phyllon*, meaning "fire" and "leaf," in reference to this mineral's behavior when heated.

#### *Hand Specimen Identification*

Softness, greasy feel, cleavage, and association help identify pyrophyllite, but it cannot be told from other clays without X-ray data. It is easily confused with talc. See Figure 9.

#### *Physical Properties*

hardness	1 to 2
specific gravity	2.8



**FIGURE 9** Radiating splays of pyrophyllite,  $\text{Al}_2\text{Si}_4\text{O}_{10}(\text{OH})_2$  from Mariposa County, California. Mineralogists often group pyrophyllite with clay minerals although it has less water and a more ordered structure than true clays.

cleavage/fracture	perfect basal (001)
luster/transparency	pearly/translucent
color	white
streak	white

#### *Optical Properties*

High birefringence, perfect cleavage, bird's-eye maple appearance, and lack of color identify pyrophyllite. Talc and muscovite have smaller 2Vs. Biaxial (-),  $\alpha = 1.553$ ,  $\beta = 1.588$ ,  $\gamma = 1.600$ ,  $\delta = 0.047$ ,  $2V = 52^\circ$  to  $62^\circ$ .

#### *Crystallography*

Triclinic,  $a = 5.16$ ,  $b = 8.96$ ,  $c = 9.35$ ,  $\alpha = 90.03^\circ$ ,  $\beta = 100.37^\circ$ ,  $\gamma = 89.75^\circ$ ,  $Z = 2$ ; space group  $P\bar{1}$ ; point group 1.

#### *Habit*

Individual crystals are unknown. Pyrophyllite is usually massive and foliated, sometimes forming platy or radiating masses, such as in Figure 9.

#### *Structure and Composition*

The three-layered structure consists of individual sheets of  $\text{Al}(\text{O},\text{OH})_6$  octahedra sandwiched between sheets of  $\text{SiO}_4$  tetrahedra. Fe may replace some of the Al; minor Mg, Ca, Na, or K may also be present.

#### *Occurrence and Associations*

Pyrophyllite is found in low- and medium-grade metamorphosed shales. Associated minerals include kyanite, feldspar, and quartz.

#### *Related Minerals*

Pyrophyllite is isostructural with talc,  $\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$ , and structurally similar to minnesotaite,  $\text{Fe}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$ .

**Talc****Mg<sub>3</sub>Si<sub>4</sub>O<sub>10</sub>(OH)<sub>2</sub>***Origin of Name*

Unknown; perhaps from the Arabic word *talg*, meaning "pure."

*Hand Specimen Identification*

Softness, greasy feel, massive habit, cleavage, and association help identify talc. It may be confused with pyrophyllite, serpentine, or chlorite.

*Physical Properties*

hardness	1
specific gravity	2.8
cleavage/fracture	perfect basal (001)/flexible
luster/transparency	resinous, silky/translucent
color	gray, white
streak	white

*Optical Properties*

Talc is similar to muscovite, chlorite, and pyrophyllite, but has a smaller  $2V$  and often appears smeared or poorly defined when viewed under crossed polars. Biaxial (-),  $\alpha = 1.54$ ,  $\beta = 1.58$ ,  $\gamma = 1.58$ ,  $\delta = 0.05$ ,  $2V = 6^\circ$  to  $30^\circ$ .

*Crystallography*

Monoclinic,  $a = 5.29$ ,  $b = 9.10$ ,  $c = 18.81$ ,  $\beta = 100.00^\circ$ ,  $Z = 4$ ; space group *Cc*; point group *m*.

*Habit*

Rare tabular pseudohexagonal crystals have been found, but talc is usually very fine grained and massive.

*Structure and Composition*

Talc is isostructural with pyrophyllite, being composed of layers of Mg(O,OH)<sub>6</sub> octahedra sandwiched between layers of SiO<sub>4</sub> tetrahedra. Talc may contain some Ti, Ni, Fe, or Mn but is generally quite pure.

*Occurrence and Associations*

Talc is a primary mineral in some low-grade metamorphic rocks, including marbles and ultramafic rocks, and less commonly a secondary mineral in mafic igneous rocks.

*Varieties*

When massive, talc is sometimes called *steatite* or *soapstone*.

*Related Minerals*

Talc is isostructural with pyrophyllite, Al<sub>2</sub>Si<sub>4</sub>O<sub>10</sub>(OH)<sub>2</sub>, and structurally similar to minnesotaite, Fe<sub>3</sub>Si<sub>4</sub>O<sub>10</sub>(OH)<sub>2</sub>.

**Mica Group Minerals***Biotite Series*

phlogopite	KMg <sub>3</sub> (AlSi <sub>3</sub> O <sub>10</sub> )(OH) <sub>2</sub>
annite	KFe <sub>3</sub> (AlSi <sub>3</sub> O <sub>10</sub> )(OH) <sub>2</sub>

*Other Micas*

muscovite	KAl <sub>2</sub> (AlSi <sub>3</sub> O <sub>10</sub> )(OH) <sub>2</sub>
margarite	CaAl <sub>2</sub> (Al <sub>2</sub> Si <sub>2</sub> O <sub>10</sub> )(OH) <sub>2</sub>
lepidolite	K(Li,Al) <sub>2-3</sub> (AlSi <sub>3</sub> O <sub>10</sub> )(OH) <sub>2</sub>

The mica group consists of a number of minerals, the principal ones being biotite and muscovite. The name *biotite* refers to a series dominated by end members phlogopite and annite. Mg-rich biotite (phlogopite) and Fe-rich biotite (annite) are often difficult to distinguish without detailed X-ray or chemical analyses. In common use, mineralogists call any black mica *biotite* and reserve the term *phlogopite* for brown micas. Muscovite, sometimes referred to as a "white mica," is in sharp contrast to biotite. However, it may be confused with margarite, lepidolite, and some other rarer micas. Margarite is one of the "brittle micas," a group that includes rarer clintonite and xanthophyllite. Lepidolite is a Li-rich mica found in pegmatites. Although annite and phlogopite enjoy complete solid solution, only limited solution is possible among other end members.

**Phlogopite****KMg<sub>3</sub>(AlSi<sub>3</sub>O<sub>10</sub>)(OH)<sub>2</sub>***Origin of Name*

From the Greek word *phlogopos*, meaning "fiery," in reference to this mineral's brown color.

*Hand Specimen Identification*

Phlogopite, an end member biotite, is identified by cleavage, color, and association. If not brown, it is indistinguishable from other biotites without additional analytical data.

*Physical Properties*

hardness	2½ to 3
specific gravity	2.8
cleavage/fracture	perfect basal (001)/elastic
luster/transparency	pearly/transparent
color	yellow-brown
streak	white

*Optical Properties*

Phlogopite is similar to other micas in thin section. It has a smaller  $2V$  than muscovite and is often colored light brown. It may be pleochroic, but not as much as the Fe-rich biotites. Biaxial (-),  $\alpha = 1.56$ ,  $\beta = 1.60$ ,  $\gamma = 1.60$ ,  $\delta = 0.04$ ,  $2V = 0^\circ$  to  $20^\circ$ .

*Crystallography*

Monoclinic,  $a = 5.31$ ,  $b = 9.19$ ,  $c = 10.15$ ,  $\beta = 95.18^\circ$ ,  $Z = 2$ ; space group  $C2/m$ ; point group  $2/m$ .

*Habit*

Coarse books of pseudohexagonal crystals are distinctive but uncommon. More frequently, phlogopite is disseminated as irregular grains or flakes or foliated masses.

*Structure and Composition*

The basic phlogopite structure is similar to that of talc and pyrophyllite: Two tetrahedral  $\text{SiO}_4$  layers surround an octahedral  $\text{Mg}(\text{O},\text{OH})_6$  layer. Unlike talc and pyrophyllite, however, the three-layer sandwiches are linked by  $\text{K}^+$  ions occupying large sites between them. Fe often substitutes for Mg, leading to complete solid solution with annite,  $\text{KFe}_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ . Al substitutes for both Mg and Si, creating solid solutions with siderophilite,  $\text{K}(\text{Fe},\text{Al})_3(\text{Si},\text{Al})_4\text{O}_{10}(\text{OH})_2$ . Limited solid solutions with muscovite,  $\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ , are also possible. Mn, Ti, and a number of alkalis and alkaline earths may also be present, and F may replace some OH.

*Occurrence and Associations*

Phlogopite is a common mineral in marbles where it associates with calcite, dolomite, quartz, diopside, and tremolite; less commonly, it is found in highly magnesium-rich igneous rocks.

*Related Minerals*

Phlogopite has several different polymorphs, which are difficult to tell apart without detailed X-ray studies. It is isostructural with muscovite,  $\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ , and isotypal with other micas, forming complete or limited solutions with most.

**Biotite** **$\text{K}(\text{Mg},\text{Fe})_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$** *Origin of Name*

Named after J. B. Biot (1774–1862), a French scientist who conducted detailed studies of micas.

*Hand Specimen Identification*

Biotite is distinguished by its association, micaceous nature, and dark color. It may be confused with other micas, especially chlorite. Composition is variable and cannot be determined without detailed analytical work.

*Physical Properties*

hardness	$2\frac{1}{2}$ to 3
specific gravity	2.9 to 3.1
cleavage/fracture	perfect basal {001}/ragged
luster/transparency	vitreous/transparent to opaque

## color

black, greenish black,  
brown-black

## streak

white

*Optical Properties*

Brown, red, or green in thin section, biotite exhibits strong pleochroism, perfect cleavage, bird's-eye extinction, and parallel or near-parallel extinction. Biaxial  $(-)$ ,  $\alpha = 1.57$ ,  $\beta = 1.60$ ,  $\gamma = 1.61$ ,  $\delta = 0.04$ ,  $2V = 0^\circ$  to  $32^\circ$ . Plates 5.3, 5.4, 5.7, and 5.9 show biotite in thin section. Stilpnomelane, a rarer related sheet silicate, looks much like biotite but lacks "bird's eye" extinction.

*Crystallography*

Monoclinic, pseudohexagonal,  $a = 5.33$ ,  $b = 9.31$ ,  $c = 10.16$ ,  $\beta = 99.3^\circ$ ,  $Z = 2$ ; space group  $C2/m$ ; point group  $2/m$ .

*Habit*

Rare, foliated books of pseudohexagonal crystals are distinctive but uncommon (Plate 6.6). More frequently, biotite is disseminated as irregular grains or flakes or foliated masses.

*Structure and Composition*

The basic biotite structure is identical to that of phlogopite: Two tetrahedral layers surround an octahedral layer. The three-layer sandwiches are linked by  $\text{K}^+$  ions occupying large sites between them. Fe mixes freely with Mg in octahedral sites, leading to complete solid solution between the two principal biotite end members: annite,  $\text{KFe}_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ , and phlogopite,  $\text{KMg}_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ . Coupled substitution of Al for both Mg and Si creates limited solid solutions with siderophilite,  $\text{K}(\text{Fe},\text{Al})_3(\text{Si},\text{Al})_4\text{O}_{10}(\text{OH})_2$ . Minor solid solution with muscovite,  $\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ , is also possible: Two Al replace three (Fe,Mg), leaving every third octahedral site vacant. Mn, Ti, and a number of alkalis and alkaline earths may also be present, and F may replace some OH.

*Occurrence and Associations*

Biotite is common in a wide variety of igneous and metamorphic rocks and in immature sediments. Associated minerals include other micas, amphiboles, quartz, and feldspars.

*Varieties*

Annite, phlogopite, and siderophilite are names given to end member Fe-, Mg-, and Al-biotite.

*Related Minerals*

Several biotite polymorphs differ in the ways the tetrahedral and octahedral sheets are stacked. Biotite is isostructural or isotypal with other micas, and similar in many ways to other sheet silicates.

**Muscovite***Origin of Name*

Named after the Muscovy principality of thirteenth-century Russia, which produced muscovite for use in window panes.

*Hand Specimen Identification*

Micaceous character (Figure 10a) and silver color distinguish muscovite. It may be confused with other white micas, such as paragonite or margarite. Certain identification requires optical, X-ray, or chemical analysis.

*Physical Properties*

hardness	2 to 2½
specific gravity	2.8
cleavage/fracture	perfect basal (001)/elastic
luster/transparency	vitreous/transparent
color	white, gray-brown
streak	white



(a)



(b)

**FIGURE 10** Muscovite and vermiculite: (a) Books of muscovite that give a hint of hexagonal symmetry; (b) vermiculite, a claylike sheet silicate related to micas, puffs up and expands when heated above 150°C.

*Optical Properties*

In thin section, muscovite appears clear, has moderate to high birefringence, sometimes has bird's-eye extinction, a high index of refraction, and one perfect cleavage. It may be confused with colorless phlogopite or with other white micas. Biaxial (−),  $\alpha = 1.565$ ,  $\beta = 1.596$ ,  $\gamma = 1.600$ ,  $\delta = 0.035$ ,  $2V = 30^\circ$  to  $40^\circ$ .

*Crystallography*

Monoclinic,  $a = 5.19$ ,  $b = 9.04$ ,  $c = 20.08$ ,  $\beta = 95.5^\circ$ ,  $Z = 4$ ; space group  $C2/c$ ; point group  $2/m$ .

*Habit*

Individual crystals are rare. Muscovite typically forms books of mica, often in massive aggregates (Figure 10a), with or without a pseudohexagonal outline, or is found as disseminated grains within a quartz-feldspar matrix. Penetration twins may be present.

*Structure and Composition*

The muscovite structure is identical to that of biotite except that Al has replaced two out of every three (Fe,Mg). Very limited solid solution with annite,  $\text{KFe}_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ , and with phlogopite,  $\text{KMg}_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ , are possible. Na may be present, resulting in solid solution toward paragonite,  $\text{NaAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ . Other alkalis and alkaline earths may also replace K. Li may replace some Al, and F may replace some OH.

*Occurrence and Associations*

Muscovite, the most common mica, is found in many silicic to intermediate igneous rocks, in a wide variety of metamorphic rocks, and in some immature sediments. Associated minerals include other micas, K-feldspar, and quartz.

*Varieties*

Sericite is a fine-grained form of muscovite created by alteration of feldspars and other alkali-aluminum silicates.

*Related Minerals*

Several different muscovite polymorphs are known. Muscovite is isotypical with biotite and other micas, such as lepidolite,  $\text{K}(\text{Li},\text{Al})_{2-3}(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ . It shares many properties with paragonite,  $\text{NaAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ , and with margarite,  $\text{CaAl}_2(\text{Al}_2\text{Si}_2\text{O}_{10})(\text{OH})_2$ .

**Margarite***Origin of Name*

From the Greek word *margarites*, meaning “pearl,” a reference to margarite’s color and luster.

*Hand Specimen Identification*

Margarite is characterized by its micaceous nature, brittleness, and pearly luster. Association and brittleness usually distinguish it from other white micas.

*Physical Properties*

hardness	$3\frac{1}{2}$ to 5
specific gravity	3.1
cleavage/fracture	perfect basal {001}/uneven
luster/transparency	vitreous/transparent to translucent
color	gray-yellow, pinkish silver
streak	white

*Optical Properties*

Margarite is colorless in thin section, resembling muscovite and other white micas. It is distinguished by a higher index of refraction, lower birefringence, and a  $6^\circ$ – $8^\circ$  extinction angle. Biaxial (–),  $\alpha = 1.635$ ,  $\beta = 1.645$ ,  $\gamma = 1.648$ ,  $\delta = 0.013$ ,  $2V = 45^\circ$ .

*Crystallography*

Monoclinic,  $a = 5.14$ ,  $b = 9.00$ ,  $c = 19.81$ ,  $\beta = 100.8^\circ$ ,  $Z = 4$ ; space group  $C2/c$ ; point group  $2/m$ .

*Habit*

Margarite is typically found in massive, micaceous books and aggregates; individual crystals are rare.

*Structure and Composition*

Margarite has a structure transitional between muscovite and chlorite. Because the interlayer site is occupied by  $\text{Ca}^{2+}$  rather than  $\text{K}^+$ , bonds between layers are stronger; thus, margarite is more brittle. Minor  $\text{Na}^+$  and  $\text{K}^+$  may replace  $\text{Ca}^{2+}$ ; charge balance is maintained by replacement of  $\text{Al}^{3+}$  by  $\text{Si}^{4+}$ . Be, Ba, Sr, K, Mn, Fe, Mg, and excess OH may also be present.

*Occurrence and Associations*

Margarite, typically found with corundum and diasporite, is an alteration product of corundum.

*Related Minerals*

Margarite is a member of the brittle mica group. Other members include clintonite and xanthophyllite, both having compositions  $\text{Ca}(\text{Mg},\text{Al})_{2-3}(\text{Al}_2\text{Si}_2)\text{O}_{10}(\text{OH})_2$ . Margarite also shares similarities with stilpnomelane,  $\text{K}(\text{Fe},\text{Al})_{10}\text{Si}_{12}\text{O}_{30}(\text{OH})_{12}$ .

**Lepidolite***Origin of Name*

From the Greek word *lepid*, meaning “scale,” referring to this mineral’s usual habit.

*Hand Specimen Identification*

Micaceous habit (see Figure 11), often a distinctive lilac-gray or rose color, and association usually serve to identify lepidolite.

*Physical Properties*

hardness	2.5 to 4
specific gravity	2.9
cleavage/fracture	perfect basal {001}/uneven
luster/transparency	pearly/translucent
color	lilac to rose-red; less commonly, yellow, gray, white
streak	white

*Optical Properties*

Lepidolite is generally colorless in thin section. It resembles muscovite but has lower relief and lower birefringence. Biaxial (–),  $\alpha = 1.53$  to  $1.55$ ,  $\beta = 1.55$ – $1.59$ ,  $\gamma = 1.55$  to  $1.59$ ,  $\delta = 0.02$  to  $0.04$ ,  $2V = 0^\circ$  to  $60^\circ$ .

*Crystallography*

Monoclinic,  $a = 5.21$ ,  $b = 8.97$ ,  $c = 20.16$ ,  $\beta = 100.8^\circ$ ,  $Z = 4$ ; space group  $C2/m$ ; point group  $2/m$ .

*Habit*

Lepidolite usually forms coarse- to fine-grained scaly aggregates. It is less commonly disseminated as fine flakes.

*Structure and Composition*

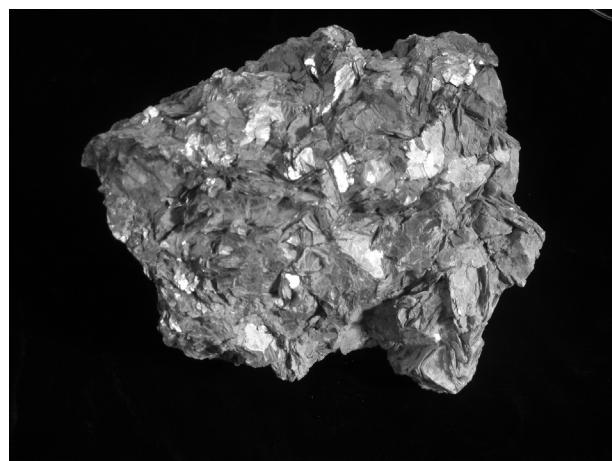
Lepidolite is actually a complex solid solution series with a structure similar to muscovite. Chemically, it is equivalent to muscovite with half or more of the octahedral Al replaced by Li, and perhaps Fe or Mg. In addition, other alkalis may substitute for K, and O or F may replace OH.

*Occurrence and Associations*

Lepidolite is restricted to Li-rich pegmatites. Associated minerals include other Li minerals such as tourmaline, amblygonite, and spodumene, as well as the more common muscovite, feldspar, and quartz.

*Related Minerals*

Lepidolite has several polymorphs that cannot be differentiated without detailed X-ray study. It is isostructural with other micas.



**FIGURE 11** Coarse lepidolite flakes from a pegmatite mine in the Black Hills, South Dakota.

## Chlorite Group Minerals

### Ideal End Members

clinochlore	$(\text{Mg}_5\text{Al})(\text{AlSi}_3)\text{O}_{10}(\text{OH})_8$
chamosite	$(\text{Fe}_5\text{Al})(\text{AlSi}_3)\text{O}_{10}(\text{OH})_8$
nimite	$(\text{Ni}_5\text{Al})(\text{AlSi}_3)\text{O}_{10}(\text{OH})_8$
pennantite	$(\text{Mn},\text{Al})_6(\text{Si},\text{Al})_4\text{O}_{10}(\text{OH})_8$

Chlorite is the general name given to a number of Mg-rich sheet silicates with similar chemistry and structure. Compositions vary widely, especially Mg, Fe, and Al contents, but cannot be determined without careful X-ray, chemical, or optical studies. The complex chemical variations and similarity of all chlorites make identifying individual species problematic, but a few ideal end member compositions have been given names. Structurally, all chlorites consist of alternating talclike and brucitelike layers. In both kinds of layers, Fe and Al may substitute for Mg; other elements, such as Ni, may also be present.

## Chlorite

### Composition variable; common chlorites are close to $(\text{Mg},\text{Fe},\text{Al})_6(\text{Si},\text{Al})_4\text{O}_{10}(\text{OH})_8$

#### Origin of Name

From the Greek word *chloros*, meaning “green.”

#### Hand Specimen Identification

Deep green color, and micaceous habit and cleavage are usually adequate to identify chlorite. The many individual species and varieties are difficult to tell apart. Chlorite is sometimes confused with talc.

#### Physical Properties

hardness	2 to $2\frac{1}{2}$
specific gravity	3.0
cleavage/fracture	perfect basal (001)/flexible
luster/transparency	vitreous/transparent
color	to translucent
streak	green, variable
	white, green

#### Optical Properties

Chlorite is generally green and sometimes green-brown in thin section. It usually exhibits yellow-green-brown pleochroism and has moderate to moderately high relief. Birefringence is low. Interference colors normally are between anomalous blue, brown, or purple and first-order yellow. Biaxial (-),  $\alpha = 1.56$  to 1.60,  $\beta = 1.57$  to 1.61,  $\gamma = 1.58$  to 1.61,  $\delta = 0.006$  to 0.020,  $2V = 0^\circ$  to  $40^\circ$ .

#### Crystallography

Monoclinic,  $a = 5.37$ ,  $b = 9.30$ ,  $c = 14.25$ ,  $\beta = 97.4^\circ$ ,  $Z = 2$ ; space group  $C2/m$ ; point group  $2/m$ .

#### Habit

Chlorite has habits similar to the other micas: Foliated books, scaly aggregates, and individual flakes in a quartz-feldspar matrix are common. Rare pseudohexagonal crystals are known.

#### Structure and Composition

The structure of chlorite consists of stacked talc,  $\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$  and brucite,  $\text{Mg}(\text{OH})_2$ , layers. The stacking order is variable, leading to a great deal of variety. In both kinds of layers, Al replaces some of the Mg, and in most chlorites Fe is present as well. A general formula,  $(\text{Mg},\text{Fe},\text{Al})_6(\text{Si},\text{Al})_4\text{O}_{10}(\text{OH})_8$ , does not describe all of the compositional variability.

#### Occurrence and Associations

Chlorite is a common mineral in low- to intermediate-grade metamorphic rocks, diagnostic of the greenschist facies. It is also a common secondary mineral after biotite, muscovite, and other mafic silicates in igneous and metamorphic rocks, and is sometimes found in sediments. Many greenish rocks owe their color to the presence of chlorite. Associated minerals include quartz and feldspars, epidote, muscovite, actinolite, albite, and a number of ferromagnesian silicates.

#### Varieties

Names given to some idealized chlorite compositions are clinochlore,  $(\text{Mg}_5\text{Al})(\text{AlSi}_3\text{O}_{10})(\text{OH})_8$ ; chamosite,  $(\text{Fe}_5\text{Al})(\text{AlSi}_3\text{O}_{10})(\text{OH})_8$ ; nimite,  $(\text{Ni}_5\text{Al})(\text{AlSi}_3\text{O}_{10})(\text{OH})_8$ ; and pennantite,  $(\text{Mn},\text{Al})_6(\text{Si},\text{Al})_4\text{O}_{10}(\text{OH})_8$ .

#### Related Minerals

Chlorite has many varieties and polymorphs. Other similar minerals include cookeite,  $\text{LiAl}_4(\text{AlSi}_3\text{O}_{10})(\text{OH})_8$ ; sudoite,  $\text{Mg}_2(\text{Al},\text{Fe})_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_8$ ; and a number of other hydrated aluminosilicates.

## Other Sheet Silicates

prehnite	$\text{Ca}_2\text{Al}(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$
apophyllite	$\text{KCa}_4\text{Si}_8\text{O}_{20}\text{F} \cdot 8\text{H}_2\text{O}$
sepiolite	$\text{Mg}_4\text{Si}_6\text{O}_{15}(\text{OH})_2 \cdot 6\text{H}_2\text{O}$
chrysocolla	$\text{Cu}_4\text{Si}_4\text{O}_{10}\text{H}_4(\text{OH})_8 \cdot n\text{H}_2\text{O}$
glauconite	$\sim(\text{K},\text{Na})(\text{Fe},\text{Mg},\text{Al})_2(\text{Si},\text{Al})_4\text{O}_{10}(\text{OH})_2$

A number of other minerals may be considered sheet silicates but do not fit into any of the groups previously discussed; five examples are listed above. Prehnite and apophyllite are secondary minerals, similar in occurrence and association to zeolites. Due to highly variable properties, chemistry, and structure, glauconite, sepiolite, and chrysocolla are not discussed in detail. Glauconite and sepiolite are both claylike minerals, and chrysocolla is a secondary copper mineral of highly variable chemistry. Okenite (Figure 12), a mineral closely related to zeolites and the others listed in this box, contains both chains and sheets of silicon tetrahedra.

**Prehnite***Origin of Name*

Named after H. van Prehn, who discovered this mineral in 1774.

*Hand Specimen Identification*

Prehnite, although not a zeolite, occurs in many of the same places that zeolites occur. When green and botryoidal (typical) it is easily identified. Otherwise it may be difficult to distinguish from zeolites, and may also be confused with hemimorphite and smithsonite.

*Physical Properties*

hardness	6 to $6\frac{1}{2}$
specific gravity	2.9
cleavage/fracture	good basal (001)/uneven
luster/transparency	vitreous/transparent to translucent
color	pale green
streak	white

*Optical Properties*

Prehnite is colorless in thin section. It has moderate birefringence but often exhibits anomalous interference figures, sometimes with an "hourglass" or "bow tie" structure. It may be confused with lawsonite, pumpellyite, epidote, datolite, and a number of zeolites but has higher birefringence than all of them. Biaxial (+),  $\alpha = 1.625$ ,  $\beta = 1.635$ ,  $\gamma = 1.655$ ,  $\delta = 0.03$ ,  $2V = 65^\circ$  to  $70^\circ$ .

*Crystallography*

Orthorhombic,  $a = 4.65$ ,  $b = 5.48$ ,  $c = 18.49$ ,  $Z = 2$ ; space group  $P2/n2_1/c2/m$ ; point group  $2/m2/m2/m$ .

*Habit*

Botryoidal, globular, barrel-shaped, and reniform aggregates are typical. Rarely, prehnite is found as individual tabular or prismatic crystals.

*Structure and Composition*

Prehnite consists of tetrahedral  $(\text{Si}, \text{Al})\text{O}_4$  sheets connected by  $\text{Al}(\text{O}, \text{OH})_6$  octahedra. Fe may replace some of the Al.

*Occurrence and Associations*

Prehnite may be a product of low-grade metamorphism but is more commonly a secondary mineral that forms as crusts or fillings in basalt and other mafic igneous rocks. Associated minerals include pumpellyite, zeolites, datolite, pectolite, and calcite.

*Related Minerals*

Prehnite is sometimes grouped with the zeolites because of its similar occurrences. Its structure, however, is significantly different.

**Apophyllite***Origin of Name*

From the Greek words for "form" and "leaf," because it becomes flaky on heating.

*Hand Specimen Identification*

Like prehnite, apophyllite often occurs where zeolites occur. Perfect one direction of cleavage, form, color, and luster help identify it.

*Physical Properties*

hardness	$4\frac{1}{2}$ to 5
specific gravity	2.3
cleavage/fracture	one perfect (001), poor {110}/uneven
luster/transparency	pearly/transparent to translucent
color	colorless, white, gray
streak	white

*Optical Properties*

Apophyllite has negative relief, is colorless, and has very low birefringence. It has perfect (001) cleavage, and often exhibits anomalous interference colors. Uniaxial (+),  $\omega = 1.535$ ,  $\epsilon = 1.537$ ,  $\delta = 0.002$ .

*Crystallography*

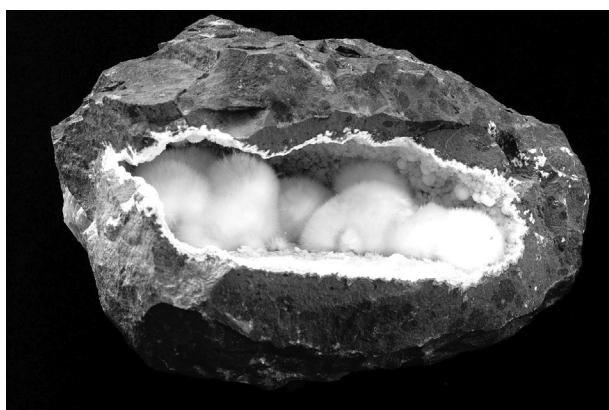
Tetragonal,  $a = 8.96$ ,  $c = 15.78$ ,  $Z = 2$ ; space group  $P4/m2_1/n2/c$ ; point group  $4/m2/m2/m$ .

*Habit*

Apophyllite has a varied habit, including short prisms, pinacoids, and bipyramids. It often has pseudosymmetry, appearing to be combinations of cubes and octahedra.

*Structure and Composition*

Sheets in the apophyllite structure are composed of 4- and 8-member rings of  $\text{SiO}_4$  tetrahedra. Interlayer Ca, K, and F link the tetrahedral sheets.



**FIGURE 12** Okenite, a zeolite mineral related to apophyllite, that has grown to form "cotton balls" in a vug in basalt.

*Occurrence and Associations*

Apophyllite is a secondary mineral, which sometimes lines openings in basalt and other mafic igneous rocks. Associated minerals include zeolites, datolite, calcite, and pectolite.

**CHAIN SILICATES****Pyroxene Group Minerals***Orthopyroxene Series*

enstatite	$Mg_2Si_2O_6$
ferrosilite	$Fe_2Si_2O_6$

*Clinopyroxene (Diopside) Series*

diopside	$CaMgSi_2O_6$
hedenbergite	$CaFeSi_2O_6$

*Pyroxene Solid Solutions*

hypersthene	$(Mg,Fe)_2Si_2O_6$
pigeonite	$(Ca,Mg,Fe)_2Si_2O_6$
augite	$(Ca,Mg,Fe,Na)(Mg,Fe,Al)(Si,Al)_2O_6$
omphacite	$(Ca,Na)(Fe,Mg,Al)(Si,Al)_2O_6$
aegirine	$Na(Al,Fe^{3+})Si_2O_6$

*Na- and Li-pyroxenes*

jadeite	$NaAlSi_2O_6$
spodumene	$LiAlSi_2O_6$

All pyroxenes have a structure based on chains of  $SiO_4$  tetrahedra linked by shared (bridging) oxygen. Octahedral cations (Ca, Na, Mg, Fe, Al) occupy sites between nonbridging oxygens of adjacent chains. Small amounts of Al sometimes replace tetrahedral Si.

Mineralogists divide pyroxenes into two groups based on their crystal symmetry. Orthopyroxenes (orthorhombic) have two principal end members: enstatite,  $Mg_2Si_2O_6$ , and ferrosilite,  $Fe_2Si_2O_6$ . Compositions between are generally called hypersthene but more specific names can be found in the literature. Clinopyroxenes (monoclinic) include diopside-hedenbergite solid solutions, high-temperature polymorphs of hypersthene, and a number of other Ca- and Na-bearing species. The most important end member is diopside,  $CaMgSi_2O_6$ ; many natural clinopyroxenes are close to diopside composition, so the name *diopside* is often used to refer to any green or greenish black clinopyroxene. Petrologists use the names *hypersthene*, *pigeonite*, *augite*, *omphacite*, and *aegirine* to describe solid solution clinopyroxenes having specific physical properties or compositions.

Except at very high temperature, a large solvus exists between monoclinic calcic pyroxenes and orthorhombic Ca-free pyroxenes. Consequently, many mafic rocks contain both clinopyroxene and orthopyroxene.

**Enstatite** **$Mg_2Si_2O_6$** *Origin of Name*

From the Greek word *enstatis*, meaning "adversary," which refers to this mineral's resistance to melting.

*Hand Specimen Identification*

Association, luster, color, and two cleavages at about  $90^\circ$  to each other identify pyroxene, but distinguishing enstatite from other pyroxenes can be problematic. Exact composition cannot be determined without additional analytical data. It may also be confused with amphibole, but the latter has two cleavages at about  $60^\circ$  to each other.

*Physical Properties*

hardness	5 to 6
specific gravity	3.2 to 3.5
cleavage/fracture	two perfect prismatic {210}/uneven
luster/transparency	vitreous, pearly/translucent
color	gray, green
streak	white, gray

*Optical Properties*

Enstatite is nearly colorless in thin section. If Fe has replaced some of the Mg, it may exhibit slight to pronounced pink to green pleochroism. An  $86^\circ$  cleavage angle, parallel extinction in prismatic section, and relatively low birefringence distinguish it from clinopyroxene. Biaxial (+),  $\alpha = 1.657$ ,  $\beta = 1.659$ ,  $\gamma = 1.665$ ,  $\delta = 0.008$ ,  $2V = 54^\circ$ .

Orthorhombic,  $a = 18.22$ ,  $b = 8.81$ ,  $c = 5.21$ ,  $Z = 4$ ; space group  $P2_1/b2_1/c2_1/a$ ; point group  $2/m2/m2/m$ .

*Habit*

Enstatite is usually massive, blocky, fibrous, or lamellar. Individual crystals may be prismatic or acicular.

*Structure and Composition*

Enstatite is one of two principal orthopyroxene end members; the other is ferrosilite,  $Fe_2Si_2O_6$ . Enstatite and other pyroxenes contain chains of zigzagging  $SiO_4$  tetrahedra running parallel to the c-axis. Each tetrahedron shares two oxygens with neighbors in its chain and has one unshared oxygen at an apex pointing perpendicular to the c-axis. Pairs of chains face each other; Mg is located in four adjacent octahedral sites between unshared apices of tetrahedra. Complete solid solution exists between enstatite and ferrosilite. Except at high temperature, only limited solid solution exists with the clinopyroxene end members diopside,  $CaMgSi_2O_6$ , and hedenbergite,  $CaFeSi_2O_6$ . Mn, Cr, Al, and Ti may also be present in small amounts.

*Occurrence and Associations*

Enstatite is common in mafic igneous rocks, including gabbro, basalt, and norite, commonly associating

with plagioclase and clinopyroxene. It is also found in some high-grade metamorphic rocks and is considered diagnostic for the granulite facies.

#### Varieties

Bronzite ( $Mg >> Fe$ ) and hypersthene ( $Mg > Fe$ ) are varietal names given to Mg-Fe orthopyroxene.

#### Related Minerals

Enstatite is isostructural or isotypical with other pyroxenes. It is closely related to ferrosilite,  $Fe_2Si_2O_6$ , and donpeacorite,  $(Mn,Mg)_2Si_2O_6$ . Most natural orthopyroxenes are Mg-Fe solid solutions with Mg dominant.

## Diopsid

## $CaMgSi_2O_6$

#### Origin of Name

From the Greek words *dis* and *opsis*, meaning “two” and “appearance,” in reference to the fact that diopside appears different when viewed in different ways.

#### Hand Specimen Identification

Association, form, two cleavages at  $86^\circ$  to each other, and color identify diopside (Figure 13). It may be confused with other pyroxenes or with hornblende, but the latter has two cleavages at  $60^\circ$  to each other. Diopside may contain substantial Fe, Al, or other impurities; exact composition cannot be determined without additional analytical data. Diopside is often white to green or pale green; augite tends to be darker green or black. Plates 6.2 and 6.3 contain color photos of diopside.

#### Physical Properties

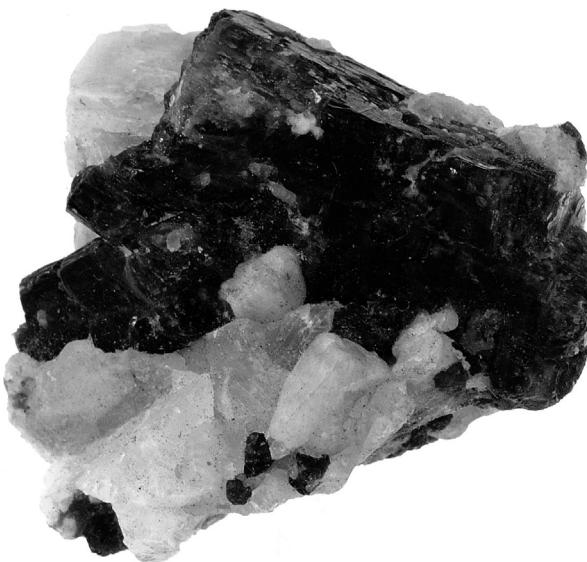
hardness	$5\frac{1}{2}$ to $6\frac{1}{2}$
specific gravity	3.2 to 3.5
cleavage/fracture	two perfect prismatic {110}/uneven
luster/transparency	vitreous/transparent to translucent
color	light green, variable
streak	white, gray

#### Optical Properties

Diopside is colorless in thin section when Fe-free. With increasing iron content, it may become pleochroic in greens or browns. Higher birefringence and inclined extinction distinguish clinopyroxene from orthopyroxene. Grains are prismatic or blocky, depending on orientation. Extinction angle, optic sign, and  $2V$  help distinguish the different clinopyroxenes, but telling them apart may be difficult. Biaxial (+),  $\alpha = 1.665$ ,  $\beta = 1.672$ ,  $\gamma = 1.695$ ,  $\delta = 0.030$ ,  $2V = 56^\circ$  to  $62^\circ$ .

#### Crystallography

Monoclinic,  $a = 9.7$ ,  $b = 8.9$ ,  $c = 5.25$ ,  $\beta = 105.83^\circ$ ,  $Z = 4$ ; space group  $C2/c$ ; point group  $2/m$ .



**FIGURE 13** This sample of a marble, from near Chenaux, Quebec, contains diopside (dark) and calcite (light). Diopside is common in marbles, but usually is not as darkly colored as in this sample.

#### Habit

Prismatic crystals often have a square or octahedral cross section. Diopside may also be massive or finely disseminated. Polysynthetic twins are common but may not be visible without a microscope.

#### Structure and Composition

The structure of diopside is similar to that of other pyroxenes. Chains of  $SiO_4$  tetrahedra run parallel to the c-axis, with octahedral Ca and Mg connecting opposing chains to each other. Ca and Mg occupy different structural sites; Ca: Mg ratios are always  $\leq 1:1$ . A complete solid solution series exists between diopside, hedenbergite,  $CaFeSi_2O_6$ , and johannsenite,  $CaMn(Si_2O_6)$ . Small amounts of Al, Mn, Na, Ti, and Cr may be present.

#### Occurrence and Associations

Diopside is a very common pyroxene. It is found in mafic and ultramafic igneous rocks, associated with plagioclase, hornblende, and olivine. It is found in marbles (Plate 6.3) associated with calcite, quartz or forsterite, tremolite, scapolite, and garnet. It is also found in medium- and high-grade metamorphosed mafic rocks.

#### Varieties

Chrome diopside is a chromium-rich variety known for its vivid green color (Plate 6.2).

#### Related Minerals

All pyroxenes are closely related. Hedenbergite,  $CaFeSi_2O_6$ , is the iron end member of the diopside series. Augite,  $(Ca,Mg,Fe,Na)(Mg,Fe,Al)Si_2O_6$ , is a related pyroxene with slightly different structure. Pigeonite is a high-temperature, subcalcic pyroxene with compositions that approach those of Fe-Mg diopside.

**Pigeonite***Origin of Name*

Named after the locality where this mineral was originally found, Pigeon Cove, Minnesota.

*Hand Specimen Identification*

Occurrence as phenocrysts in volcanic rock, form, two cleavages at  $86^\circ$ , and color identify pyroxene, but telling pigeonite from the other dark-colored pyroxenes is difficult. Only X-ray studies can make the distinction.

*Physical Properties*

hardness	6
specific gravity	3.40
cleavage/fracture	two perfect prismatic {110}/uneven
luster/transparency	vitreous/transparent to translucent
color	brown, green, black
streak	white

*Optical Properties*

Pigeonite is similar to other clinopyroxenes in thin section (see diopside) but has a lower  $2V$ . Biaxial (+),  $\alpha = 1.69$ ,  $\beta = 1.69$ ,  $\gamma = 1.72$ ,  $\delta = 0.025$ ,  $2V = 0^\circ$  to  $32^\circ$ .

*Crystallography*

Monoclinic,  $a = 9.73$ ,  $b = 8.95$ ,  $c = 5.26$ ,  $\beta = 108.55^\circ$ ,  $Z = 4$ ; space group  $C2/c$ ; point group  $2/m$ .

*Habit*

Rare euhedral crystals are prismatic. Pigeonite is most commonly in granular masses or in columnar aggregates or is found as fine grains or zones associated with other pyroxenes.

*Structure and Composition*

Pigeonite is similar in structure to other pyroxenes (enstatite and diopside), and may contain the same impurities. It contains more Ca than enstatite and less than diopside, resulting in a slightly different structure.

*Occurrence and Associations*

Pigeonite is only found in high-temperature igneous rocks that have cooled rapidly. In many cases, it inverts to lower temperature pyroxenes with cooling, but its former presence may be inferred from textural features or from the presence of exsolved grains of augite and orthopyroxene.

*Related Minerals*

Pigeonite is closely related to other pyroxenes, especially augite.

**Augite***Origin of Name*

From the Greek word *augites*, meaning "brightness," referring to its shiny cleavage surfaces.

*Hand Specimen Identification*

Association, form, two cleavages at  $86^\circ$  to  $87^\circ$ , and color identify pyroxene, but differentiating augite is problematic without X-ray data. White to green or pale green pyroxenes are often diopside; augite tends to be dark green or black. Augite is occasionally confused with hornblende. Plate 6.1 is a color photo of massive augite.

*Physical Properties*

hardness	5 to 6
specific gravity	3.2 to 3.4
cleavage/fracture	two perfect {110}/uneven
luster/transparency	vitreous/transparent to translucent
color	black, dark green
streak	white

*Optical Properties*

Augite is similar to other clinopyroxenes in thin section. Grains are prismatic or blocky, depending on orientation. Color may be various shades of light brown, yellow-brown, or green. Augite may exhibit weak pleochroism. Extinction angle, optic sign, and  $2V$  help distinguish the different clinopyroxenes, but telling them apart may be difficult. Biaxial (+),  $\alpha = 1.671$  to  $1.735$ ,  $\beta = 1.672$  to  $1.741$ ,  $\gamma = 1.703$  to  $1.761$ ,  $\delta = 0.030$ ,  $2V = 25^\circ$  to  $60^\circ$ .

*Crystallography*

Monoclinic,  $a = 9.8$ ,  $b = 9.0$ ,  $c = 5.25$ ,  $\beta = 105^\circ$ ,  $Z = 4$ ; space group  $C2/c$ ; point group  $2/m$ .

*Habit*

Individual crystals are typically poorly formed stubby black or green prisms with octagonal or square cross sections. Simple and polysynthetic twins may be present.

*Structure and Composition*

The structure of augite is similar to that of the other clinopyroxenes (see diopside). Its chemistry is, however, more complex and variable. Ca:Mg:Fe ratios vary. Significant solid solution occurs with jadeite,  $\text{NaAlSi}_2\text{O}_6$ ; aegirine,  $\text{Na}(\text{Al}, \text{Fe})\text{Si}_2\text{O}_6$ ; and Ca-Tschermark's pyroxene,  $\text{CaAl}_2\text{SiO}_6$ . Ti, Li, Mn, and a number of other elements may also be present in small amounts.

*Occurrence and Associations*

Augite is the most common pyroxene found in mafic to intermediate igneous rocks, both plutonic and volcanic. Associated minerals include hornblende and plagioclase.

*Related Minerals*

Augite is equivalent in composition to diopside with many impurities, especially Na. It is structurally and chemically closely related to other pyroxenes, especially pigeonite, and to pyroxenoids. Omphacite is a bright green variety of augite rich in Na and Al.

**Jadeite****NaAlSi<sub>2</sub>O<sub>6</sub>***Origin of Name*

Name of unknown origin. The term *jade* refers to either jadeite or to the amphibole, nephrite.

*Hand Specimen Identification*

Association with other high-pressure minerals, form, two (rarely seen) cleavages at near 90°, green color, and tenacity identify jadeite. It is distinguished from nephrite by its luster. An optical microscope may be needed to confirm identification.

*Physical Properties*

hardness	6½ to 7
specific gravity	3.30
cleavage/fracture	two perfect {110}/uneven
luster/transparency	vitreous, greasy/translucent
color	variable shades of green to white
streak	white

*Optical Properties*

Jadeite is colorless to very pale green in thin section. Birefringence is low; anomalous blue interference colors are common, maximum interference colors are first-order red or yellow. Jadeite exhibits typical clinopyroxene shape and cleavage but has a higher  $2V$  than most. Biaxial (+),  $\alpha = 1.65$ ,  $\beta = 1.66$ ,  $\gamma = 1.67$ ,  $\delta = 0.02$ ,  $2V = 70^\circ$  to  $75^\circ$ .

*Crystallography*

Monoclinic,  $a = 9.50$ ,  $b = 8.61$ ,  $c = 5.24$ ,  $\beta = 110.46^\circ$ ,  $Z = 4$ ; space group  $C2/c$ ; point group  $2/m$ .

*Habit*

Jadeite is usually granular, forming tenacious masses; less commonly, in prismatic or tabular crystals.

*Structure and Composition*

Jadeite is similar in structure to other clinopyroxenes and may contain some of the same impurities (see diopside). It forms limited solid solutions with aegirine,  $\text{NaFeSi}_2\text{O}_6$ , with omphacite,  $(\text{Ca},\text{Na})(\text{Fe},\text{Mg},\text{Al})\text{Si}_2\text{O}_6$ , and with other pyroxene end members.

*Occurrence and Associations*

Jadeite is a high-pressure pyroxene found in metamorphic rocks of the blueschist facies. It is associated with other high-pressure minerals such as glaucophane, lawsonite, or aragonite, and with quartz and

epidote. A bright green variety of jadeite, omphacite, occurs in eclogites with pyrope-rich garnet. Omphacite is also found in kimberlites.

*Related Minerals*

Jadeite is closely related to other Na-pyroxenes: aegirine,  $\text{NaFeSi}_2\text{O}_6$ ; omphacite,  $(\text{Ca},\text{Na})(\text{Fe},\text{Mg},\text{Al})\text{Si}_2\text{O}_6$ ; and aegirine-augite,  $(\text{Ca},\text{Na})(\text{Fe}^{2+},\text{Fe}^{3+},\text{Mg})\text{Si}_2\text{O}_6$ . It is chemically similar to nepheline,  $(\text{Na},\text{K})\text{AlSiO}_4$ , and to albite,  $\text{NaAlSi}_3\text{O}_8$ .

**Spodumene****LiAlSi<sub>2</sub>O<sub>6</sub>***Origin of Name*

From the Greek word *spodoumenos*, meaning "ashes."

*Hand Specimen Identification*

Spodumene is typically found in pegmatites where it may form very large crystals. Prismatic cleavage, hardness, color, and association help identify it, but it may be difficult to tell from feldspar or scapolite. It often has the appearance of a log or of petrified wood.

*Physical Properties*

hardness	6½ to 7
specific gravity	3.15
cleavage/fracture	two perfect prismatic {110}/uneven
luster/transparency	vitreous/transparent to translucent
color	highly variable: colorless, white, gray, pink, green, yellow, purple, or tan
streak	white

*Optical Properties*

Spodumene is similar to other clinopyroxenes in thin section. Its occurrence in pegmatites and its small extinction angle ( $20^\circ$  to  $26^\circ$ ) help identify it. Biaxial (+),  $\alpha = 1.65$ ,  $\beta = 1.66$ ,  $\gamma = 1.67$ ,  $\delta = 0.02$ ,  $2V = 60^\circ$  to  $80^\circ$ .

*Crystallography*

Monoclinic,  $a = 9.52$ ,  $b = 8.32$ ,  $c = 5.25$ ,  $\beta = 110.46^\circ$ ,  $Z = 4$ ; space group  $C2/c$ ; point group  $2/m$ .

*Habit*

Prismatic crystals with well-developed {100} faces showing vertical striations are common. Crystals are often polysynthetically twinned and may be very large. In some pegmatites they are tens of meters long. Spodumene also occurs as cleavable masses.

*Structure and Composition*

Spodumene is a pyroxene with structure similar to that of diopside. Minor Na substitutes for Li, Fe, Ca, Mn, Mg, and rare earths are also present in small amounts.

***Occurrence and Associations***

Spodumene is found in granitic pegmatites, where it associates with K-feldspar, muscovite, quartz, tourmaline, beryl, and lepidolite.

***Varieties***

Hiddenite is a name given to emerald-green spodumene; kunzite to lilac/pink spodumene; and triphane to colorless or yellow spodumene.

***Related Minerals***

Spodumene is similar to other pyroxenes (see **diopside**). It is similar in composition to eucryptite,  $\text{LiAlSiO}_4$ .

**Amphibole Group Minerals*****Monoclinic Amphiboles***

## cummingtonite series

cummingtonite	$(\text{Mg},\text{Fe})_7\text{Si}_8\text{O}_{22}(\text{OH})_2$
grunerite	$\text{Fe}_7\text{Si}_8\text{O}_{22}(\text{OH})_2$

## actinolite series

tremolite	$\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$
actinolite	$\text{Ca}_2(\text{Mg},\text{Fe})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$

## hornblende



## Na-amphiboles

glaucophane	$\text{Na}_2\text{Mg}_3\text{Al}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$
riebeckite	$\text{Na}_2(\text{Fe},\text{Mg})_3(\text{Fe},\text{Al})_2\text{Si}_8\text{O}_{22}(\text{OH})_2$

***Orthorhombic Amphiboles***

anthophyllite	$(\text{Mg},\text{Fe})_7\text{Si}_8\text{O}_{22}(\text{OH})_2$
gedrite	$(\text{Mg},\text{Fe},\text{Al})_7(\text{Al},\text{Si})_8\text{O}_{22}(\text{OH})_2$

Amphiboles are double-chain silicates, sharing many physical and chemical properties with pyroxenes. Major chemical variations mirror those of the pyroxene group. Calcic amphiboles are monoclinic; Ca-free amphiboles are generally orthorhombic. A solvus between calcic and non-calcic amphiboles results in many rocks containing two, or in some cases three, different amphibole species.

Many end member amphiboles have specific names, the most important are listed above (see **hornblende** entry for additional names). The detailed entries that follow do not include gedrite and riebeckite because they are similar to the more common anthophyllite and glaucophane.

The name *hornblende* is used by petrologists to refer to the common black amphibole found in many igneous and metamorphic rocks. Hornblendes have complex and highly variable chemistry; the formula above only partially reflects the variations.

**Cummingtonite  $(\text{Mg},\text{Fe})_7\text{Si}_8\text{O}_{22}(\text{OH})_2$** ***Origin of Name***

Named after Cummington, Massachusetts, its type locality.

***Hand Specimen Identification***

Prismatic habit, two perfect cleavages intersecting at near  $60^\circ$  when viewed in basal section, habit, color (if light brown), and association identify cummingtonite. It may be confused with other amphiboles, especially anthophyllite and gedrite.

***Physical Properties***

hardness	$5\frac{1}{2}$ to 6
specific gravity	2.9 to 3.2
cleavage/fracture	two perfect prismatic {110}/uneven
luster/transparency	vitreous, silky, fibrous/transparent to translucent
color	light brown, whitish, or green
streak	white

***Optical Properties***

Cummingtonite is colorless to pale green in thin section and exhibits weak pleochroism. Interference colors may be up to second order. Basal sections show typical amphibole cleavage displaying  $56^\circ$  and  $b = 18.01$  angles. Extinction is inclined  $c = 5.33$  to prismatic cleavage, polysynthetic twinning is common, and birefringence is greater than for anthophyllite-gedrite. Biaxial (+),  $\alpha = 1.644$ ,  $\beta = 1.657$ ,  $\gamma = 1.674$ ,  $\delta = 0.030$ ,  $2V = 80^\circ$  to  $90^\circ$ .

***Crystallography***

Monoclinic,  $a = 9.51$ ,  $b = 18.19$ ,  $c = 5.33$ ,  $\beta = 101.83^\circ$ ,  $Z = 2$ ; space group  $C2/m$ ; point group  $2/m$ .

***Habit***

Cummingtonite forms prismatic, fibrous crystals; aggregates of radiating fibers or blades are common.

***Structure and Composition***

Cummingtonite, like other amphiboles, has a double-chain structure.  $\text{SiO}_4$  tetrahedra are linked to make double chains that run parallel to the c-axis. Each tetrahedron shares two or three oxygen with neighbors, and has an unshared oxygen at the vertex pointing perpendicular to c. Chains are paired; unshared oxygens point toward each other and are bonded to the five octahedral cations occupying sites between them. A complete solid solution series exists between Mg-cummingtonite,  $\text{Mg}_7\text{Si}_8\text{O}_{22}(\text{OH})_2$ , and grunerite,  $(\text{Fe}_7\text{Si}_8\text{O}_{22}(\text{OH})_2$ . The name *cummingtonite* is given to intermediate compositions,  $(\text{Mg},\text{Fe})_7\text{Si}_8\text{O}_{22}(\text{OH})_2$ , with  $\text{Mg} > \text{Fe}$ . Substantial Mn may replace Mg; Al and Ca may be present in small amounts.

*Occurrence and Associations*

Cummingtonite occurs in mafic or marly medium-grade metamorphic rocks. Common associated minerals include other amphiboles (hornblende, actinolite, or anthophyllite), garnet, plagioclase, and cordierite. Cummingtonite also occurs in a few rare kinds of igneous rocks.

*Varieties*

Amosite is an asbestosiform amphibole similar to Fe-rich cummingtonite.

*Related Minerals*

Cummingtonite is closely related to the other amphiboles and is polymorphic with members of the anthophyllite series.

**Grunerite** **$\text{Fe}_7\text{Si}_8\text{O}_{22}(\text{OH})_2$** *Origin of Name*

Named after L. E. Grüner, a nineteenth-century mineralogist who first analyzed grunerite.

*Hand Specimen Identification*

Habit, color, two prominent cleavages at  $56^\circ$  to each other, and association help identify grunerite, but it cannot be distinguished from other members of the cummingtonite series without chemical or X-ray analysis.

*Physical Properties*

hardness	6
specific gravity	3.1 to 3.6
cleavage/fracture	two perfect prismatic {110}/uneven
luster/transparency	silky, vitreous/transparent to translucent
color	dark green or brown
streak	white

*Optical Properties*

Grunerite is similar to other members of the cummingtonite-grunerite series (see **cummingtonite**), but exhibits less pleochroism than cummingtonite, has an extinction angle of  $10^\circ$  to  $15^\circ$  prismatic cleavage, and may show interference colors up to third order. Biaxial (-),  $\alpha = 1.69$ ,  $\beta = 1.71$ ,  $\gamma = 1.73$ ,  $\delta = 0.040$ ,  $2V = 80^\circ$  to  $90^\circ$ .

*Crystallography*

Monoclinic,  $a = 9.6$ ,  $b = 18.3$ ,  $c = 5.3$ ,  $\beta = 101.8^\circ$ ,  $Z = 2$ ; space group  $C2/m$ ; point group  $2/m$ .

*Habit*

Grunerite typically forms fibrous, bladed, or columnar crystals, often radiating.

*Structure and Composition*

Grunerite is an end member of the cummingtonite-grunerite series. Structure and composition are analogous to cummingtonite. The name *grunerite* is by definition restricted to compositions close to end member  $\text{Fe}_7\text{Si}_8\text{O}_{22}(\text{OH})_2$ .

*Occurrence and Associations*

Grunerite is found with Fe-rich minerals such as magnetite, hematite, minnesotaite, hedenbergite, fayalite, or garnet in metamorphosed Fe-rich sediments.

*Related Minerals*

Grunerite is closely related to the other amphiboles, especially cummingtonite.

**Tremolite** **$\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$** *Origin of Name*

Named after Val Tremola, Switzerland, where it was first found.

*Hand Specimen Identification*

Association, perfect prismatic cleavages, and  $56^\circ$  cleavage angle when viewed in basal section, fibrous/bladed or thin columnar crystals, and generally very light color identify tremolite. A  $56^\circ$  cleavage angle distinguishes it from pyroxenes and pyroxenoids; light color distinguishes it from hornblende. It may also be confused with vesuvianite or wollastonite.

*Physical Properties*

hardness	5 to 6
specific gravity	3.0 to 3.3
cleavage/fracture	two perfect prismatic {110}/uneven
luster/transparency	transparent to translucent
color	white, green
streak	white

*Optical Properties*

Generally colorless when Fe-free, tremolite may be green and pleochroic when Fe is present. Amphibole cleavage angles ( $56^\circ$  and  $124^\circ$ ),  $10^\circ$  to  $21^\circ$  extinction angle in prismatic section, large  $2V$ , and upper first- to second-order interference colors identify tremolite. Biaxial (-),  $\alpha = 1.608$ ,  $\beta = 1.618$ ,  $\gamma = 1.630$ ,  $\delta = 0.022$ ,  $2V = 85^\circ$ .

*Crystallography*

Monoclinic,  $a = 9.86$ ,  $b = 18.11$ ,  $c = 5.34$ ,  $\beta = 105.00^\circ$ ,  $Z = 2$ ; space group  $C2/m$ ; point group  $2/m$ .

*Habit*

Tremolite is typically prismatic. It may be in radiating or parallel blades, fibrous, asbestosiform, or columnar. It is commonly twinned parallel to {100}.

*Structure and Composition*

Tremolite,  $\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ , is the Mg end member of the calcic amphibole series. Complete solid solution exists between tremolite and Fe-actinolite,  $\text{Ca}_2\text{Fe}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ . Intermediate compositions are simply termed *actinolite*. Like other amphiboles, tremolite has a double-chain structure.  $\text{SiO}_4$  tetrahedra are linked to make double chains that run parallel to the c-axis. Each tetrahedron shares two or three oxygen with neighbors and has an unshared oxygen at the vertex pointing perpendicular to c. Chains are paired; unshared oxygens point toward each other and are bonded to the five octahedral cations occupying sites between them. The two larger octahedral sites are occupied by Ca. Other alkalis and alkaline earths may substitute in small amounts for Ca, and some Al may be present in either the octahedral or tetrahedral sites. If impurities are present in sufficient quantities, the amphibole becomes dark and, in the absence of analytical data, we call it *hornblende*.

*Occurrence and Associations*

Tremolite is one of the first minerals to form when impure carbonates are metamorphosed. It is associated with calcite, dolomite, talc, quartz or forsterite, diopside and phlogopite.

*Related Minerals*

All amphiboles are structurally similar. Tremolite is closely related to Fe-actinolite  $\text{Ca}_2\text{Fe}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ , the other principal calcic amphibole end member.

**Actinolite** **$\text{Ca}_2(\text{Fe,Mg})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$** *Origin of Name*

From the Greek word *actis* (ray), referring to its common habit of radiating needles (see Plate 3.2).

*Hand Specimen Identification*

A needlelike or columnar habit, prismatic cleavages,  $56^\circ$  and  $124^\circ$  cleavage angles, and distinctive green color usually serve to identify actinolite. It is sometimes confused with epidote because of its green color. Mg:Fe ratios may vary; exact composition cannot be determined in hand specimen. Plate 3.2 shows a color photo of massive actinolite.

*Physical Properties*

hardness	5 to 6
specific gravity	3.0 to 3.3
cleavage/fracture	two perfect prismatic {110}/uneven
luster/transparency	vitreous/transparent to translucent
color	dark green
streak	white

*Optical Properties*

Actinolite is similar to tremolite in thin section (see **tremolite**), but is generally more strongly colored and pleochroic. Biaxial (-),  $\alpha = 1.66$  to  $1.67$ ,  $\beta = 1.62$  to  $1.68$ ,  $\gamma = 1.63$  to  $1.69$ ,  $\delta = 0.03$ ,  $2V = 70^\circ$  to  $80^\circ$ .

*Crystallography*

Monoclinic,  $a = 9.84$ ,  $b = 18.05$ ,  $c = 5.27$ ,  $\beta = 104.7^\circ$ ,  $Z = 2$ ; space group  $C2/m$ ; point group  $2/m$ .

*Habit*

Actinolite typically forms needles—either radiating or in parallel aggregates—or columnar masses.

*Structure and Composition*

Actinolite is the name given to green amphiboles with compositions intermediate between tremolite,  $\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ , and Fe-actinolite,  $\text{Ca}_2\text{Fe}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ . Mn, Al, F, and Cr are sometimes present in minor amounts. Actinolite has the same structure as tremolite and other calcic amphiboles.

*Occurrence and Associations*

Actinolite is characteristic of medium-grade metamorphosed mafic rocks. It is one of the minerals that give greenschists their characteristic color. Associated minerals typically include albite, epidote, chlorite, and quartz.

*Varieties*

Nephrite is a Na-Al variety of actinolite.

*Related Minerals*

All amphiboles are structurally similar. Actinolite is closely related to tremolite,  $\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ , the other calcic amphibole end member.

**Hornblende** **$(\text{K},\text{Na})_{0-1}(\text{Ca},\text{Na},\text{Fe,Mg})_2(\text{Mg},\text{Fe},\text{Al})_5(\text{Si},\text{Al})_8\text{O}_{22}(\text{OH})_2$** *Origin of Name*

From the German word *horn* (horn) and *blenden* (blind), referring to its luster and its lack of value.

*Hand Specimen Identification*

Habit,  $56^\circ$  angle between two prominent cleavages, and dark color usually serve to identify hornblende. It is occasionally confused with augite, but augite has a near  $90^\circ$  cleavage angle. In the absence of compositional data, the name hornblende is often used for any black amphibole.

*Physical Properties*

hardness	5 to 6
specific gravity	3.0 to 3.5

cleavage/fracture	two perfect prismatic {110}/uneven
luster/transparency	vitreous/translucent
color	black or dark green
streak	white

#### Optical Properties

Hornblende may be various shades of brown, green, blue-green, or yellow-brown in thin section. Moderate to strong pleochroism is typical. Cross sections may be pseudohexagonal or diamond shaped. It may appear superficially like biotite, but has two good cleavages, and generally higher birefringence.  $56^\circ$  and  $124^\circ$  cleavage angles distinguish it from pyroxenes. Biaxial ( $-$ ),  $\alpha = 1.65$ ,  $\beta = 1.66$ ,  $\gamma = 1.67$ ,  $\delta = 0.02$ ,  $2V = 50^\circ$  to  $80^\circ$ . Plates 5.3, 5.4, 5.5, and 5.6 show hornblende in thin section.

#### Crystallography

Monoclinic,  $a = 8.97$ ,  $b = 18.01$ ,  $c = 5.33$ ,  $\beta = 105.75^\circ$ ,  $Z = 2$ ; space group  $C2/m$ ; point group  $2/m$ .

#### Habit

Hornblende may be massive or prismatic and is sometimes bladed, columnar, or fibrous. Euhedral crystals are often prismatic with a pseudohexagonal cross section. {100} contact twins are common.

#### Structure and Composition

Hornblende structure is similar to other amphiboles (see **cummingtonite** and **tremolite**), except that a large site, vacant in most of them, is partly occupied by Na or K. Thus, hornblende contains close to eight octahedral cations instead of seven. Hornblende composition varies greatly. Many end members have names; some of the more commonly used ones are

edenite	$\text{Ca}_2\text{NaMg}_5(\text{AlSi}_7)\text{O}_{22}(\text{OH})_2$
ferro-edenite	$\text{Ca}_2\text{NaFe}_5(\text{AlSi}_7)\text{O}_{22}(\text{OH})_2$
pargasite	$\text{Ca}_2\text{NaMg}_4\text{Al}(\text{Al}_2\text{Si}_6)\text{O}_{22}(\text{OH})_2$
ferro-pargasite	$\text{Ca}_2\text{NaFe}_4\text{Al}(\text{Al}_2\text{Si}_6)\text{O}_{22}(\text{OH})_2$
tschermakite	$\text{Ca}_2\text{Mg}_3\text{Al}_2(\text{Al}_2\text{Si}_6)\text{O}_{22}(\text{OH})_2$
ferrro-tschermakite	$\text{Ca}_2\text{Fe}_3\text{Al}_2(\text{Al}_2\text{Si}_6)\text{O}_{22}(\text{OH})_2$
tremolite	$\text{Ca}_2(\text{Mg},\text{Fe}_5)\text{Si}_8\text{O}_{22}(\text{OH})_2$
ferro-actinolite	$\text{Ca}_2(\text{Fe},\text{Mg}_5)\text{Si}_8\text{O}_{22}(\text{OH})_2$
glaucophane	$\text{Na}_2\text{Mg}_3\text{Al}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$
kaersutite	$\text{Ca}_2\text{Na}(\text{Mg},\text{Fe})_4\text{Ti}(\text{Al}_2\text{Si}_6)\text{O}_{22}(\text{OH})_2$

Besides compositional variations described by the end members just listed, some hornblende varieties include  $\text{F}^-$  or  $\text{O}^{2-}$  substituting for  $(\text{OH})^-$ , or  $\text{Fe}^{3+}$  substituting for  $\text{Fe}^{2+}$ .

#### Occurrence and Associations

Hornblende is common in many kinds of igneous rocks covering a wide range of composition. It is usually associated with plagioclase and may coexist with quartz or with mafic minerals such as pyroxene

or olivine. It is an essential mineral in those of intermediate composition such as syenite or diorite. Hornblende is also found in metamorphosed mafic rocks, especially in amphibolites that have hornblende and plagioclase as dominant minerals.

#### Related Minerals

All of the amphiboles are closely related in composition and structure. Hornblende has a more variable composition than most of the others.

## Glaucophane



#### Origin of Name

From Greek words meaning "to appear bluish."

#### Hand Specimen Identification

Association with other high-pressure minerals in blueschists, fibrous habit, near  $60^\circ$  cleavage angle, and blue color are distinctive of glaucophane and related Na-amphiboles crossite and riebeckite.

#### Physical Properties

hardness	6 to $6\frac{1}{2}$
specific gravity	3.1 to 3.2
cleavage/fracture	two perfect prismatic {110}/uneven
luster/transparency	vitreous/transparent to translucent
color	blue, gray
streak	white to very light blue

#### Optical Properties

Glaucophane may be difficult to tell from other blue amphiboles (such as riebeckite or crocidolite). It is colorless to blue or violet in thin section and often strongly pleochroic. Interference colors may range up to low second order, but are sometimes masked by mineral color. It exhibits typical amphibole cleavage and often forms fine prisms or needles with diamond-shaped cross sections. Biaxial ( $-$ ),  $\alpha = 1.66$ ,  $\beta = 1.67$ ,  $\gamma = 1.65$ ,  $\delta = 0.01$  to  $0.02$ ,  $2V = 0^\circ - 50^\circ$ .

#### Crystallography

Monoclinic,  $a = 9.78$ ,  $b = 17.80$ ,  $c = 5.30$ ,  $\beta = 103.76^\circ$ ,  $Z = 2$ ; space group  $C2/m$ ; point group  $2/m$ .

#### Habit

Acicular, asbestiform, or fibrous habit characterizes glaucophane.

#### Structure and Composition

Glaucophane has a structure similar to the calcic amphiboles (see **tremolite**). Although glaucophane has end member composition  $\text{Na}_2\text{Mg}_3\text{Al}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$ , most natural samples contain substantial Fe:  $\text{Fe}^{2+}$  replaces  $\text{Mg}^{2+}$  and  $\text{Fe}^{3+}$  replaces  $\text{Al}^{3+}$ . If  $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$

replace most of the  $Mg^{2+}$  and  $Al^{3+}$ , the amphibole becomes riebeckite. In riebeckite, some of the Na enters a normally vacant interlayer site. Compositions intermediate between glaucophane and riebeckite are called *crossite*.

#### *Occurrence and Associations*

Glaucophane is a high-pressure metamorphic mineral characteristic of the blueschist facies. Other blueschist minerals include jadeite, lawsonite, and aragonite.

#### *Related Minerals*

Glaucophane,  $Na_2Mg_3Al_2Si_8O_{22}(OH)_2$ , is similar in structure and chemistry to all amphiboles, but in particular the sodic amphiboles: riebeckite,  $Na_2Fe_3Fe_2Si_8O_{22}(OH)_2$ ; eckermannite,  $NaNa_2Mg_4AlSi_8O_{22}(OH)_2$ ; and arfvedsonite,  $NaNa_2Fe_5Si_8O_{22}(OH)_2$ . In the latter two, substantial Na occupies a normally unoccupied interlayer site.

## **Anthophyllite      $(Mg,Fe)_7Si_8O_{22}(OH)_2$**

#### *Origin of Name*

From the Latin word *anthophyllum*, meaning “clove leaf,” referring to this mineral’s color.

#### *Hand Specimen Identification*

Anthophyllite is characterized by its clove-brown color, usual prismatic habit, and prismatic cleavages with a  $54^\circ$  to  $55^\circ$  cleavage angle, but it is difficult to distinguish from other amphiboles such as grunerite or cummingtonite. Some samples of anthophyllite are fibrous (Plate 3.4).

#### *Physical Properties*

hardness	$5\frac{1}{2}$ to 6
specific gravity	2.9 to 3.2
cleavage/fracture	two perfect prismatic {210}, poor (100)/uneven
luster/transparency	vitreous/transparent to translucent
color	brown to green
streak	white

#### *Optical Properties*

In thin section, anthophyllite is colorless to pale brown or green and may be weakly pleochroic. It shows typical amphibole cleavage angles ( $56^\circ$  and  $124^\circ$ ) and up to second-order interference colors. It is difficult to tell from gedrite, but parallel extinction distinguishes it from clinoamphiboles. Biaxial (+ or -),  $\alpha = 1.60$ ,  $\beta = 1.62$ ,  $\gamma = 1.63$ ,  $\delta = 0.03$ ,  $2V = 65^\circ$  to  $90^\circ$ .

#### *Crystallography*

Orthorhombic,  $a = 18.56$ ,  $b = 18.01$ ,  $c = 5.28$ ,  $Z = 4$ ; space group  $P2/n2/m2/a$ ; point group  $2/m2/m2/m$ .

#### *Habit*

Crystals are prismatic, fibrous, bladed, or columnar with diamond-shaped cross sections.

#### *Structure and Composition*

Anthophyllite is part of a solid solution series extending from  $Mg_7Si_8O_{22}(OH)_2$  toward  $Fe_7Si_8O_{22}(OH)_2$ . Although compositionally identical to the monoclinic cummingtonite-grunerite amphiboles, anthophyllite is orthorhombic. Anthophyllite is usually Mg-rich; Fe-rich compositions yield cummingtonite. Al and Na may be present in anthophyllite; if Al content is great enough, the amphibole is called *gedrite*. The structure of anthophyllite is similar to that of cummingtonite and other amphiboles (see **cummingtonite**).

#### *Occurrence and Associations*

Anthophyllite is found in low-grade Mg-rich metamorphic rocks where it may be associated with cordierite. It is sometimes secondary after high-temperature minerals such as pyroxene and olivine, and is common in some serpentines.

#### *Varieties*

Amosite is asbestos-form anthophyllite.

#### *Related Minerals*

Anthophyllite is similar to all the other amphiboles, especially gedrite,  $(Mg,Fe,Mn)_2(Mg,Fe,Al)_5(Si,Al)_8O_{22}(OH)_2$ , and holmquistite,  $Li_2(Mg,Fe)_3Al_2Si_8O_{22}(OH)_2$ . It is polymorphic with cummingtonite.

## **Pyroxenoid Group Minerals**

wollastonite	$CaSiO_3$
rhodonite	$MnSiO_3$
pectolite	$NaCa_2(SiO_3)_3H$

Pyroxenoids are chain silicates having structures similar, but not identical, to pyroxenes. In pyroxene chains,  $SiO_4$  tetrahedra zigzag back and forth. Every other tetrahedron has the same orientation; the chains have a repeat distance of two tetrahedra, approximately  $5.2 \text{ \AA}$ . In pyroxenoids, repeat distances involve three or more tetrahedra, sometimes in complex arrangements.  $Ca^{2+}$ ,  $Mn^{2+}$ , and other cations, bonded to unshared chain oxygens, occupy distorted octahedral sites between chains. The less regular structures of pyroxenoids have less symmetry; pyroxenoids are triclinic, whereas pyroxenes are monoclinic or orthorhombic.

**Wollastonite****CaSiO<sub>3</sub>***Origin of Name*

Named after W. H. Wollaston (1766–1828), who discovered palladium and rhodium, invented the reflecting goniometer, and developed the camera lucida.

*Hand Specimen Identification*

Wollastonite's restricted occurrence, splintery nature due to two perfect cleavages, and habit make it distinctive. Tremolite has many features in common with wollastonite, but wollastonite can be distinguished by its two perfect cleavages about 84° apart (c.f., 56° in tremolite). Pectolite may be confused with wollastonite.

*Physical Properties*

hardness	5 to 5½
specific gravity	3.1
cleavage/fracture	perfect {100} and {001}, good {102}/uneven
luster/transparency	silky/transparent to translucent
color	white
streak	white

*Optical Properties*

In thin section, wollastonite is clear and has low birefringence. It has two good-perfect cleavages in cross section and one in prismatic section, and it has near-parallel extinction. Wollastonite is distinguished from tremolite, pectolite, and diopside by its lower birefringence. Biaxial (−),  $\alpha = 1.620$ ,  $\beta = 1.632$ ,  $\gamma = 1.634$ ,  $\delta = 0.014$ ,  $2V = 39^\circ$ .

*Crystallography*

Triclinic,  $a = 7.94$ ,  $b = 7.32$ ,  $c = 7.07$ ,  $\alpha = 90.03^\circ$ ,  $\beta = 95.37^\circ$ ,  $\gamma = 103.43^\circ$ ,  $Z = 4$ ; space group  $P\bar{1}$ ; point group  $\bar{1}$ .

*Habit*

Wollastonite typically forms cleavable masses or fibrous aggregates. Occasionally, tabular or prismatic crystals may be found.

*Structure and Composition*

Wollastonite, generally close to 100% CaSiO<sub>3</sub>, may contain minor Mn substituting for Ca. Its structure is similar to other pyroxenoids and to pyroxenes (see the introduction to pyroxenoid group minerals and **enstatite**).

*Occurrence and Associations*

Wollastonite is common in high-grade marbles and other calcareous metamorphic rocks, especially contact metamorphic rocks. Common associated minerals are calcite, dolomite, tremolite, epidote, garnet, diopside, and vesuvianite.

*Related Minerals*

Wollastonite and other pyroxenoids are related to pyroxenes in both chemistry and structure. Other pyroxenoids include rhodonite, MnSiO<sub>3</sub>; pectolite, NaCa<sub>2</sub>(SiO<sub>3</sub>)<sub>3</sub>H; and bustamite, (Mn,Ca,Fe)SiO<sub>3</sub>. Pseudowollastonite, a high-temperature polymorph, is similar to wollastonite, and several other wollastonite polymorphs are known.

**Rhodonite****MnSiO<sub>3</sub>***Origin of Name*

From the Greek word *rhodon*, meaning “rose,” in reference to rhodonite's color.

*Hand Specimen Identification*

Rhodonite is one of the few pink minerals and has a nearly perfect 90° cleavage angle. It is occasionally confused with rhodochrosite but is harder and has a different habit.

*Physical Properties*

hardness	5½ to 6
specific gravity	3.5 to 3.7
cleavage/fracture	perfect {110}, perfect {110} /conchoidal
luster/transparency	vitreous/transparent to translucent
color	pink, occasionally red; weathers to dark-colored Mn-oxide
streak	white

*Optical Properties*

Rhodonite is weakly pleochroic, colorless to light pink in thin section; maximum interference color is first-order yellow. Inclined extinction, high index of refraction, and low birefringence help identify it. Biaxial (+),  $\alpha = 1.717$ ,  $\beta = 1.720$ ,  $\gamma = 1.730$ ,  $\delta = 0.013$ ,  $2V = 63^\circ$  to  $76^\circ$ .

*Crystallography*

Triclinic,  $a = 7.68$ ,  $b = 11.82$ ,  $c = 6.71$ ,  $\alpha = 92.35^\circ$ ,  $\beta = 93.95^\circ$ ,  $\gamma = 105.67^\circ$ ,  $Z = 2$ ; space group  $P\bar{1}$ ; point group  $\bar{1}$ .

*Habit*

Cleavable masses or discrete grains are typical of rhodonite; large, as are irregular tabular crystals.

*Structure and Composition*

The rhodonite structure is similar to that of other pyroxenoids (see the introduction to pyroxene group minerals on the previous page). Rhodonite always contains some Ca substituting for Mn. If Ca content is great enough, it becomes bustamite. Fe and Zn may be present as well.

*Occurrence and Associations*

Rhodonite is found in manganese deposits and some iron formations. It is often found with Zn-minerals. Other associated minerals include the Mn-minerals rhodochrosite, bustamite, pyrolusite, tephroite, zincite, willemite, calcite, and quartz.

*Related Minerals*

Rhodonite is similar in composition and structure to other pyroxenoids, especially pyroxmangite,  $(\text{Mn},\text{Fe})\text{SiO}_3$ , and bustamite,  $(\text{Mn},\text{Ca},\text{Fe})\text{SiO}_3$ . Pyroxmangite, however, contains less Ca and more Fe, and bustamite contains significantly more Ca.

**Pectolite***Origin of Name*

From the Greek word *pectos*, meaning “well put together.”

*Hand Specimen Identification*

Association, habit, two cleavages, and opacity help identify pectolite. It breaks into sharp acicular fragments when cleaved. It is occasionally confused with wollastonite or zeolites. Plate 3.1 shows a color photo of pectolite.

*Physical Properties*

hardness	5
specific gravity	2.9
cleavage/fracture	two perfect prismatic {100}, perfect {001}
luster/transparency	silky/translucent
color	white
streak	white

*Optical Properties*

Pectolite is colorless in thin section, has moderate birefringence and relief, and shows two perfect cleavages with parallel extinction. Biaxial (+),  $\alpha = 1.59$ ,  $\beta = 1.61$ ,  $\gamma = 1.63$ ,  $\delta = 0.04$ ,  $2V = 35^\circ$  to  $63^\circ$ .

*Crystallography*

Triclinic,  $a = 7.99$ ,  $b = 7.04$ ,  $c = 7.02$ ,  $\alpha = 90.05^\circ$ ,  $\beta = 95.28^\circ$ ,  $\gamma = 102.47^\circ$ ,  $Z = 2$ ; space group  $P\bar{1}$ ; point group  $\bar{1}$ .

*Habit*

Pectolite is typically fibrous or acicular. Acicular radiating crystals forming compact masses are common.

*Structure and Composition*

Pectolite is similar in structure to wollastonite. Twisted chains of  $\text{SiO}_4$  tetrahedra run parallel to the b-axis and are connected by Na and Ca in octahedral coordination. Pectolite may contain small amounts of Fe, K, or Al.

*Occurrence and Associations*

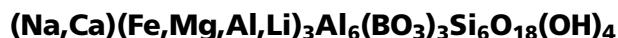
Pectolite is usually a secondary mineral, resembling zeolites in appearance and occurrence. It is typically found as crusts, in cavities, or along joints in basalt. Associated minerals include zeolites, calcite, and prehnite. It is occasionally found as a primary mineral in alkalic igneous rocks or in calcic metamorphic rocks.

*Related Minerals*

Pectolite is structurally and chemically related to other pyroxenoids and pyroxenes.

**RING SILICATES**

Ring silicates have structures consisting of planar rings of silica tetrahedra not connected to each other by other tetrahedra. Using this definition, tourmaline is the only common example. Mineralogists sometimes group beryl and cordierite with tourmaline, but in beryl and cordierite, tetrahedral rings are connected by additional silica tetrahedra. The very rare minerals dioptase,  $\text{CuSiO}_2(\text{OH})_2$ , and benitoite,  $\text{BaTiSi}_3\text{O}_9$ , are also ring silicates.

**Tourmaline***Origin of Name*

From the Sinhalese word *toramalli*, meaning “brown,” the color of some tourmaline gemstones from Ceylon.

*Hand Specimen Identification*

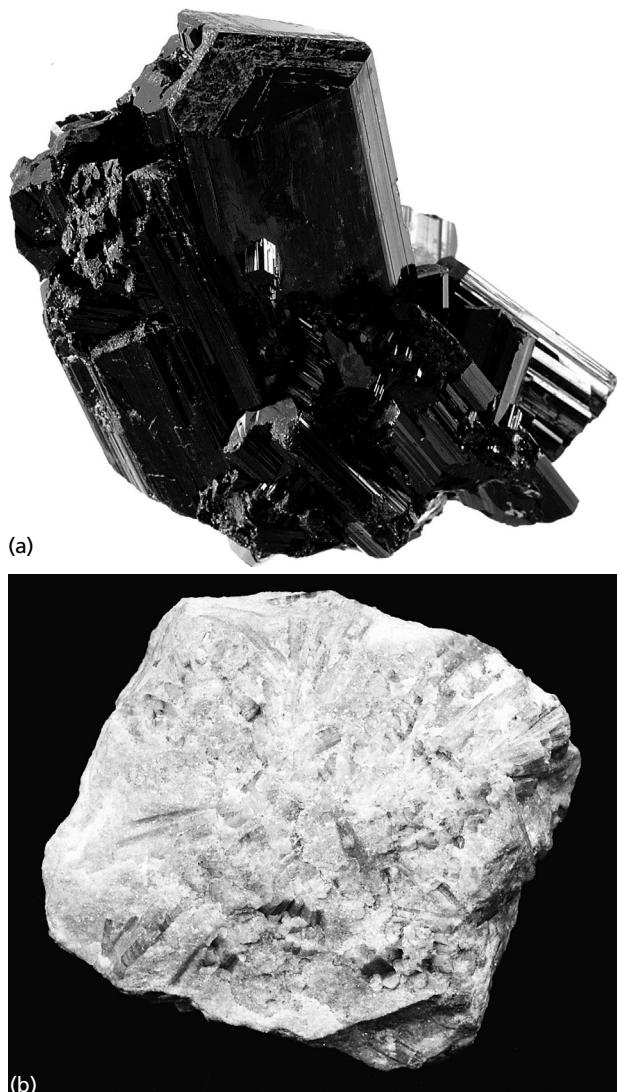
Crystal habit, deformed triangular cross section, vitreous luster, hardness, and conchoidal fracture are characteristic. Black tourmaline may be confused with hornblende; small crystals may superficially resemble staurolite. Plates 1.1, 3.3, and 8.5 show color photographs of tourmaline; see also Figure 14.

*Physical Properties*

hardness	7 to $7\frac{1}{2}$
specific gravity	2.9
cleavage/fracture	poor {101}, poor {110}/ subconchoidal
luster/transparency	resinous/translucent
color	variable black, blue, green, red, colorless; often zoned
streak	white

*Optical Properties*

Color and pleochroism are strong and variable: black, brown, green, blue, yellow, red, or pink. The color usually masks the birefringence. Pseudo-hexagonal or triangular cross sections are typical. Uniaxial (-), typically  $\omega = 1.645$  to 1.670,  $\epsilon = 1.625$  to 1.640,  $\delta = 0.020$  to 0.030.



**FIGURE 14** Black tourmaline (schorl) from Minas Gerais, Brazil (8 cm tall). (b) Rubellite, a pink variety of tourmaline, in quartz from the Black Hills, South Dakota, USA (6 cm tall).

#### Crystallography

Hexagonal (rhombohedral),  $a = 15.84$  to  $1.603$ ,  $c = 7.10$  to  $0.722$ ,  $Z = 3$ ; space group  $R\bar{3}m$ ; point group  $3m$ .

#### Habit

Elongate trigonal prisms with vertical striations are common (Figure 14). Cross sections appear hexagonal or ditrigonal, with or without some rounded angles between faces. Tourmaline may occur as parallel or radiating crystal aggregates or may be massive and compact.

#### Structure and Composition

One of the few common boron minerals, tourmaline's composition is highly variable, leading to many different colored varieties. Fe-rich varieties are black; Mg-rich varieties are often brown or yellow; Li-rich

varieties may be blue or green. The basic structure consists of rings of six  $(\text{SiO}_4)^{4-}$  tetrahedra. The rings are connected to borate groups  $(\text{BO}_3)^{-}$  and to  $(\text{O}^{2-}, \text{OH}^{-})$ , which form octahedra around  $(\text{Al}^{3+}, \text{Mg}^{2+}, \text{Fe}^{2+})$ . Cations such as  $\text{Na}^+$  occupy positions in the center of the rings.

#### Occurrence and Associations

Tourmaline is a common accessory mineral in many granitic igneous rocks and in some metamorphic rocks. Rarely, it is found as detrital grains in sediments. It commonly associates with quartz and K-feldspar. It may be a major mineral in pegmatites, where it is often associated with lepidolite, beryl, apatite, spodumene, or fluorite.

#### Varieties

The most common varieties are

Black-blue: schorl  $\text{NaFe}_3\text{Al}_6\text{B}_3\text{O}_9\text{Si}_6\text{O}_{18}(\text{OH})_4$

Brown-yellow: dravite  $\text{NaMg}_3\text{Al}_6\text{B}_3\text{O}_9\text{Si}_6\text{O}_{18}(\text{OH})_4$

Blue-variable: elbaite  $\text{Na}(\text{Al, Li})_3\text{Al}_6\text{B}_3\text{O}_9\text{Si}_6\text{O}_{18}(\text{OH})_4$

#### Related Minerals

Tourmaline is structurally related to beryl,  $\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$ ; cordierite,  $(\text{Mg, Fe})_2\text{Al}_4\text{Si}_5\text{O}_{18}$ ; diopside,  $\text{CaSiO}_3$ ; and benitoite,  $\text{BaTiSi}_3\text{O}_9$ .

### ISOLATED TETRAHEDRAL SILICATES

#### Garnet Group Minerals

##### Pyrospite Series

pyrope	$\text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12}$
almandine	$\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$
spessartine	$\text{Mn}_3\text{Al}_2\text{Si}_3\text{O}_{12}$

##### Ugrandite Series

grossular	$\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$
andradite	$\text{Ca}_3\text{Fe}_2\text{Si}_3\text{O}_{12}$
uvarovite	$\text{Ca}_3\text{Cr}_2\text{Si}_3\text{O}_{12}$

The garnets all have chemistries  $\text{A}_3\text{B}_2\text{Si}_3\text{O}_{12}$ . Their structures consist of isolated  $(\text{SiO}_4)^{4-}$  tetrahedra linked to distorted octahedrons containing  $(\text{Al}^{3+}, \text{Fe}^{3+})$  and to distorted dodecahedrons containing  $(\text{Ca}^{2+}, \text{Mg}^{2+}, \text{Fe}^{2+}, \text{Mn}^{2+})$ . Mineralogists conveniently divide garnets into two series, the pyrospites (pyrope-almandine-spessartine) and the ugrandites (uvarovite-grossular-andradite). Complete solid solution exists within each series, but only limited solid solution occurs between the two.

**Pyrope***Origin of Name*

From the Greek word *pyropos*, meaning “fiery,” a reference to this mineral’s luster.

*Hand Specimen Identification*

Crystal form, lack of cleavage, luster, and color identify garnets. The different species can sometimes be distinguished by color or association. Determining exact composition requires analytical data.

*Physical Properties*

hardness	7
specific gravity	3.54
cleavage/fracture	none/subconchoidal
luster/transparency	resinous/transparent to translucent
color	red; occasionally black
streak	white

*Optical Properties*

Pyrope is generally clear or very pale in thin section, has high relief, and exhibits no cleavage. Euhedral and subhedral crystals are common. Isotropic,  $n = 1.83$ .

*Crystallography*

Cubic,  $a = 11.46$ ,  $Z = 8$ ; space group  $I\bar{4}_1/a\bar{3}2/d$ ; point group  $4/m\bar{3}2/m$ .

*Habit*

Equant grains, sometimes displaying dodecahedral or trapezohedral faces, characterize pyrope and other garnets. Massive occurrences are rare.

*Structure and Composition*

The name *pyrope* refers to garnets close in composition to the Mg end member of the pyralspite series. The structure of pyrope is similar to those of other garnets.

*Occurrence and Associations*

Pyrope is only stable in high-pressure rocks and is found in eclogites and other mafic and ultramafic rocks from deep in the Earth. Commonly associated minerals include olivine, pyroxene, spinel, and, occasionally, diamond.

**Almandine***Origin of Name*

From Alabanda, a Middle Eastern trade center where garnets were cut and polished in the first century A.D.

*Hand Specimen Identification*

Equant shape, lack of cleavage, luster, and red color help identify almandine. Plate 8.4 shows almandine.

*Physical Properties*

hardness	7
specific gravity	4.33
cleavage/fracture	none/subconchoidal
luster/transparency	resinous/transparent to translucent
color	deep red
streak	white

*Optical Properties*

Almandine is generally clear or very pale in thin section, has high relief, and exhibits no cleavage. Euhedral and subhedral crystals are common. Isotropic,  $n = 1.83$ .

*Crystallography*

Cubic,  $a = 11.53$ ,  $Z = 8$ ; space group  $I\bar{4}_1/a\bar{3}2/d$ ; point group  $4/m\bar{3}2/m$ .

*Habit*

Almandine is characterized by euhedral to subhedral equant grains displaying dodecahedral or trapezohedral faces. Massive occurrences are rare.

*Composition and Structure*

Almandine, the Fe end member garnet of the pyralspite series, may contain appreciable amounts of Ca, Mg, or Mn replacing Fe. It has the same structure as other garnets.

*Occurrence and Associations*

Almandine is a common mineral in medium- and high-grade metamorphic rocks. It is often found with quartz, feldspar, micas, staurolite, cordierite, chloritoid, tourmaline, and kyanite or sillimanite.

**Spessartine***Origin of Name*

From Spessart, a district in Germany.

*Hand Specimen Identification*

Spessartine is often pink to violet. Like other garnets, it is characterized by equant crystals, lack of cleavage, and a shiny luster. If not pink or violet, identification may require analytical data.

*Physical Properties*

hardness	7
specific gravity	4.19
cleavage/fracture	none/subconchoidal
luster/transparency	resinous/transparent to translucent
color	pink to violet
streak	white

*Optical Properties*

Spessartine is generally clear or very pale in thin section, has high relief, and exhibits no cleavage. Euhedral and subhedral crystals are common. Isotropic,  $n = 1.80$ .

*Crystallography*

Cubic,  $a = 11.62$ ,  $Z = 8$ ; space group  $I\bar{4}_1/a\bar{3}2/d$ ; point group  $4/m\bar{3}2/m$ .

*Habit*

Euhedral to subhedral equant grains displaying dodecahedral or trapezohedral faces characterize spessartine. Massive occurrences are rare.

*Structure and Composition*

Spessartine is the Mn end member of the pyralspite series. Natural spessartine may contain appreciable amounts of Ca, Mg, or Fe replacing Mn. Spessartine has the same structure as other garnets.

*Occurrence and Associations*

Spessartine is found with other Mn minerals in Mn-rich skarns, low-grade metamorphic rocks, some rare granites and rhyolites, and, occasionally, in pegmatites. Common associated minerals in igneous rocks are quartz, feldspar, and micas.

**Grossular***Origin of Name*

From *grossularia*, the Latin name for the pale green gooseberry, which is the same color as some grossular.

*Hand Specimen Identification*

Like all garnets, grossular forms equant crystals and has no cleavage. Grossular is typically pink, red-pink, or light green. If not, analytical data may be needed to distinguish it from other garnets. See Figure 15.



**FIGURE 15** Subhedral and euhedral grossular from Chihuahua, Mexico.

*Physical Properties*

hardness	6½
specific gravity	3.56
cleavage/fracture	none/subconchoidal
luster/transparency	resinous/transparent to translucent
color	pink, brown, yellow, or green
streak	white

*Optical Properties*

Grossular is generally clear or very pale in thin section, has high relief, and exhibits no cleavage. Euhedral and subhedral crystals are common. Isotropic,  $n = 1.75$ .

*Crystallography*

Cubic,  $a = 11.85$ ,  $Z = 8$ ; space group  $I\bar{4}_1/a\bar{3}2/d$ ; point group  $4/m\bar{3}2/m$ .

*Habit*

Grossular is characterized by euhedral to subhedral equant grains displaying dodecahedral or trapezohedral faces (Figure 15). Massive occurrences are rare.

*Structure and Composition*

Grossular is the Al end member of the ugrandite series,  $\text{Ca}_3(\text{Fe}^{3+},\text{Al}^{3+},\text{Cr}^{3+})_2\text{Si}_3\text{O}_{12}$ , but natural grossular may contain appreciable amounts of  $\text{Fe}^{3+}$  or  $\text{Cr}^{3+}$  in solid solution. The structure is the same as other garnets.

*Occurrence and Associations*

Grossular is found in marbles where it may be associated with calcite, dolomite, quartz, tremolite, diopside, and wollastonite.

*Varieties*

Hydrogrossular (hibschite) is the name given to grossular in which a substantial amount of  $\text{Si}^{4+}$  has been replaced by  $4\text{H}^+$ .

**Andradite***Origin of Name*

Named after J. B. d'Andrade e Silva (1763–1838), a Portuguese mineralogist.

*Hand Specimen Identification*

Crystal form, lack of cleavage, luster, and color identify garnets. The different species can sometimes be inferred by color or association. Determining exact composition requires analytical data.

*Physical Properties*

hardness	7
specific gravity	3.86
cleavage/fracture	none/subconchoidal
luster/transparency	resinous/transparent to translucent

color	yellow, brown, green
streak	white

*Optical Properties*

Andradite is generally clear or very pale in thin section, has high relief, and exhibits no cleavage. Euhedral and subhedral crystals are common. Isotropic,  $n = 1.87$ .

*Crystallography*

Cubic,  $a = 12.05$ ,  $Z = 8$ ; space group  $I\bar{4}_1/a\bar{3}2/d$ ; point group  $4/m\bar{3}2/m$ .

*Habit*

Andradite is characterized by euhedral to subhedral equant grains displaying dodecahedral or trapezohedral faces. Massive occurrences are rare.

*Structure and Composition*

Andradite, the  $\text{Fe}^{3+}$  end member of the garnet ugrandite series, may contain appreciable amounts of  $\text{Al}^{3+}$  or  $\text{Cr}^{3+}$  replacing  $\text{Fe}^{3+}$ . It has the same structure as other garnets.

*Occurrence and Associations*

Andradite is found in marbles and occasionally as an accessory mineral in igneous rocks. Typical associated minerals include hedenbergite and magnetite.

*Varieties*

Melanite is a black variety of andradite.

**Uvarovite***Origin of Name*

Named after Count S. S. Uvarov (1785–1855), president of the St. Petersburg Academy in Russia.

*Hand Specimen Identification*

Crystal form, lack of cleavage, luster, and color identify garnets. The different species can sometimes be inferred by color or association. Uvarovite, like some other chrome minerals, often has a strong emerald green color. Determining exact composition requires analytical data.

*Physical Properties*

hardness	$7\frac{1}{2}$
specific gravity	3.80
cleavage/fracture	none/subconchoidal
luster/transparency	resinous/transparent to translucent
color	emerald green
streak	white

*Optical Properties*

Uvarovite is generally clear or very pale in thin section, has high relief, and exhibits no cleavage. Euhedral and subhedral crystals are common. Isotropic,  $n = 1.85$ .

*Crystallography*

Cubic,  $a = 12.00$ ,  $Z = 8$ ; space group  $I\bar{4}_1/a\bar{3}2/d$ ; point group  $4/m\bar{3}2/m$ .

*Habit*

Uvarovite is characterized by euhedral to subhedral equant grains displaying dodecahedral or trapezohedral faces. Massive occurrences are rare.

*Structure and Composition*

Uvarovite, the  $\text{Cr}^{3+}$  end member of the garnet ugrandite series, may contain appreciable amounts of  $\text{Fe}^{3+}$ , or  $\text{Al}^{3+}$  replacing  $\text{Cr}^{3+}$ . It has the same structure as other garnets.

*Occurrence and Associations*

Uvarovite is a rare mineral found primarily in peridotites and often associated with chrome ore. Associated minerals include chromite, olivine, pyroxene, and serpentine. It is more rarely found in metamorphic rocks.

**Olivine Group Minerals**

forsterite	$\text{Mg}_2\text{SiO}_4$
fayalite	$\text{Fe}_2\text{SiO}_4$
tephroite	$\text{Mn}_2\text{SiO}_4$
monticellite	$\text{CaMgSiO}_4$

Olivine, an abundant mineral in mafic and ultramafic igneous rocks, has the general formula  $(\text{Mg}, \text{Fe}, \text{Mn})\text{SiO}_4$ . Its structure is similar to that of garnet: Isolated  $\text{SiO}_4$  tetrahedra are linked by divalent cations in octahedral coordination. Complete solid solution exists between important end members forsterite and fayalite, and, less important, tephroite. Limited solid solution toward a  $\text{Ca}_2\text{SiO}_4$  end member is also possible, but the rare mineral larnite, with composition  $\text{Ca}_2\text{SiO}_4$ , does not have the olivine structure. Monticellite,  $\text{CaMgSiO}_4$ , is grouped with the other olivines, but because of its highly distorted structure is not considered a true olivine.

**Forsterite***Origin of Name*

Named after J. Forster, a scientist and founder of Heuland Cabinet.

*Hand Specimen Identification*

Olivine is distinguished by its glassy luster, conchoidal fracture, and usually olive-green color. Association and alteration to serpentine help identification. Olivines are sometimes confused with epidote

or pyroxene. Telling forsterite from other olivines requires detailed optical or X-ray data. Plate 6.5 shows some typical forsterite in a basalt from San Carlos, Arizona.

#### *Physical Properties*

hardness	6½
specific gravity	3.2
cleavage/fracture	poor (010) and (100)/conchoidal
luster/transparency	vitreous/transparent to translucent
color	colorless or green
streak	white

#### *Optical Properties*

Mg-rich olivines are colorless in thin section. Index of refraction and birefringence are high. Poor cleavage, irregular fracture, often equant grains, relatively high birefringence, and alteration to serpentine or chlorite help identification. Biaxial (+),  $\alpha = 1.635$ ,  $\beta = 1.651$ ,  $\gamma = 1.670$ ,  $\delta = 0.035$ ,  $2V = 85^\circ$  to  $90^\circ$ .

#### *Crystallography*

Orthorhombic,  $a = 4.78$ ,  $b = 10.28$ ,  $c = 6.00$ ,  $Z = 4$ ; space group  $P2_1/b2/n2/m$ ; point group  $2/m2/m2/m$ .

#### *Habit*

Rare crystals are combinations of prisms and dipyramids, often having a tabular or lozenge shape. Granular forms that resemble green sand, or embedded grains, are common.

#### *Structure and Composition*

Isolated  $\text{SiO}_4$  tetrahedra are linked by octahedral Mg. Complete solid solution exists between forsterite,  $\text{Mg}_2\text{SiO}_4$ ; fayalite,  $\text{Fe}_2\text{SiO}_4$ ; and tephroite. Minor Ca or Ni may also be present as replacement for Mg.

#### *Occurrence and Associations*

Mg-rich olivine, a primary mineral in many mafic and ultramafic rocks, is typically associated with pyroxenes, plagioclase, spinel, garnet, and serpentine. It is common as both an igneous and a metamorphic mineral (in marbles) and more rarely is found in sediments.

#### *Varieties*

Peridot is a gemmy green transparent variety of forsterite.

#### *Related Minerals*

The principal olivine end members are forsterite,  $\text{Mg}_2\text{SiO}_4$ ; fayalite,  $\text{Fe}_2\text{SiO}_4$ ; and tephroite,  $\text{Mn}_2\text{SiO}_4$ .



(a)



(b)

**FIGURE 16** (a) Olivine crystals from a peridot (gem olivine) mine near Globe, Arizona. The crystals grew as phenocrysts in a basalt. (b) Crystals from the same mine that have been tumbled to give them polished, smooth surfaces.

Olivine is isostructural with chrysoberyl,  $\text{BeAl}_2\text{O}_4$ . Minerals with similar but not identical structures include monticellite,  $\text{CaMgSiO}_4$ ; sinhalite,  $\text{MgAl}(\text{BO}_4)_2$ ; larnite,  $\text{Ca}_2\text{SiO}_4$ ; and kirschsteinite,  $\text{CaFe}(\text{SiO}_4)_2$ .

#### **Fayalite**



#### *Origin of Name*

Named after Fayal Island of the Azores, where fayalite was once found.

#### *Hand Specimen Identification*

Common olivine is distinguished by its glassy luster, conchoidal fracture, and usually olive-green color.

Fayalite, Fe-rich olivine, however, may be various shades of brown or yellow and difficult to identify. Exact composition cannot be determined without additional X-ray or optical data.

#### *Physical Properties*

hardness	6½
specific gravity	4.4
cleavage/fracture	poor (010) and (100)/conchoidal
luster/transparency	vitreous/transparent to translucent
color	green to yellow
streak	white yellow

#### *Optical Properties*

Fe-rich olivines are pale yellow or green in thin section and may be weakly pleochroic. Index of refraction and birefringence are high. Poor cleavage, often equant grains, and alteration to serpentine or chlorite help identification. Biaxial (–),  $\alpha = 1.827$ ,  $\beta = 1.877$ ,  $\gamma = 1.880$ ,  $\delta = 0.053$ ,  $2V = 47^\circ$  to  $54^\circ$ .

#### *Crystallography*

Orthorhombic,  $a = 4.81$ ,  $b = 10.61$ ,  $c = 6.11$ ,  $Z = 4$ ; space group  $P2_1/b2/n2/m$ ; point group  $2/m2/m2/m$ .

#### *Habit*

Rare crystals are combinations of prisms and dipyramids, often having a tabular or lozenge shape. Embedded grains are common.

#### *Structure and Composition*

Fayalite structure is the same as that of other olivines: Isolated  $\text{SiO}_4$  tetrahedra are linked by octahedral Fe. Complete solid solution exists between fayalite,  $\text{Fe}_2\text{SiO}_4$ ; forsterite,  $\text{Mg}_2\text{SiO}_4$ ; and tephroite,  $\text{Mn}_2\text{SiO}_4$ . Minor Ca or Ni may also be present as replacement for Fe.

#### *Occurrence and Associations*

Fayalite, less common than Mg-rich olivine, is found in some Fe-rich granitic igneous or metamorphic rocks.

#### *Related Minerals*

The principal olivine end members are forsterite,  $\text{Mg}_2\text{SiO}_4$ ; fayalite,  $\text{Fe}_2\text{SiO}_4$ ; and tephroite,  $\text{Mn}_2\text{SiO}_4$ . Many other minerals have related structures (see **forsterite**).

## **Monticellite**

## **$\text{CaMgSiO}_4$**

#### *Origin of Name*

Named after Italian mineralogist T. Monticelli (1759–1846).

#### *Hand Specimen Identification*

Association, color, conchoidal fracture, and habit help identify monticellite. It is difficult to distinguish from other olivine minerals without optical or X-ray data.

#### *Physical Properties*

hardness	5½
specific gravity	3.15
cleavage/fracture	poor (010) and (100)/conchoidal
luster/transparency	vitreous/transparent to translucent
color	colorless, gray, or green
streak	white

#### *Optical Properties*

Monticellite is similar to olivine but has greater  $2V$ . Biaxial (–),  $\alpha = 1.645$ ,  $\beta = 1.655$ ,  $\gamma = 1.665$ ,  $\delta = 0.020$ ,  $2V = 72^\circ$  to  $82^\circ$ .

#### *Crystallography*

Orthorhombic,  $a = 4.82$ ,  $b = 11.08$ ,  $c = 6.38$ ,  $Z = 4$ ; space group  $P2_1/b2/n2/m$ ; point group  $2/m2/m2/m$ .

#### *Habit*

Crystals tend to be subequant combinations of prisms and dipyramids. Monticellite is usually embedded grains or massive patches in a carbonate-rich host.

#### *Structure and Composition*

The structure of monticellite is similar to that of olivine, but the mismatch in size between Ca and Mg leads to some slight differences (see **forsterite**). Fe may substitute for Mg, leading to solid solutions with kirschsteinite,  $\text{CaFeSiO}_4$ . Minor Al and Mn may also be present.

#### *Occurrence and Associations*

A rare mineral, monticellite is found in skarns and, less commonly, in regionally metamorphosed rocks. Associated minerals include calcite, forsterite, åkermanite, merwinite, and tremolite. Very minor occurrences have been reported from ultramafic igneous rocks.

#### *Related Minerals*

The true olivines (forsterite, fayalite, tephroite) are closely related to monticellite. Kirschsteinite,  $\text{CaFe}(\text{SiO}_4)$ , is isostructural with monticellite. Minerals with similar but not identical structures include sinhalite,  $\text{MgAl}(\text{BO}_4)$ , and larnite,  $\text{Ca}_2\text{SiO}_4$ .

**Humite Group Minerals**

norbergite	$Mg_3SiO_4(OH,F)_2$
chondrodite	$Mg_5(SiO_4)_2(OH,F)_2$
clinohumite	$Mg_9(SiO_4)_4(OH,F)_2$

Chondrodite is the most common of the humite minerals. All are isolated tetrahedral silicates with structural similarity to olivine. Their general formula is  $nMg_2SiO_4 \cdot Mg(OH,F)_2$ , where  $n$  is 1, 2, 3, and 4, respectively, for norbergite, chondrodite, humite, and clinohumite.

**Norbergite** **$Mg_3SiO_4(OH,F)_2$** *Origin of Name*

Named after the type locality at Norberg, Sweden.

*Hand Specimen Identification*

The members of the humite group (norbergite, chondrodite, and clinohumite) cannot be distinguished without optical or X-ray data. They are usually identified by association, light color, and form, but may be difficult to tell from olivine.

*Physical Properties*

hardness	$6\frac{1}{2}$
specific gravity	3.16
cleavage/fracture	none/subconchoidal
luster/transparency	vitreous/transparent to translucent
color	white, yellow, brown, red
streak	white

*Optical Properties*

Norbergite and other humite minerals resemble olivine in thin section, but most olivines are biaxial (-), and humites have lower birefringence. Biaxial (+),  $\alpha = 1.561$ ,  $\beta = 1.570$ ,  $\gamma = 1.587$ ,  $\delta = 0.026$ ,  $2V = 44^\circ$  to  $50^\circ$ .

*Crystallography*

Orthorhombic,  $a = 4.70$ ,  $b = 10.22$ ,  $c = 8.72$ ,  $Z = 4$ ; space group  $P2_1/b2_1/n2_1/m$ ; point group  $2/m2/m2/m$ .

*Habit*

Crystals, usually found as isolated grains, are variable and display many forms. Highly modified orthorhombic or pseudoorthorhombic crystals are common.

*Structure and Composition*

The structure consists of alternating layers of forsterite and brucite structure. Norbergite is usually close to end member composition, although F:OH ratios are variable. Some Fe may replace Mg.

*Occurrence and Associations*

Norbergite is a rare mineral found in metamorphosed carbonate rocks. Associated minerals include calcite, dolomite, phlogopite, diopside, spinel, wollastonite, grossular, forsterite, and monticellite.

**Chondrodite** **$Mg_5(SiO_4)_2(OH,F)_2$** *Origin of Name*

From the Greek word meaning "grain," referring to this mineral's occurrence as isolated grains.

*Hand Specimen Identification*

The members of the humite group (norbergite, chondrodite, and clinohumite) are usually identified by association, light color, and form. Chondrodite is difficult to distinguish from other humite minerals and from olivine, even under an optical microscope.

*Physical Properties*

hardness	$6$ to $6\frac{1}{2}$
specific gravity	3.16 to 3.26
cleavage/fracture	poor (100)/subconchoidal
luster/transparency	vitreous/transparent to translucent
color	white to yellow
streak	white

*Optical Properties*

Chondrodite and other humite minerals resemble olivines in thin section, but most olivines are biaxial (-), and humites have lower birefringence. Biaxial (+),  $\alpha = 1.60$ ,  $\beta = 1.62$ ,  $\gamma = 1.63$ ,  $\delta = 0.03$ ,  $2V = 60^\circ$  to  $90^\circ$ .

*Crystallography*

Monoclinic,  $a = 4.73$ ,  $b = 10.27$ ,  $c = 7.87$ ,  $\beta = 109.1^\circ$ ,  $Z = 2$ ; space group  $P2_1/b$ ; point group  $2/m$ .

*Habit*

Usually found as isolated grains, crystals are variable and display many forms. Highly modified orthorhombic or pseudoorthorhombic crystals, with or without {001} twinning, are common.

*Structure and Composition*

The structure consists of layers of forsterite and brucite structure. Chondrodite contains two forsterite layers for each brucite layer. F:OH ratios are variable. Some Fe may replace Mg, and Ti content can be substantial.

*Occurrence and Associations*

Like norbergite, chondrodite is a rare mineral found in metamorphosed carbonate rocks. Associated minerals include calcite, dolomite, phlogopite, diopside, spinel, wollastonite, grossular, forsterite, and monticellite. Chondrodite has also been found in a few rare carbonatites.

**Clinohumite****Mg<sub>9</sub>(SiO<sub>4</sub>)<sub>4</sub>(OH,F)<sub>2</sub>***Origin of Name*

Named after English mineralogist Sir Abraham Hume (1749–1839).

*Hand Specimen Identification*

The members of the humite group (norbergite, chondrodite, and clinohumite) cannot be distinguished from each other, and sometimes from olivine, without very detailed optical or X-ray data. They are usually identified by association, light color, and form.

*Physical Properties*

hardness	6
specific gravity	3.21 to 3.35
cleavage/fracture	poor (100)/subconchoidal
luster/transparency	vitreous/transparent to translucent
color	white to yellow
streak	white

*Optical Properties*

Clinohumite and other humite minerals resemble olivines in thin section, but most olivines are biaxial (−), and humites have lower birefringence. Biaxial (+),  $\alpha = 1.63$ ,  $\beta = 1.64$ ,  $\gamma = 1.59$ ,  $\delta = 0.03$  to 0.04,  $2V = 73^\circ$  to  $76^\circ$ .

*Crystallography*

Monoclinic,  $a = 4.75$ ,  $b = 10.27$ ,  $c = 13.68$ ,  $\beta = 100.8^\circ$ ,  $Z = 2$ ; space group  $P2_1/b$ ; point group  $2/m$ .

*Habit*

Usually found as isolated grains, crystals are variable and display many forms. Highly modified pseudo-orthorhombic crystals with or without {001} twinning are common.

*Structure and Composition*

Structure is similar to the other humite minerals (see **chondrodite**) except that the ratio of forsterite: brucite is 4:1. Some Fe may replace Mg, and F:OH ratios are variable. Ti is almost always present in small amounts.

*Occurrence and Associations*

The occurrences of clinohumite are primarily in metamorphosed carbonate rocks, similar to other humite minerals.

*Varieties*

Titanoclinohumite, an especially Ti-rich variety, has been reported from a few rare serpentinites and gabbros.

**Aluminosilicate Group Minerals**

kyanite	Al <sub>2</sub> SiO <sub>5</sub>
andalusite	Al <sub>2</sub> SiO <sub>5</sub>
sillimanite	Al <sub>2</sub> SiO <sub>5</sub>

The aluminosilicate polymorphs vary little from end member Al<sub>2</sub>SiO<sub>5</sub> composition. All are isolated tetrahedral silicates but have distinctly different structures: In kyanite all the Al is in 6-fold coordination, in andalusite half is in 5-fold coordination and half is in 6-fold coordination, and in sillimanite half is in 4-fold coordination and half is in 6-fold coordination. The aluminosilicates are important minerals in pelitic metamorphic rocks. The presence of a particular polymorph indicates a general range of pressure-temperature at which the rock must have formed. For this reason, and because they are relatively common, the aluminosilicates are key metamorphic index minerals.

**Kyanite****Al<sub>2</sub>SiO<sub>5</sub>***Origin of Name*

From the Greek word *kyanos*, meaning “blue.”

*Hand Specimen Identification*

Kyanite is brittle, forms blue bladed crystals, and is easily cleaved into acicular fragments (Plate 3.6).

*Physical Properties*

hardness	5 to 7
specific gravity	3.60
cleavage/fracture	two prominent: perfect (100), good (010)/uneven
luster/transparency	pearly, vitreous/transparent to translucent
color	blue to white
streak	white

*Optical Properties*

Kyanite is typically colorless in thin section, but may be weakly blue and pleochroic. High relief, low birefringence, and excellent cleavage aid identification. It may be confused with sillimanite or andalusite, but sillimanite has a small  $2V$ , and andalusite has parallel extinction. Biaxial (−),  $\alpha = 1.712$ ,  $\beta = 1.720$ ,  $\gamma = 1.728$ ,  $\delta = 0.016$ ,  $2V = 82^\circ$  to  $83^\circ$ .

*Crystallography*

Triclinic,  $a = 7.10$ ,  $b = 7.74$ ,  $c = 5.57$ ,  $\alpha = 90.08^\circ$ ,  $\beta = 101.03^\circ$ ,  $\gamma = 105.73^\circ$ ,  $Z = 4$ ; space group  $\bar{P}\bar{1}$ ; point group  $\bar{1}$ .

**Habit**

Kyanite is usually in long blade-shaped or tabular crystals, sometimes forming parallel or radiating aggregates.

**Structure and Composition**

Chains of  $\text{AlO}_6$  octahedra are linked by additional  $\text{AlO}_6$  octahedra and by  $\text{SiO}_4$  tetrahedra. Kyanite is always near to end member composition; it may contain very minor Fe, Mn, or Cr.

**Occurrence and Associations**

Kyanite is primarily a metamorphic mineral found in medium- to high-pressure schists and gneisses. Typical associated minerals are quartz, feldspar, mica, garnet, corundum, and staurolite. It is known from a few aluminous eclogites and other rocks of deep origin.

**Related Minerals**

Kyanite has two polymorphs, andalusite and sillimanite.

**Andalusite****Origin of Name**

Named for Andalusia, a province of Spain.

**Hand Specimen Identification**

Andalusite is recognized primarily by crystal form and association. Hardness and nearly square (diamond) cross sections help identify andalusite. A variety called *chiastolite* displays a “maltese cross” pattern that is diagnostic. Andalusite is sometimes confused with scapolite.

**Physical Properties**

hardness	$7\frac{1}{2}$
specific gravity	3.18
cleavage/fracture	rarely seen, good {110}, poor (100)/subconchoidal
luster/transparency	vitreous/transparent to translucent
color	brown to red
streak	white

**Optical Properties**

Usually clear in thin section, andalusite may be weakly colored and pleochroic. Euhedral crystals with a square outline, sometimes showing penetration twins or a maltese cross pattern, are diagnostic. Andalusite is length fast and has a high  $2V$ . Biaxial ( $-$ ),  $\alpha = 1.632$ ,  $\beta = 1.640$ ,  $\gamma = 1.642$ ,  $\delta = 0.010$ ,  $2V = 75^\circ$  to  $85^\circ$ .

**Crystallography**

Orthorhombic,  $a = 7.78$ ,  $b = 7.92$ ,  $c = 5.57$ ,  $Z = 4$ ; space group  $P2_1/n2_1/n2/m$ ; point group  $2/m2/m2/m$ .

**Habit**

Stubby to elongate square prisms characterize andalusite. Individual crystals may be rounded. Massive and granular forms are also known.

**Structure and Composition**

Andalusite consists of chains of  $\text{AlO}_6$  octahedra parallel to the c-axis, linked by  $\text{SiO}_4$  tetrahedra and by  $\text{AlO}_5$  polyhedra. Andalusite is usually close to  $\text{Al}_2\text{SiO}_5$  in composition. Small amounts of Mn, Fe, Cr, and Ti may be present.

**Occurrence and Associations**

Andalusite is a metamorphic mineral characteristic of relatively low pressures. It occurs in pelitic rocks, often associated with cordierite, sillimanite, kyanite, garnet, micas, and quartz.

**Varieties**

*Chiastolite* is a variety of andalusite that has a square cross section (001) displaying a “maltese cross” pattern. The pattern results from carbonaceous impurities included during crystal growth.

**Related Minerals**

Andalusite has two polymorphs, sillimanite and kyanite.

**Sillimanite****Origin of Name**

Named after Benjamin Silliman (1779–1864), a chemistry professor at Yale University.

**Hand Specimen Identification**

Sillimanite is found in high-grade pelites, often forming thin, acicular crystals with square cross sections. Aggregates may be masses or splays. Very fine-grained sillimanite mats, often having a satiny appearance under the microscope, are termed *fibrolite*. Sillimanite is occasionally confused with anthophyllite.

**Physical Properties**

hardness	6 to 7
specific gravity	3.23
cleavage/fracture	perfect but rarely seen (010)/uneven
luster/transparency	vitreous/transparent to translucent
color	white to brown
streak	white

**Optical Properties**

Sillimanite typically forms needles, often in masses or mats, with square cross sections showing one

good diagonal cleavage. It has high relief, small  $2V$ , (+) optic sign, and is length slow. Biaxial (+),  $\alpha = 1.658$ ,  $\beta = 1.662$ ,  $\gamma = 1.680$ ,  $\delta = 0.022$ ,  $2V = 20^\circ$  to  $30^\circ$ .

#### *Crystallography*

Orthorhombic,  $a = 7.44$ ,  $b = 7.60$ ,  $c = 5.75$ ,  $Z = 4$ ; space group  $P2_1/b2/m2/n$ ; point group  $2/m2/m2/m$ .

#### *Habit*

Long, slender prisms, needles, or fibers are common. Subparallel aggregates and splays are typical. Fine-grained fibrous mats are also common.

#### *Structure and Composition*

The structure consists of chains of  $\text{AlO}_6$  octahedra, parallel to the c-axis, linked by  $\text{SiO}_4$  and  $\text{AlO}_4$  tetrahedra. Composition is always close to end member  $\text{Al}_2\text{SiO}_5$ ; small amounts of Fe may be present.

#### *Occurrence and Associations*

Sillimanite is the high-temperature  $\text{Al}_2\text{SiO}_5$  polymorph, found in high-grade pelites associated with garnet, cordierite, spinel, hypersthene, orthoclase, biotite, and quartz.

#### *Varieties*

Fibrolite is the name given to fine-grained fibrous masses of sillimanite.

#### *Related Minerals*

Sillimanite has two polymorphs: andalusite and kyanite.

### Other Isolated Tetrahedral Silicates

staurolite	$\text{Fe}_2\text{Al}_9\text{Si}_4\text{O}_{23}(\text{OH})$
chloritoid	$(\text{Fe},\text{Mg})\text{Al}_2\text{SiO}_5(\text{OH})_2$
titanite	$\text{CaTiSiO}_5$
topaz	$\text{Al}_2\text{SiO}_4(\text{F},\text{OH})_2$
zircon	$\text{ZrSiO}_4$

Besides those already listed, a number of other isolated tetrahedral silicates are common and important minerals. Although they have structures based on isolated  $\text{SiO}_4$  tetrahedra, they do not fit into any of the previously discussed structural groups. Staurolite and chloritoid are important metamorphic minerals in rocks rich in Fe and Al. Titanite and zircon are common accessory minerals in silicic igneous rocks and in many metamorphic rocks. Topaz is most commonly found in pegmatites and hydrothermal veins associated with granites and other silicic igneous rocks.

### Staurolite



#### *Origin of Name*

From the Greek word *stauros*, meaning "cross," in reference to its cruciform twins.

#### *Hand Specimen Identification*

Staurolite is often easily recognized by its characteristic penetration twins and prismatic crystals with a diamond-shaped cross section. It is sometimes confused with andalusite but has different habit. Pyroxene, tourmaline, titanite, and amphibole may look superficially like staurolite.

#### *Physical Properties*

hardness	7 to $7\frac{1}{2}$
specific gravity	3.75
cleavage/fracture	poor {010}/subconchoidal
luster/transparency	vitreous, resinous/translucent
color	brown to black
streak	white or gray

#### *Optical Properties*

Staurolite may be clear to yellow or light brown in thin section, often pleochroic. Birefringence is low; maximum colors are first-order yellow. Anhedral to euhedral porphyroblasts, often exhibiting a "sieve" structure due to quartz inclusions, or penetration twins, are common. Biaxial (+),  $\alpha = 1.740$ ,  $\beta = 1.744$ ,  $\gamma = 1.753$ ,  $\delta = 0.013$ ,  $2V = 80^\circ$  to  $88^\circ$ .

#### *Crystallography*

Monoclinic,  $a = 7.82$ ,  $b = 16.52$ ,  $c = 5.63$ ,  $\beta = 90.0^\circ$ ,  $Z = 2$ ; space group  $C2/m$ ; point group  $2/m$ .

#### *Habit*

Staurolite is usually found as prismatic crystals, often flattened in one direction and having several terminating forms. Massive varieties are rare. Penetration twins are common, sometimes resulting in perfect "cruciform" crosses.

#### *Structure and Composition*

Staurolite structure is closely related to that of kyanite. Layers of  $\text{Al}_2\text{SiO}_5$ , including  $\text{AlO}_6$  octahedra in chains, alternate with layers of  $\text{Fe}(\text{OH})_2$ . Pure end member Fe-staurolite does not exist in nature; Mg is always present, replacing up to 35% of the Fe. Small amounts of Ti and Mn are generally present as well. Water content is slightly variable.

#### *Occurrence and Associations*

Staurolite is a metamorphic mineral common in medium- to high-grade metamorphic rocks. Associated minerals include kyanite, garnet, chloritoid, micas, and tourmaline.

**Chloritoid****(Fe,Mg)Al<sub>2</sub>SiO<sub>5</sub>(OH)<sub>2</sub>***Origin of Name*

Named for its resemblance to chlorite.

*Hand Specimen Identification*

Green color, cleavage, and association help identify chloritoid. In many metamorphic rocks it appears as small dark grains and patches in a micaceous matrix and is hard to see. Thin sections may be required to distinguish it from chlorite, biotite, or stilpnomelane.

*Physical Properties*

hardness	$6\frac{1}{2}$
specific gravity	3.50
cleavage/fracture	poor {110}/uneven
luster/transparency	pearly/transparent
color	dark green
streak	gray

*Optical Properties*

Chloritoid is typically colorless to green in thin section and may exhibit pleochroism in various shades of green, yellow, or blue. It has high relief and anomalous interference colors and is frequently twinned. Chlorite looks superficially like chloritoid but has lower RI and relief and a smaller  $2V$ . Biaxial (+),  $\alpha = 1.715$ ,  $\beta = 1.720$ ,  $\gamma = 1.725$ ,  $\delta = 0.010$ ,  $2V = 45^\circ$  to  $65^\circ$ .

*Crystallography*

Monoclinic,  $a = 9.52$ ,  $b = 5.47$ ,  $c = 18.19$ ,  $\beta = 101.65^\circ$ ,  $Z = 6$ ; space group  $C2/c$ ; point group  $2/m$ .

*Habit*

Coarse masses or thin scales are typical; individual crystals are rare. Tabular crystals are platy and foliated with common {001} twinning.

*Structure and Composition*

The chloritoid structure is layered. Alternating brucite-like and corundumlike layers, perpendicular to the  $c$ -axis, are linked by  $\text{SiO}_4$  tetrahedra and hydrogen bonds. Chloritoid is not a layer silicate, like chlorite, because the  $\text{SiO}_4$  tetrahedra do not share oxygen. Chloritoid is generally Fe-rich, but Fe:Mg ratios are variable; end members are not found in nature. Some Mn may be present.

*Occurrence and Associations*

Chloritoid is common in low- or medium-grade Fe- and Al-rich schists. Associated minerals include quartz, feldspars, muscovite, chlorite, staurolite, garnet, andalusite, and kyanite. In some rare high-pressure metamorphic rocks, it occurs with glaucophane and other blueschist minerals.

*Varieties*

Ottrelite is Mn-rich chloritoid; carboirite is Ge-containing chloritoid.

*Related Minerals*

Several different polytypes and polymorphs have been described.

**Titanite (Sphene)****CaTiSiO<sub>5</sub>***Origin of Name*

This mineral's name refers to its titanium content. Its older name, *sphene*, refers to its crystal shape.

*Hand Specimen Identification*

Luster, color, and wedge-shaped crystals help identify titanite. It may be confused with staurolite and zircon, but is softer; or with sphalerite, but is harder.

*Physical Properties*

hardness	5 to $5\frac{1}{2}$
specific gravity	3.50
cleavage/fracture	good prismatic {110}, poor {100}/uneven
luster/transparency	adamantine/transparent to translucent
color	gray, black, brown, greenish yellow
streak	white

*Optical Properties*

Very high relief and birefringence and crystal form characterize titanite. Biaxial (+),  $\alpha = 1.86$ ,  $\beta = 1.93$ ,  $\gamma = 2.10$ ,  $\delta = 0.15$ ,  $2V = 23^\circ$  to  $50^\circ$ .

*Crystallography*

Monoclinic,  $a = 6.56$ ,  $b = 8.72$ ,  $c = 7.44$ ,  $\beta = 119.72^\circ$ ,  $Z = 4$ ; space group  $C2/c$ ; point group  $2/m$ .

*Habit*

Sphenoidal crystals, tabular with a wedge or diamond shape in cross section, are typical. Less commonly, titanite is massive or lamellar. Titanite is normally fine grained but occasionally occurs as large crystals (Figure 17).

*Structure and Composition*

The structure contains  $\text{TiO}_6$  polyhedra and  $\text{SiO}_4$  tetrahedra that share corners, forming distorted chains parallel to  $a$ . Ca is in 7-fold coordination, in large holes between the Ti- and Si-polyhedra. Many elements may substitute in titanite; especially important are the rare earths.

*Occurrence and Associations*

Titanite is an often overlooked common and widespread accessory mineral. In many rocks it is the only important Ti mineral present. It is common in many igneous rocks, especially silicic to intermediate



**FIGURE 17** Large black crystals of titanite surrounded by quartz and mica. This sample is from Eganville, Ontario, Canada.

ones, and many metamorphic rocks. It also has been found in some limestones and a few rare clastic sediments. Associated minerals include just about all the important rock forming minerals, including pyroxene, amphibole, feldspar, and quartz.

#### Varieties

Greenovite is the name given to red or pink titanite.

#### Related Minerals

Titanite is isostructural with tilasite,  $\text{CaMg}(\text{AsO}_4)\text{F}$ ; malayaite,  $\text{CaSn}(\text{SiO}_4)\text{O}$ ; and with fersmantite,  $(\text{Ca},\text{Na})_4(\text{Ti},\text{Nb})_2\text{Si}_2\text{O}_{11}(\text{F},\text{OH})_2$ . Other related minerals include perovskite,  $\text{CaTiO}_3$ ; benitoite,  $\text{BaTiSi}_3\text{O}_9$ ; and neptunite,  $\text{KNa}_2\text{Li}(\text{Fe},\text{Mn})_2\text{Ti}_2\text{O}(\text{Si}_4\text{O}_{11})_2$ .

## Topaz

## $\text{Al}_2\text{SiO}_4(\text{F},\text{OH})_2$

#### Origin of Name

Named after an island in the Red Sea, Topazion.

#### Hand Specimen Identification

Orthorhombic form, hardness, one good cleavage, color, and luster identify topaz. It may be confused with quartz but is not hexagonal. The very rare mineral danburite,  $\text{Ca}(\text{B}_2\text{Si}_2\text{O}_8)$ , is similar to topaz in form and properties, and cannot be distinguished without chemical analysis. Gem topaz is shown in Figure 18.

#### Physical Properties

hardness	8
specific gravity	3.5 to 3.6
cleavage/fracture	one perfect (001)/ subconchoidal
luster/transparency	vitreous/transparent to translucent



**FIGURE 18** Clear topaz crystals look superficially like quartz but have orthorhombic instead of hexagonal symmetry. These samples are from Topaz Mountain, Utah.

color	colorless or variable
streak	white

#### Optical Properties

Topaz is typically colorless in thin section and has low birefringence. It resembles quartz and apatite but has one perfect cleavage and higher relief than quartz, is biaxial, and is length slow. Biaxial (+),  $\alpha = 1.61$ ,  $\beta = 1.61$ ,  $\gamma = 1.62$ ,  $\delta = 0.01$ ,  $2V = 48^\circ$  to  $65^\circ$ .

#### Crystallography

Orthorhombic,  $a = 4.65$ ,  $b = 8.80$ ,  $c = 8.40$ ,  $Z = 4$ ; space group  $P2_1/b2/n2/m$ ; point group  $2/m2/m2/m$ .

#### Habit

Typical crystals are orthorhombic prisms, terminated by dipyrramids and pinacoids in combination (Figure 18). Prism faces show striations. Cross sections may be square, rectangular, diamond shaped, or octagonal. Coarse- or fine-grained masses are also common.

#### Structure and Composition

The structure consists of chains, parallel to the c-axis, containing pairs of edge-sharing  $\text{Al}(\text{OH},\text{F})_6$  octahedra alternating with  $\text{SiO}_4$  tetrahedra. F and OH content are variable, but F:OH ratio is usually in excess of 6:1. No other significant substitutions are known.

#### Occurrence and Associations

Topaz is a late-stage igneous or hydrothermal mineral. It is an accessory in granite, rhyolite, and granitic pegmatites and may be found in contact aureoles adjacent to silicic plutons. It is often associated with lithium and tin mineralization. Associated minerals include quartz, feldspar, muscovite, tourmaline, fluorite, cassiterite, apatite, and beryl.

#### Related Minerals

Euclase,  $\text{BeAl}(\text{SiO}_4)(\text{OH})$ , is isotypical with topaz.

**Zircon****ZrSiO<sub>4</sub>***Origin of Name*

From the Persian *zar* ("gold") and *gun* ("color").

*Hand Specimen Identification*

Zircon is usually identified by its distinctive crystal shape, color, luster, hardness, and density.

*Physical Properties*

hardness	$7\frac{1}{2}$
specific gravity	4.68
cleavage/fracture	poor {100}, poor {101}/conchoidal
luster/transparency	adamantine/transparent to translucent
color	brown to green, also gray, red, or colorless
streak	colorless to white

*Optical Properties*

Zircon is normally colorless but may be pale yellow or brown and faintly pleochroic. Grains are typically small, exhibiting very high relief and birefringence. Pleochroic halos around grains are due to decay of radioactive elements. Uniaxial (+),  $\omega = 1.99$ ,  $\epsilon = 1.93$ ,  $\delta = 0.06$ .

*Crystallography*

Tetragonal,  $a = 6.59$ ,  $c = 5.99$ ,  $Z = 4$ ; space group  $I4_1/a2/m2/d$ ; point group  $4/m2/m2/m$ .

*Habit*

Zircon typically is found as square prisms, pyramids, or as combinations of the two. Rounded grains are also common.

*Structure and Composition*

The zircon structure contains SiO<sub>4</sub> tetrahedra sharing corners or edges with distorted cubic polyhedra containing Zr. Zircon is generally close to end member composition, but frequently contains small amounts of Al, Fe, Mg, Ca, rare earths, and water.

*Occurrence and Associations*

Zircon is a common and widespread accessory mineral in igneous rocks, especially silicic ones. It is found in many metamorphic rocks and is common in sediments and sedimentary rocks. It is an important mineral for some kinds of radiometric dating.

*Varieties*

Zircon is often metamict (structurally damaged by the decay of radioactive elements in its structure), causing variation in color and optical properties.

*Related Minerals*

Zircon has a number of isotypes, including thorite, (Th,U)(SiO<sub>4</sub>); xenotime, Y(PO<sub>4</sub>); and huttonite, ThSiO<sub>4</sub>. Baddeleyite, ZrO<sub>2</sub>, is another Zr-rich mineral.

**PAIRED TETRAHEDRAL SILICATES**

lawsonite	CaAl <sub>2</sub> Si <sub>2</sub> O <sub>7</sub> (OH) <sub>2</sub> ·H <sub>2</sub> O
epidote	Ca <sub>2</sub> (Al, Fe) <sub>3</sub> Si <sub>3</sub> O <sub>12</sub> (OH)
clinozoisite	Ca <sub>2</sub> Al <sub>3</sub> Si <sub>3</sub> O <sub>12</sub> (OH)
vesuvianite	Ca <sub>10</sub> (Mg,Fe) <sub>2</sub> Al <sub>4</sub> Si <sub>9</sub> O <sub>34</sub> (OH) <sub>4</sub>

Mineralogists often group these four minerals together because they all contain pairs of SiO<sub>4</sub> tetrahedra sharing a single bridging oxygen. In lawsonite all silica tetrahedra are paired. However, in epidote, clinozoisite, and vesuvianite, structures are more complicated because some SiO<sub>4</sub> tetrahedra are unpaired. For this reason, these three minerals are sometimes not considered to be paired tetrahedral silicates. Åkermanite and gehlenite, rare minerals belonging to the melilite group, are also paired tetrahedral silicates but are not considered here.

**Lawsonite****CaAl<sub>2</sub>Si<sub>2</sub>O<sub>7</sub>(OH)<sub>2</sub>·H<sub>2</sub>O***Origin of Name*

Named after A. C. Lawson (1861–1952), a professor at the University of California.

*Hand Specimen Identification*

Hardness, bladed character, color, and association help identify lawsonite, but it is often very fine grained.

*Physical Properties*

hardness	8
specific gravity	3.1
cleavage/fracture	perfect {100} and {010}, fair {101}/uneven
luster/transparency	greasy, vitreous/transparent
color	gray, white, colorless
streak	white

*Optical Properties*

Lawsonite is usually colorless and exhibits high relief and interference colors no higher than first-order red. Biaxial (+),  $\alpha = 1.665$ ,  $\beta = 1.674$ ,  $\gamma = 1.685$ ,  $\delta = 0.020$ ,  $2V = 76^\circ$  to  $86^\circ$ .

*Crystallography*

Orthorhombic,  $a = 8.90$ ,  $b = 5.76$ ,  $c = 13.33$ ,  $Z = 4$ ; space group  $C2/c2/m2/m$ ; point group  $2/m2/m2/m$ .

*Habit*

Lawsonite may form tabular or prismatic crystals. Simple or lamellar twins are common.

*Structure and Composition*

Lawsonite is the only relatively common silicate in which all (SiO<sub>4</sub>)<sup>4-</sup> tetrahedra are paired, thus producing Si<sub>2</sub>O<sub>7</sub> groups. The Si<sub>2</sub>O<sub>7</sub> groups link Al(O,OH) octahedra; Ca occupies holes between the Si<sub>2</sub>O<sub>7</sub> groups and the

octahedra. Small amounts of Ti, Fe, Mg, Na, and K may be present, but no major solid solutions are known.

#### *Occurrence and Associations*

Lawsonite is a metamorphic mineral typical of the blueschist facies. Associated high-pressure minerals include glaucophane, jadeite, pumpellyite, or aragonite. Other associated minerals include chlorite, plagioclase, titanite, quartz, and epidote.

#### *Related Minerals*

Hemimorphite,  $Zn_4(Si_2O_7)(OH)_2 \cdot H_2O$ , and ilvaite,  $CaFe_3O(Si_2O_7)(OH)$ , are other paired tetrahedral silicates in which all  $SiO_4$  tetrahedra are paired. Other minerals usually considered in the same group are epidote,  $Ca_2(Al,Fe)_3Si_3O_{12}(OH)$ ; clinozoisite,  $Ca_2Al_3Si_3O_{12}(OH)$ ; piemontite,  $Ca_2(Al,Mn)_3Si_3O_{12}(OH)$ ; allanite,  $(Ca,Ce)_2(Al,Fe,Mg)_3Si_3O_{12}(OH)$ ; and vesuvianite,  $Ca_{10}(Mg,Fe)_2Al_4Si_9O_{34}(OH,F)_4$ .

## Epidote

### **$Ca_2(Al,Fe)_3Si_3O_{12}(OH)$**

#### *Origin of Name*

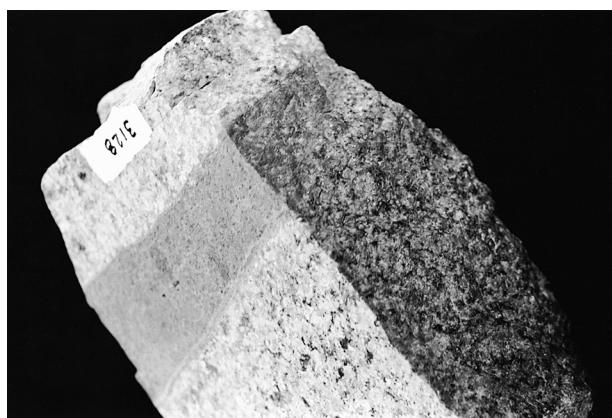
From the Greek word *epididonai*, meaning “increase,” referring to the base of an epidote prism, one side of which is longer than the other.

#### *Hand Specimen Identification*

Epidote is characterized by its pistachio-green color, habit, one perfect cleavage, and association. It is often fine grained and massive (Figure 19).

#### *Physical Properties*

hardness	6 to 7
specific gravity	3.4 to 3.5
cleavage/fracture	perfect (001), poor (100)/uneven
luster/transparency	vitreous/transparent to translucent
color	pistachio-green, yellow-green to black
streak	white



**FIGURE 19** A vein of epidote in a granite, probably formed by alteration of feldspar.

#### *Optical Properties*

Epidote has high relief and is usually colorless, but may be light green or pink and pleochroic, depending on composition. Interference colors range up to third order as Fe content increases. Football-shaped grains with concentric interference color rings are diagnostic of epidote. Biaxial (-),  $\alpha = 1.71$ , to  $1.75$ ,  $\beta = 1.72$  to  $1.78$ ,  $\gamma = 1.73$  to  $1.80$ ,  $\delta = 0.01$  to  $0.05$ ,  $2V = 90^\circ$  to  $115^\circ$

#### *Crystallography*

Monoclinic,  $a = 8.98$ ,  $b = 5.64$ ,  $c = 10.22$ ,  $\beta = 115.4^\circ$ ,  $Z = 2$ ; space group  $P2_1/m$ ; point group  $2/m$ .

#### *Habit*

Crystals are prismatic, fibrous, or acicular, usually elongated parallel to  $b$ , with faces showing striae. Granular, massive, and fibrous aggregates are common.

#### *Structure and Composition*

Epidote is usually considered a paired tetrahedral silicate, but contains both paired and unpaired  $(SiO_4)^{4-}$  tetrahedra (see discussion under **lawsonite**). Chains of edge-sharing  $Al(O,OH)_6$  octahedra, linked by  $Si_2O_7$  and  $SiO_4$  groups, are parallel to  $b$ . Ca occupies large sites between the various groups. A complete solid solution exists between Fe-epidote,  $Ca_2Fe_3Si_3O_{12}(OH)$  and clinozoisite,  $Ca_2Al_3Si_3O_{12}(OH)$ . Limited substitution exists between epidote and piemontite,  $Ca_2(Mn,Al)_3Si_3O_{12}(OH)$ . Cr, Pb, V, Sr, Sn, and rare earths may be present in small amounts.

#### *Occurrence and Associations*

Epidote is a common and widespread mineral, characteristic of low- to medium-grade metabasites and marbles. Associated minerals include actinolite, chlorite, and albite in mafic rocks and diopside, grossular, and vesuvianite in marbles. Epidote is also produced by alteration of feldspar, pyroxene, and amphibole.

#### *Varieties*

Tanzanite is a blue epidote gem; thulite is a rose-colored variety; allanite is epidote rich in rare earth elements. *Sausserite* is a name given to fine-grained epidote produced by alteration of plagioclase.

#### *Related Minerals*

Piemontite, a rare-earth mineral, and about 12 other minerals belong to the epidote group.

## Clinzoisite

### **$Ca_2Al_3Si_3O_{12}(OH)$**

#### *Origin of Name*

Named after Baron von Zois (1747–1819), an Austrian who financed mineralogists.

*Hand Specimen Identification*

Clinzozoisite is difficult to identify in hand specimen. If green, it is mistaken for epidote; if uncolored or lightly colored, it is often overlooked. It cannot be distinguished from zoisite (orthorhombic) without X-ray analysis.

*Physical Properties*

hardness	6 to $6\frac{1}{2}$
specific gravity	3.1 to 3.4
cleavage/fracture	perfect (001)/uneven
luster/transparency	vitreous/transparent to translucent
color	light green to yellow or gray
streak	white

*Optical Properties*

Clinzozoisite has high relief, and is usually colorless. Interference colors are often anomalous; birefringence is low. Biaxial (+),  $\alpha = 1.67$ , to 1.72,  $\beta = 1.67$  to 1.72,  $\gamma = 1.69$  to 1.73,  $\delta = 0.005$  to 0.015,  $2V = 14^\circ$  to  $90^\circ$

*Crystallography*

Monoclinic,  $a = 8.94$ ,  $b = 5.61$ ,  $c = 10.23$ ,  $\beta = 115.0^\circ$ ,  $Z = 2$ ; space group  $P2_1/m$ ; point group  $2/m$ .

*Habit*

Crystals are prismatic, fibrous, or acicular, usually elongated parallel to the b-axis, with faces showing striations. Granular, massive, and fibrous aggregates are common.

*Structure and Composition*

The clinzozoisite structure is similar to epidote's, containing both paired and unpaired  $(SiO_4)^{4-}$  tetrahedra (see **epidote**).

*Occurrence and Associations*

Clinzozoisite, like epidote, is a product of metamorphism of Ca-rich rocks. It forms instead of epidote in relatively Fe-poor rocks.

*Related Minerals*

A polymorph of clinzozoisite, named simply *zoisite*, is orthorhombic. Clinzozoisite is structurally and chemically related to all the other paired tetrahedral silicates (see **lawsonite**).

**Vesuvianite***Origin of Name*

From the Italian Mount Vesuvius locality where this mineral was found.

*Hand Specimen Identification*

Occurrence in skarns, tetragonal or columnar habit, and brown color help identify vesuvianite. It is sometimes confused with epidote, tourmaline, or garnet.

*Physical Properties*

hardness	$6\frac{1}{2}$
specific gravity	3.4
cleavage/fracture	poor (001), (100), {110}/subconchoidal
luster/transparency	vitreous, resinous/transparent
color	brown, also yellow, green, blue, or red
streak	white

*Optical Properties*

Vesuvianite is usually colorless but may be pleochroic in light green, brown, or yellow. High relief, low birefringence, and anomalous interference colors are typical. It may be confused with zoisite and clinzozoisite but is uniaxial and lacks a good prismatic cleavage. Uniaxial (-),  $\omega = 1.706$ ,  $\epsilon = 1.701$ ,  $\delta = 0.005$ .

Tetragonal,  $a = 15.66$ ,  $c = 11.85$ ,  $Z = 4$ ; space group  $P4/n2/n2/c$ ; point group  $4/m2/m2/m$ .

*Habit*

Typical vesuvianite occurs as coarse, prismatic, brown tetragonal prisms. Faces may be striated and crystals may be terminated by pyramids. Crystals may combine to form striated columnar masses, fibrous sheaves, or granular aggregates.

*Structure and Composition*

Vesuvianite, usually considered a paired tetrahedral silicate, contains both paired and unpaired  $(SiO_4)^{4-}$  tetrahedra (see **lawsonite**). Its structural similarity to grossular leads to some misidentification. Composition is highly variable. Mn, Na, and K may replace Ca. Ti and Al may replace (Mg,Fe). Other elements, including B, Be, Cr, Cu, Li, Zn, and rare earths, may be present.

*Occurrence and Associations*

Vesuvianite is found primarily in contact aureoles associated with impure limestones or dolomites. Associated minerals include garnet, wollastonite, epidote, diopside, and carbonates. It is also found in altered mafic rocks, including serpentinites.

*Varieties*

Cyprine is a blue variety of vesuvianite.

*Related Minerals*

Vesuvianite is structurally and chemically similar to the garnet grossular; it is less similar to epidote and other paired tetrahedral silicates.

## II. NATIVE ELEMENTS

### Metals

gold	Au
silver	Ag
platinum	Pt
copper	Cu

### Semimetals

arsenic	As
bismuth	Bi
antimony	Sb

### Nonmetals

diamond	C
graphite	C
sulfur	S

Gold, silver, platinum, and copper are the most common of the native metals. Iron, zinc, nickel, lead, and indium have occasionally been reported from meteorites or altered igneous rocks. All native metals have similar properties: metallic luster, high thermal and electrical conductivity, malleability, and opaqueness to visible light. Complex solid solutions are possible; many natural alloys have been given their own names. Kamacite and taenite, for example, are Fe-Ni alloys.

The native semimetals, all rare, are found in hydrothermal deposits but rarely have economic importance. The native nonmetals are diverse in occurrence and properties. Graphite is common as an accessory mineral in many metamorphic rocks, sulfur exists in massive beds or as encrustations associated with fumaroles, and diamond is primarily restricted to kimberlite pipes and mantle nodules.

## Gold

## Au

### Origin of Name

The name of this mineral refers to its color.

### Hand Specimen Identification

Gold is metallic and yellow. High specific gravity, sectile nature, and slightly different color and luster distinguish gold from the yellow sulfides pyrite and chalcopyrite. Plate 8.7 shows native gold.

### Physical Properties

hardness	2½ to 3
specific gravity	15.6 to 19.3
cleavage/fracture	none/hackly
luster/transparency	metallic/opaque
color	gold-yellow
streak	gold-yellow

### Crystallography

Cubic,  $a = 4.0783$ ,  $Z = 4$ ; space group  $F\bar{4}/m\bar{3}2/m$ ; point group  $4/m\bar{3}2/m$ .

### Habit

Crystals are octahedral, rarely showing other forms. More typically, gold is arborescent, fills fractures, or is found as nuggets, grains, or wire scales.

### Structure and Composition

Gold's face-centered cubic structure is the same structure as platinum and copper. Its composition is often close to pure Au, but substantial Ag may be present in solid solution. *Electrum* is a name given to intermediate Ag-Au solutions. Small amounts of other elements, such as Cu and Fe, may be present.

### Occurrence and Associations

Gold is most often found in quartz veins associated with altered silicic igneous rocks. It is also concentrated in placer deposits. Associated minerals include quartz, pyrite, chalcopyrite, galena, stibnite, sphalerite, arsenopyrite, tourmaline, and molybdenite.

### Varieties

Most natural gold contains up to 10% alloyed metals, thus giving rise to a number of slightly different colors and properties.

### Related Minerals

Other gold minerals include calaverite,  $\text{AuTe}_2$ ; sylvanite,  $(\text{Au}, \text{Ag})\text{Te}_2$ ; petzite,  $\text{Ag}_3\text{AuTe}_2$ ; maldonite,  $\text{Au}_2\text{Bi}$ ; and uytenbogaardtite,  $\text{Ag}_3\text{AuS}_3$ .

## Silver

## Ag

### Origin of Name

From the Old English word for this metal, *seolfor*.

### Hand Specimen Identification

Silver is distinguished by its often wirelike or arborescent habit, silver or tarnished silver color, high specific gravity, and malleability (Figure 20). It is occasionally confused with the platinum group minerals.

### Physical Properties

hardness	2½ to 3
specific gravity	10.1 to 10.5
cleavage/fracture	none/hackly
luster/transparency	metallic/opaque
color	silver-white
streak	silver-white

### Crystallography

Cubic,  $a = 4.0856$ ,  $Z = 4$ ; space group  $F\bar{4}/m\bar{3}2/m$ ; point group  $4/m\bar{3}2/m$ .



**FIGURE 20** Native silver from Batopilas, Mexico. This sample is about 10 cm across.

#### Habit

Distorted cubes, octahedra, or dodecahedra are known, but silver is typically acicular. Flakes, plates, scales, and filiform or arborescent masses are common (Figure 20).

#### Structure and Composition

Silver has a face-centered cubic structure that is isostructural with copper. It may contain substantial amount of Au, Hg, Cu, As, Sb, Bi, Pt, or Fe in solid solution.

#### Occurrence and Associations

Silver is found with sulfides and arsenides in oxidized zones of ore deposits, or in hydrothermal deposits. The many associated minerals include, most significantly, species containing Co, Ni, and As.

#### Varieties

*Amalgam* is a solid solution of Ag and Hg. *Electrum* is a solid solution of Ag and Au.

#### Related Minerals

Silver is isostructural with copper. Other Ag minerals include dyscrasite,  $\text{Ag}_3\text{Sb}$ ; argentite,  $\text{Ag}_2\text{S}$ ; proustite,  $\text{Ag}_3\text{AsS}_3$ ; and pyrargyrite,  $\text{Ag}_3\text{Sb}_3$ .

## Platinum

## Pt

#### Origin of Name

From the Spanish *platina*, meaning “silver.”

#### Hand Specimen Identification

Platinum is most easily identified by its malleability, silvery-white color, and high specific gravity.

#### Physical Properties

hardness	4 to $4\frac{1}{2}$
specific gravity	21.47
cleavage/fracture	none/hackly

luster/transparency	metallic/opaque
color	gray-silver, steel-gray
streak	gray-silver, steel-gray

#### Crystallography

Cubic,  $a = 3.9237$ ,  $Z = 4$ ; space group  $F\bar{4}/m\bar{3}2/m$ ; point group  $4/m\bar{3}2/m$ .

#### Habit

Crystals, generally poorly formed, are rare. Masses, nuggets, or small grains are typical.

#### Structure and Composition

Platinum has a cubic closest packed structure similar to gold's. It forms alloys with other elements, notably Fe, Cu, Pd, Rh, and Ir.

#### Occurrence and Associations

Primary platinum is found with chromite, spinel, and olivine in ultramafic rocks. It is also found in some placer deposits.

#### Related Minerals

Platinum is isotypical with copper.

## Copper

## Cu

#### Origin of Name

From the Greek word *kyprios*, referring to Cyprus, one of the earliest places where copper was mined.

#### Hand Specimen Identification

Copper-red or pale rose-red color, with or without tarnish, hackly fracture, malleability, and specific gravity identify copper. Plate 7.7 and Figure 21 show native copper from Michigan.

#### Physical Properties

hardness	$2\frac{1}{2}$ to 3
specific gravity	8.7 to 8.9
cleavage/fracture	none/hackly
luster/transparency	metallic/opaque
color	copper-red or rose-red
streak	copper-red



**FIGURE 21** Native copper from Michigan's upper peninsula.

***Crystallography***

Cubic,  $a = 3.6153$ ,  $Z = 4$ ; space group  $F\bar{4}/m\bar{3}2/m$ ; point group  $4/m\bar{3}2/m$ .

***Habit***

Copper may form cubes, octahedra, or dodecahedra. Contact or penetration twins are common. Crystals are usually malformed, dendritic, arborescent, or in irregular plates, scales, or masses (Figure 21).

***Structure and Composition***

Copper has a cubic closest packed structure similar to gold and platinum. It often contains solid solutions of Ag, Fe, As, or other elements.

***Occurrence and Associations***

Copper is found in the oxidized zones of many copper deposits, and as primary mineralization from hydrothermal fluids passing through mafic lavas. Copper is often deposited in voids or cracks. Associated minerals include silver, sulfides, calcite, chlorite, zeolites, cuprite, malachite, and azurite.

***Related Minerals***

Gold, silver, platinum, and lead are isotypical with copper.

**Diamond****C*****Origin of Name***

From the Greek word *adamas*, meaning “invincible.”

***Hand Specimen Identification***

Diamond is distinguished from minerals that resemble it by its hardness, octahedral cleavage, and luster.

***Physical Properties***

hardness	10
specific gravity	3.5
cleavage/fracture	perfect octahedral {111}/conchoidal
luster/transparency	adamantine/transparent
color	typically colorless but rare, colored varieties may be valuable
streak	white

***Optical Properties***

Isotropic,  $n = 2.419$ .

***Crystallography***

Cubic,  $a = 3.5668$ ,  $Z = 8$ ; space group  $F\bar{4}/d\bar{3}2/m$ ; point group  $4/m\bar{3}2/m$ .

***Habit***

Crystals are usually octahedral and often distorted or twinned. More rarely, diamond forms cubes or dodecahedra. Curved faces are common.

***Structure and Composition***

Diamond is essentially pure carbon but may contain inclusions of other material.

***Occurrence and Associations***

Diamond is found in altered ultramafic rock of mantle origin or in placer deposits. Associated minerals include pyrope, olivine, kyanite, and zircon.

***Related Minerals***

Graphite is a polymorph of diamond.

**Graphite****C*****Origin of Name***

The name comes from the Greek word *graphein*, meaning “to write,” because of its use in pencils.

***Hand Specimen Identification***

Easily recognized by its greasy feel, softness, dark color, and foliated nature.

***Physical Properties***

hardness	1 to 2
specific gravity	2.1 to 2.2
cleavage/fracture	perfect basal (001)/elastic, flexible
luster/transparency	submetallic/opaque
color	lead-gray, black
streak	black

***Crystallography***

Hexagonal (rhombohedral),  $a = 2.46$ ,  $c = 10.06$ ,  $Z = 6$ ; space group  $R\bar{3}2/m$ ; point group  $\bar{3}2/m$ .

***Habit***

Individual crystals are hexagonal tablets. Foliated and scaly masses are common; radiating or granular aggregates are less common.

***Structure and Composition***

The structure is composed of stacked planes of covalently bonded C atoms arranged in a hexagonal pattern. Graphite is essentially pure carbon.

***Occurrence and Associations***

Graphite is common in a wide variety of metamorphic rocks including schists, marbles, and gneisses. It is a rare mineral in some igneous rocks. Graphite is usually disseminated as fine flakes, but may form large books.

***Related Minerals***

Diamond is a polymorph of graphite.

**Sulfur****S*****Origin of Name***

From the Middle English word *sulphur*, meaning “brimstone.”

***Hand Specimen Identification***

Sulfur can be easily identified by its yellow color, hardness, density, and sometimes odor. It is occasionally confused with orpiment or sphalerite.

*Physical Properties*

hardness	$1\frac{1}{2}$ to $2\frac{1}{2}$
specific gravity	2.1
cleavage/fracture	poor {101} and {110}/conchoidal
luster/transparency	resinous/transparent to translucent
color	bright yellow
streak	white

*Optical Properties*

Pale yellow in thin section; often pleochroic. Sulfur is characterized by extreme relief and birefringence. Biaxial (+),  $\alpha = 1.958$ ,  $\beta = 2.038$ ,  $\gamma = 2.245$ ,  $\delta = 0.29$ ,  $2V = 69^\circ$ .

*Crystallography*

Orthorhombic,  $a = 10.44$ ,  $b = 12.84$ ,  $c = 24.37$ ,  $Z = 128$ ; space group  $F2/d2/d2/d$ ; point group  $2/m2/m2/m$ .

*Habit*

Tabular crystals often display combinations of dipyramids and pinacoids. Typically, sulfur is massive, colloform, or stalactitic.

*Structure and Composition*

The sulfur structure consists of covalently bonded  $S_8$  groups, stacked parallel to the c-axis, and weakly connected to each other. Sulfur is essentially pure S but may contain small amounts of Se in solid solution.

*Occurrence and Associations*

Sulfur is found as a deposit associated with volcanic fumaroles, in veins where it forms from sulfides, or in sediments where it forms by the reduction of sulfates by bacterial action. The most substantial occurrences are thick evaporite beds in sedimentary sequences. Associated minerals include celestite, gypsum, anhydrite, and carbonates.

*Related Minerals*

Sulfur has several different polymorphs.



**FIGURE 22** Sphalerite crystals in a 10-cm wide specimen found near Joplin, Missouri.

**III. SULFIDES****Tetrahedral Sulfide Group Minerals**

sphalerite	ZnS
wurtzite	ZnS
chalcopyrite	CuFeS <sub>2</sub>
bornite	Cu <sub>5</sub> FeS <sub>4</sub>
enargite	Cu <sub>3</sub> AsS <sub>4</sub>

In the tetrahedral sulfides, sulfur and arsenic are nearly closest packed and all metal atoms are in tetrahedral coordination. Complex solid solutions are possible, especially at high temperature. At low temperature, many sulfide minerals exhibit exsolution resulting from unmixing to form more stable phases.

**Sphalerite***Origin of Name*

This mineral's name comes from the Greek word *spaleros*, meaning "treacherous," alluding to problems identifying the mineral.

*Hand Specimen Identification*

Sphalerite is generally recognized by its resinous to adamantine luster, density, and perfect cleavage. Black varieties (Figure 22) may be confused with galena but yield a brown streak. Sphalerite is also sometimes confused with siderite, sulfur, or enargite. Plates 2.7 and 7.4 show color photos of sphalerite.

*Physical Properties*

hardness	$3\frac{1}{2}$ to 4
specific gravity	4.0
cleavage/fracture	perfect dodecahedral {110}/conchoidal
luster/transparency	adamantine, resinous/transparent to opaque
color	brown-orange-red, colorless when pure, also brown to black and yellow
streak	white to brown or yellow

*Optical Properties*

Sphalerite is colorless to pale brown or yellow in thin section. It has extremely high relief and good cleavage. Isotropic,  $n = 2.42$ .

*Crystallography*

Cubic,  $a = 5.785$ ,  $Z = 4$ ; space group  $F\bar{4}3m$ ; point group  $\bar{4}3m$ .

**Habit**

Crystals may be distorted or rounded. Crystals show combinations of tetrahedra, dodecahedra, and cubes. Polysynthetic twinning is common. Sphalerite commonly forms cleavable masses. It is typically brown and resinous.

**Structure and Composition**

Sphalerite is isostructural with diamond, with S arranged in a face-centered cubic pattern and Zn occupying tetrahedral sites within the cube. Many solid solutions are possible. Fe and, to a lesser extent, Mn and Cd are nearly always present.

**Occurrence and Associations**

Sphalerite is a common mineral found in several different kinds of deposits. It is found with galena, chalcopyrite, pyrite, barite, fluorite, carbonates, and quartz in voids and fracture fillings of carbonate hosts. It is found in hydrothermal veins with pyrrhotite, pyrite, and magnetite, and is also found in contact metamorphic aureoles.

**Related Minerals**

Wurtzite is a high-temperature hexagonal polymorph of sphalerite. Greenockite, CdS, is isostructural with sphalerite at low temperature and with wurtzite at high temperature.

**Chalcopyrite****CuFeS<sub>2</sub>****Origin of Name**

From the Greek word *chalkos*, meaning “copper,” and *pyrites*, meaning “to ignite.”

**Hand Specimen Identification**

Metallic luster, brass-yellow color and tarnish, and greenish-black streak identify chalcopyrite. It may be confused with pyrite, but is softer, and with gold, but is more brittle. Plate 7.8 shows chalcopyrite.

**Physical Properties**

hardness	$3\frac{1}{2}$ to 4
specific gravity	4.2
cleavage/fracture	poor {011}/uneven
luster/transparency	metallic/opaque
color	brass-yellow, sometimes tarnished
streak	greenish black

**Crystallography**

Tetragonal,  $a = 5.25$ ,  $c = 10.32$ ,  $Z = 4$ ; space group  $\bar{I}42d$ ; point group  $\bar{4}2m$ .

**Habit**

Crystals are usually pseudotetrahedral, displaying disphenoidal faces, sometimes in combination with prisms. Polysynthetic and penetration twins are common. Massive aggregates are common.

**Structure and Composition**

The structure is similar to that of sphalerite. Cu and Fe alternate in tetrahedral sites between S arranged in a face-centered cubic pattern. Small amounts of Ag, Au, Zn, and other elements are commonly present.

**Occurrence and Associations**

Chalcopyrite, the most important Cu ore mineral, is widespread and common. It is present in most sulfide deposits, but the most significant ores are formed by hydrothermal veins or by replacement. Common associated minerals include pyrite, sphalerite, bornite, galena, and chalcocite. Chalcopyrite is also found as magmatic segregations associated with pyrrhotite and pentlandite and in black shales.

**Related Minerals**

A number of other sulfides are isotypical with chalcopyrite, including stannite,  $\text{Cu}_2\text{FeSnS}_4$ ; gallite,  $\text{CuGaS}_2$ ; and roquesite,  $\text{CuInS}_2$ . Other similar minerals include talnakhite,  $\text{Cu}_9(\text{Fe},\text{Ni})_8\text{S}_{16}$ ; mooihoekite,  $\text{Cu}_9\text{Fe}_9\text{S}_{16}$ ; and haycockite,  $\text{Cu}_4\text{Fe}_5\text{S}_8$ .

**Bornite****Cu<sub>5</sub>FeS****Origin of Name**

Named after I. von Born (1742–1791), a German mineralogist.

**Hand Specimen Identification**

Density, luster, color, and purplish blue (peacock) tarnish usually identify bornite. It may be confused with niccolite, pyrrhotite, chalcocite, and covellite.

**Physical Properties**

hardness	3
specific gravity	6
cleavage/fracture	poor {111}/conchoidal
luster/transparency	metallic/opaque
color	bronze
streak	grayish black

**Crystallography**

Tetragonal,  $a = 10.94$ ,  $c = 21.88$ ,  $Z = 16$ ; space group  $P\bar{4}2_1c$ ; point group  $\bar{4}2m$ .

**Habit**

Crystals are often pseudocubic, less commonly pseudododecahedral and pseudoctahedral. Tetragonal crystals with distorted or curved faces are rarer. Massive aggregates are common.

**Structure and Composition**

The structure is complex. S is distributed in a modified face-centered cubic arrangement. Cu and Fe are in tetrahedral sites, each coordinated to four S. The structure contains many defects. At high temperatures bornite forms solid solutions with chalcopyrite,  $\text{CuFeS}_2$ .

Consequently, Cu:Fe ratios are somewhat variable. If cooling is slow, exsolution occurs. Small amounts of Pb, Au, Ag, and other elements may also be present.

#### *Occurrence and Associations*

The most important bornite occurrences are in sulfide veins and as a secondary mineral in enriched zones of sulfide deposits. Typical associated minerals include chalcopyrite, chalcocite, covellite, pyrrhotite, pyrite, and quartz.

#### *Related Minerals*

A cubic polymorph of bornite exists above 228°C. (440°F) Related minerals include chalcopyrite, CuFeS<sub>2</sub>, and pentlandite, (Ni,Fe)<sub>9</sub>S<sub>8</sub>.

### **Enargite**



#### *Origin of Name*

From the Greek word *enarges*, meaning “distinct,” referring to its cleavage.

#### *Hand Specimen Identification*

Enargite is identified by its density, softness, prismatic cleavage, and dark gray to black color. It may be confused with stibnite or sphalerite.

#### *Physical Properties*

hardness	3
specific gravity	4.5
cleavage/fracture	perfect prismatic {110}, good (100), good (010), poor (001)/uneven
luster/transparency	metallic/opaque
color	bronze, grayish black, iron black
streak	dark gray, gray-black

#### *Crystallography*

Orthorhombic,  $a = 6.47$ ,  $b = 7.44$ ,  $c = 6.19$ ,  $Z = 1$ ; space group *Pnm2*; point group *mm2*.

#### *Habit*

Crystals are tabular or columnar, and striated. Massive, columnar, or granular aggregates are common.

#### *Structure and Composition*

The closest packed structure is closely related to that of wurtzite, the hexagonal polymorph of sphalerite. Sb commonly substitutes for some As. Some Fe, Zn, and Ge replace Cu.

#### *Occurrence and Associations*

Enargite is found in vein or replacement sulfide deposits with other sulfides such as chalcocite, covellite, galena, bornite, sphalerite, and pyrite.

#### *Related Minerals*

Enargite is the most common of the sulfosalts, a group of minerals similar to sulfides, but that have

S, As, Sb, or Bi in chains or sheets. Other related sulfosalts are pyrargyrite, Ag<sub>3</sub>SbS<sub>3</sub>; tetrahedrite, Cu<sub>12</sub>Sb<sub>4</sub>S<sub>13</sub>; and tennantite, Cu<sub>12</sub>As<sub>4</sub>S<sub>13</sub>. Enargite has a rare very low temperature tetragonal polymorph, luzonite. Luzonite is isostructural with famatinite, Cu<sub>3</sub>SbS<sub>4</sub>, with which enargite forms a partial solid solution. Other related minerals are sulvanite, Cu<sub>3</sub>VS<sub>4</sub>, and germanite, Cu<sub>3</sub>GeS<sub>4</sub>.

### **Octahedral Sulfide Group Minerals**

galena	PbS
pyrrhotite	Fe <sub>1-x</sub> S
niccolite	NiAs

Galena and pyrrhotite are the two most important octahedral sulfides; niccolite, although not containing sulfur, is included in this group because of structural similarities. In the octahedral sulfide structure, S and As are closest packed and metal atoms occupy octahedral sites. Pyrrhotite is often slightly deficient in Fe, so its formula is written as Fe<sub>1-x</sub>S, and the name *troilite* is given to end member FeS.

### **Galena**

### **PbS**

#### *Origin of Name*

From the Latin word *galene*, a name originally given to lead ore.

#### *Hand Specimen Identification*

Galena is recognized by its density, silver-gray metallic appearance, blocky habit, good cleavage, and softness. Plate 7.5 and Figure 23 show galena.

#### *Physical Properties*

hardness	2½
specific gravity	7.6
cleavage/fracture	perfect {100}/subconchoidal
luster/transparency	metallic/opaque
color	lead-gray
streak	lead-gray

#### *Crystallography*

Cubic,  $a = 5.94$ ,  $Z = 4$ ; space group *F4/m*̄*32/m*; point group *4/m*̄*32/m*.

#### *Habit*

Crystals are typically cubes or cubes modified by octahedra. Penetration and contact twins are common. Lamellar twins are less common. Aggregates are massive, fine granular, or plumose.



**FIGURE 23** Galena, PbS, often forms cubic crystals and exhibits cubic cleavage.

#### Structure and Composition

The structure of galena is similar to that of halite. Alternating Pb and S are arranged in a face-centered cubic pattern. Galena often contains small amounts of Fe, As, or Sb, and even smaller amounts of Zn, Cd, Bi, and Se. Other impurities may be present in trace amounts.

#### Occurrence and Associations

Galena is common in many types of sulfide deposits. Associated minerals include sphalerite, chalcopyrite, pyrite, fluorite, barite, marcasite, cerussite, anglesite, calcite, dolomite, and quartz. Galena is often associated with silver minerals such as silver, acanthite, or pyrargyrite.

#### Related Minerals

Besides halite, NaCl, other minerals isostructural with galena are periclase, MgO; wustite, FeO; alabandite, MnS; altaite, PbTe; and clauthalite, PbSe.

## Pyrrhotite

## Fe<sub>1-x</sub>S

#### Origin of Name

From the Greek word *pyrrhos*, meaning “flame colored.”

#### Hand Specimen Identification

Pyrrhotite is recognized by its metallic luster, bronze color and magnetism. It may be confused with pentlandite, bornite, and pyrite.

#### Physical Properties

hardness	4
specific gravity	4.6
cleavage/fracture	poor (001)/uneven
luster/transparency	metallic/opaque

color	yellow to reddish bronze
streak	gray to black

#### Crystallography

Hexagonal,  $a = 5.69$ ,  $c = 11.75$ ,  $Z = 6$ ; space group  $P\bar{6}2c$ ; point group  $\bar{6}2m$ .

#### Habit

Pyrrhotite may be massive or disseminated. Rare crystals are hexagonal plates or tabs, often twinned.

#### Structure and Composition

The complex structure is similar to that of niccolite, NiAs. Fe occupies sites between hexagonally closest packed S. The amount and distribution of Fe are complex functions of composition and crystallization history, so composition is variable. Most pyrrhotite has less Fe than S. Ni, Co, Mn, and Cu are often present in small amounts.

#### Occurrence and Associations

Pyrrhotite is typically found in mafic igneous rocks. Associated minerals include pyrite, pentlandite, galena, magnetite, and chalcopyrite. Other pyrrhotite occurrences are in pegmatites, contact aureoles, and vein deposits.

#### Related Minerals

Pyrrhotite has a hexagonal polymorph stable at high temperature. Troilite is end member FeS. Isotypical minerals include troilite, niccolite, NiAs; and breithauptite, NiSb.

## Niccolite

## NiAs

#### Origin of Name

The name refers to this mineral's nickel content.

#### Hand Specimen Identification

Niccolite is easily recognized by its pale copper-red color and its alteration to green nickel bloom (annabergite).

#### Physical Properties

hardness	5 to 5½
specific gravity	4.6
cleavage/fracture	poor (001)/uneven
luster/transparency	metallic/opaque
color	copper-red
streak	brownish black

#### Crystallography

Hexagonal,  $a = 3.58$ ,  $c = 5.11$ ,  $Z = 2$ ; space group  $P\bar{6}_3/m2/m2/c$ ; point group  $6/m2/m2/m$ .

#### Habit

Rare crystals are tabular with pyramidal faces and sometimes cyclic twins. Niccolite is usually massive and sometimes colloform or columnar.

***Structure and Composition***

The structure involves hexagonal closest packed As with Ni between. Sb usually replaces some of the As; Fe, Co, and S are also present in small amounts.

***Occurrence and Associations***

Niccolite is found in veins with Co and Ag minerals and in sulfide deposits hosted by mafic igneous rocks. Associated minerals include pyrrhotite, chalcopyrite, skutterudite, silver, and a variety of other sulfosalts.

***Related Minerals***

Breithauptite, NiSb; freboldite, CoSe; and kotulskite, Pd(Te,Bi) are isostructural with niccolite. Other related minerals include millerite, NiS; pentlandite,  $(\text{Ni},\text{Fe})_9\text{S}_8$ ; and langisite,  $(\text{Co},\text{Ni})\text{As}$ . Annabergite,  $\text{Ni}_3\text{As}_2\text{O}_8 \cdot 8\text{H}_2\text{O}$ , also called *nickel bloom*, is a common green alteration product of niccolite.

**Other Sulfide Minerals**

The eight sulfides just discussed and several other less important ones have relatively simple structures based on closest packing and metal ions occupying either tetrahedral or octahedral sites, but not both. Pentlandite, the most important ore mineral of nickel, is the only common sulfide containing metal atoms in both coordinations. Many other sulfides have more complex structures. Metal ions may be in 5-fold or other unusual coordinations, they may occupy several different sites in the structures, and the sites may be highly polarized or distorted.

**Pentlandite** **$(\text{Ni},\text{Fe})_9\text{S}_8$** ***Origin of Name***

Named after J. B. Pentland (d. 1873), the geologist working in Sudbury, Ontario, Canada, who first described the mineral.

***Hand Specimen Identification***

Metallic luster, bronze-yellow color and association help identify pentlandite. It resembles pyrrhotite in appearance but is not magnetic. Plate 8.1 shows pentlandite.

***Physical Properties***

hardness	$3\frac{1}{2}$ to 4
specific gravity	5.0
cleavage/fracture	perfect {100}, good octahedral {111}/uneven
luster/transparency	metallic/opaque
color	light bronze to yellow-bronze
streak	light bronze to brown

***Crystallography***

Cubic,  $a = 10.05$ ,  $Z = 4$ ; space group  $F\bar{4}/m\bar{3}2/m$ ; point group  $4/m\bar{3}2/m$ .

***Habit***

Crystals are very rare. Pentlandite is usually massive or in granular aggregates. Sometimes {111} parting develops.

***Structure and Composition***

Pentlandite has a complicated face-centered cubic structure. The basic structure consists of  $(\text{Ni},\text{Fe})\text{S}_6$  octahedra sharing corners. Additional Ni and Fe occupy distorted tetrahedral sites between the octahedra. Co commonly substitutes for  $(\text{Ni},\text{Fe})$ . Mn and Cu are other common impurities.

***Occurrence and Associations***

Pentlandite, the most important nickel ore mineral, is found in late-stage sulfide deposits with other nickel minerals (millerite, niccolite), pyrrhotite, and chalcopyrite. Pentlandite often occurs as exsolved blebs and lamellae within pyrrhotite.

***Related Minerals***

Pentlandite forms solid solutions with cobalt pentlandite,  $\text{Co}_9\text{S}_8$ . It is isostructural with a number of minerals, including argentopentlandite,  $\text{Ag}(\text{Fe},\text{Ni})_8\text{S}_8$ . Other related minerals are bornite,  $\text{Cu}_5\text{FeS}_4$ , and niccolite,  $\text{NiAs}$ .

**Molybdenite** **$\text{MoS}_2$** ***Origin of Name***

From the Greek word *molybdos*, meaning “lead,” which refers to a misidentification by early mineralogists.

***Hand Specimen Identification***

Metallic luster, silver color, softness, flexibility, and basal cleavage identify molybdenite. It superficially resembles graphite. Plate 8.2 shows molybdenite in quartz.

***Physical Properties***

hardness	1 to $1\frac{1}{2}$
specific gravity	4.7
cleavage/fracture	perfect basal (001)/flexible
luster/transparency	metallic/opaque
color	silver, lead-gray
streak	green-gray

***Crystallography***

Hexagonal,  $a = 3.16$ ,  $c = 12.32$ ,  $Z = 2$ ; space group  $P\bar{6}_3/m2/m2/m$ ; point group  $6/m2/m2/m$ .

***Habit***

Crystals form hexagonal plates or stubby prisms. Foliated or scaly aggregates are flexible, but not elastic.

*Structure and Composition*

The molybdenite structure involves two sheets of S, arranged in a hexagonal pattern, sandwiching a sheet of Mo atoms. Each Mo atom is bonded to three S in each of the two sheets. The three-layer units are stacked up to produce the entire structure. Molybdenite is usually quite close to end member but may contain traces of Au, Ag, Re, and Se.

*Occurrence and Associations*

Molybdenite occurs as an accessory mineral in some granitic rocks, including pegmatites. It also is found in porphyry copper deposits; in vein deposits with scheelite, cassiterite, wolframite, and fluorite; and in some contact aureoles.

**Millerite****NiS***Origin of Name*

Named after W. H. Miller (1801–1880), who was the first to study the crystals.

*Hand Specimen Identification*

Millerite is easily recognized if it forms radiating acicular crystals. Luster, brass-yellow color, and rhombohedral cleavage also aid identification.

*Physical Properties*

hardness	3 to 3½
specific gravity	5.5
cleavage/fracture	perfect {101} and {012}/uneven
luster/transparency	metallic/opaque
color	brass yellow
streak	greenish black, green-gray

*Crystallography*

Hexagonal (rhombohedral),  $a = 9.62$ ,  $c = 3.15$ ,  $Z = 9$ ; space group  $R\bar{3}m$ ; point group 3m.

*Habit*

Crystals are typically acicular or filiform. Millerite may form radiating splays or velvety crusts.

*Structure and Composition*

The structure of millerite is a complex derivative of niccolite. Both Ni and S are in 5-fold coordination. Co, Fe, and As are minor impurities.

*Occurrence and Associations*

Millerite is a low-temperature mineral that forms as a replacement for other nickel minerals or in cavities. It is associated with calcite, fluorite, dolomite, hematite, siderite, pyrrhotite, and chalcopyrite.

*Related Minerals*

Millerite has structural similarity with niccolite, NiAs, and with pyrrhotite,  $Fe_{1-x}S$ . A high-temperature polymorph exists above 379°C (714 °F).

**Cinnabar****HgS***Origin of Name*

From the Persian *zinjifrah*, perhaps referring to red resin.

*Hand Specimen Identification*

High density, red color, and streak identify cinnabar. It may be confused with hematite, cuprite, or realgar.

*Physical Properties*

hardness	2½
specific gravity	8.1
cleavage/fracture	perfect prismatic {100}/subconchoidal
luster/transparency	adamantine/transparent to translucent
color	bright red to brownish red
streak	scarlet

*Optical Properties*

Uniaxial (+),  $\omega = 2.90$ ,  $\epsilon = 3.25$ ,  $\delta = 0.35$ .

*Crystallography*

Hexagonal (trigonal),  $a = 4.15$ ,  $c = 9.50$ ,  $Z = 3$ ; space group  $P\bar{3}_121$ ; point group 32.

*Habit*

Rare crystals are rhombohedral, thick tabs or prisms; less commonly acicular. Most occurrences are granular or earthy masses; often they are crusty, sometimes disseminated.

*Structure and Composition*

Cinnabar's structure consists of Hg-S-Hg chains spiraling parallel to the c-axis. It is usually close to HgS in composition; only traces of other elements are present.

*Occurrence and Associations*

Cinnabar is the most significant Hg ore mineral. It is found as masses in volcanic or sedimentary rocks, in veins, or as disseminated grains. Associated minerals include native mercury, realgar, stibnite, pyrite, marcasite, calcite, quartz, and opal.

*Related Minerals*

Metacinnabar (cubic) and hypercinnabar (hexagonal) are polymorphs of cinnabar. Other related minerals include coloradoite, HgTe, and tiemannite, HgSe.

**Covellite****CuS***Origin of Name*

Named after N. I. Covelli (1790–1829), who discovered Vesuvian covellite.

*Hand Specimen Identification*

Density, luster, indigo-blue color, and association identify covellite. Plate 7.3 shows covellite forming on pyrite and distinctive "peacock" coloration.

*Physical Properties*

hardness	$1\frac{1}{2}$ to 2
specific gravity	4.6
cleavage/fracture	perfect basal (001)/conchoidal
luster/transparency	metallic/opaque
color	indigo-blue; purplish tarnish
streak	dark gray to black

*Crystallography*

Hexagonal,  $a = 3.80$ ,  $c = 16.36$ ,  $Z = 6$ ; space group  $P6_3/m2/m2/c$ ; point group  $6/m2/m2/m$ .

*Habit*

Rare hexagonal crystals are tabular or platy; covellite is usually in massive or foliated aggregates or in overgrowths and coatings on other copper minerals.

*Structure and Composition*

Covalent sulfur bonds link layers of  $\text{CuS}_4$  tetrahedra. Weak bonds between the layers result in excellent planar cleavage. Fe often replaces some Cu; Se replaces some S.

*Occurrence and Associations*

Primarily a secondary (supergene) mineral, covellite occurs with other Cu sulfides in veins or disseminated deposits. Associated minerals include bornite, chalcopyrite, chalcocite, and enargite.

*Related Minerals*

Covellite is similar in some ways to klockmannite,  $\text{CuSe}$ , with which it forms solid solutions.

**Chalcocite** **$\text{Cu}_2\text{S}$** *Origin of Name*

From the Greek word *chalkos*, meaning "copper."

*Hand Specimen Identification*

Gray, often sooty color with blue tarnish, luster, hardness, sectile nature, and density identify chalcocite.

*Physical Properties*

hardness	$2\frac{1}{2}$ to 3
specific gravity	5.8
cleavage/fracture	poor prismatic {110}/conchoidal
luster/transparency	metallic/opaque
color	blue-white, shining
streak	lead-gray, dull sooty gray grayish black

*Crystallography*

Monoclinic,  $a = 15.25$ ,  $b = 11.88$ ,  $c = 13.49$ ,  $\beta = 116.35^\circ$ ,  $Z = 48$ ; space group  $P2_1/c$ ; point group  $2/m$ .

*Habit*

Chalcocite is usually fine grained and massive with conchoidal fracture. Squat prisms or tabular

crystals—sometimes with a hexagonal outline, sometimes displaying striations—are rare.

*Structure and Composition*

Hexagonal close packed S atoms characterize the structure. Two-thirds of the Cu atoms occupy trigonal sites in the planes of S atoms; the other third is in octahedral coordination between planes. Fe and Ag are common replacements for Cu; Se may replace some S.

*Occurrence and Associations*

Chalcocite is a common primary or secondary copper ore mineral. It occurs both in veins and in altered zones. Associated primary minerals include bornite, chalcopyrite, enargite, galena, tetrahedrite, cuprite, and pyrite. Covellite, malachite, or azurite are common alteration products.

*Related Minerals*

Normal chalcocite is monoclinic, but a hexagonal polymorph exists at elevated temperatures. Solid solution with berzelianite,  $\text{Cu}_2\text{Se}$ , is common. Similar minerals include stromeyerite,  $\text{AgCuS}$ , and digenite,  $\text{Cu}_{2-x}\text{S}$ .

**Argentite (Acanthite)** **$\text{Ag}_2\text{S}$** *Origin of Name*

From the Latin word *argentum*, which means "silver."

*Hand Specimen Identification*

High density, luster, dark color, and sectility identify argentite. It may be confused with chalcocite and tetrahedrite.

*Physical Properties*

hardness	2 to $2\frac{1}{2}$
specific gravity	7.1
cleavage/fracture	poor cubic {100}/subconchoidal
luster/transparency	metallic/opaque
color	lead-gray to black
streak	black or shiny black

*Crystallography*

Cubic,  $a = 4.89$ ,  $Z = 2$ ; space group  $I\bar{4}/m\bar{3}2/m$ ; point group  $4/m\bar{3}2/m$ .

*Habit*

Wiry, branching, columnar, and massive habit are common. Crystals are cubes, octahedra, dodecahedra, or combinations. Penetration twins are common.

*Structure and Composition*

Sulfur atoms are arranged in a distorted bodycentered arrangement. Ag atoms occupy 2-fold and 3-fold sites between S.

*Occurrence and Associations*

Argentite, an important Ag ore mineral, is found in veins associated with other silver minerals, galena, sphalerite, tetrahedrite, and Co-Ni sulfides.

*Related Minerals*

Argentite has both high-temperature and low-temperature polymorphs. Argentite is the proper name of the high-temperature cubic polymorph, and acanthite is the name of the low-temperature monoclinic polymorph. However, because low-temperature  $\text{Ag}_2\text{S}$  is usually twinned, appearing pseudocubic, it is also commonly referred to as argentite. Other related minerals include hessite,  $\text{Ag}_2\text{Te}$ ; petzite,  $\text{Ag}_3\text{AuTe}$ ; fischesserite,  $\text{Ag}_3\text{AuSe}_2$ ; naumannite,  $\text{Ag}_2\text{Se}$ ; eucairite,  $\text{CuAgSe}$ ; jalpaite,  $\text{Ag}_3\text{CuS}_2$ ; and aguilarite,  $\text{Ag}_4\text{SeS}$ .

**Pyrite** **$\text{FeS}_2$** *Origin of Name*

From the Greek word *pyr*, meaning “fire,” because it sparks when struck by steel.

*Hand Specimen Identification*

Density, metallic luster, brass-yellow color, and hardness identify pyrite. It is sometimes confused with chalcopyrite and marcasite, both of which have slightly different colors. Plates 1.3 and 2.7 show color photos of pyrite.

*Physical Properties*

hardness	6 to $6\frac{1}{2}$
specific gravity	5.1
cleavage/fracture	poor {100}/subconchoidal
luster/transparency	metallic/opaque
color	brass-yellow
streak	greenish black to green-gray

*Crystallography*

Cubic,  $a = 5.42$ ,  $Z = 4$ ; space group  $P2_1/a\bar{3}$ ; point group  $2/m\bar{3}$ .

*Habit*

Crystals are typically cubes, pyritohedra, or octahedra. Striated faces, combinations of forms, and penetration twinning (“iron cross twins”) are common.

*Structure and Composition*

The structure is closely related to that of NaCl; Fe and  $\text{S}_2$  alternate in a three-dimensional cubic array. Pyrite commonly contains some Ni and Co as replacements for Fe. Cu, V, Mo, Cr, W, Au, or Tl may also be present.

*Occurrence and Associations*

Pyrite is the most common and widespread sulfide and is often called “fool’s gold.” It is an accessory

mineral in many igneous, sedimentary, and metamorphic rocks. It is common in all sulfide deposits, associated with a wide variety of ore minerals. It also replaces organic material in coal, wood, or shells.

*Related Minerals*

Marcasite is an orthorhombic polymorph of pyrite. Pyrite forms solid solutions with vaesite,  $\text{NiS}_2$ , and cattierite,  $\text{CoS}_2$ . Cobaltite,  $\text{CoAsS}$ , and hauerite,  $\text{MnS}_2$ , are isostructural with pyrite. Many other minerals are isotypical with pyrite. Other similar minerals include arsenoferrite,  $\text{FeAs}_2$ ; pyrrhotite and mackinawite,  $\text{Fe}_{1-x}\text{S}$ ; greigite,  $\text{Fe}_3\text{S}_4$ ; and smythite,  $(\text{Fe},\text{Ni})_9\text{S}_{11}$ .

**Cobaltite** **$(\text{Co},\text{Fe})\text{AsS}$** *Origin of Name*

From the German word *kobold*, meaning “goblin,” because early miners found it difficult to mine.

*Hand Specimen Identification*

Density, luster, whitish color, cleavage, and habit identify cobaltite. It is sometimes confused with skutterudite.

*Physical Properties*

hardness	$5\frac{1}{2}$
specific gravity	6.3
cleavage/fracture	good cubic {100}/uneven
luster/transparency	metallic/opaque
color	tin-white or silver-white
streak	gray-black

*Crystallography*

Orthorhombic,  $a = 5.58$ ,  $b = 5.58$ ,  $c = 5.58$ ,  $Z = 4$ ; space group  $Pa2c$ ; point group  $mm2$ .

*Habit*

Cobaltite is usually massive. Aggregates may be granular or compact. Rare individual crystals are pseudocubic, similar in form to pyrite.

*Structure and Composition*

Cobaltite is isostructural with pyrite. Co replaces much of the Fe, and As replaces half the S. Fe and Ni commonly substitute for Co; Sb substitutes for As.

*Occurrence and Associations*

Cobaltite is commonly found with other cobalt and nickel sulfides, arsenides, and related minerals. Pyrrhotite, chalcopyrite, galena, and magnetite are also associated minerals. It may be veined or disseminated. Cobaltite is also found in a few rare metamorphic rocks.

*Related Minerals*

Cobaltite forms solid solutions with gersdorffite,  $\text{NiAsS}$ ; ullmanite,  $\text{NiSbS}$ ; and willyamite,  $(\text{Co},\text{Ni})\text{SbS}$ . Other similar minerals include hollingworthite,  $(\text{Rh},\text{Pt},\text{Pd})\text{AsS}$ ; irarsite,  $(\text{Ir},\text{Ru},\text{Rh},\text{Pt})\text{AsS}$ ; platarsite,  $(\text{Pt},\text{Rh},\text{Ru})\text{AsS}$ ; and tolovkite,  $\text{IrSbS}$ .

**Marcasite****FeS<sub>2</sub>***Origin of Name*

From Markashitu, an ancient province of Persia.

*Hand Specimen Identification*

Metallic luster, pale brass-yellow color, and orthorhombic habit identify marcasite. Cockscomb groups are diagnostic. Marcasite may be confused with its cubic polymorph, pyrite, if crystals are not distinct.

*Physical Properties*

hardness	6 to 6½
specific gravity	4.9
cleavage/fracture	poor {101}/uneven
luster/transparency	metallic/opaque
color	white-green to pale bronze yellow, often slightly tarnished
streak	grayish black

*Crystallography*

Orthorhombic,  $a = 4.44$ ,  $b = 5.41$ ,  $c = 3.38$ ,  $Z = 2$ ; space group  $P2_1/n2_1/n2/m$ ; point group  $2/m2/m2/m$ .

*Habit*

Crystals are typically tabular, often with curved faces, showing orthorhombic symmetry. They combine to form needlelike groups, sometimes radiating, colloform, globular, reniform, or stalactitic. Twinning often produces cockscomb aggregates.

*Structure and Composition*

Zigzagging FeS<sub>2</sub> chains run parallel to the c-axis; FeS<sub>6</sub> octahedra share corners and edges. Marcasite is nearly pure FeS<sub>2</sub>; traces of Cu may be present.

*Occurrence and Associations*

Marcasite is a low-temperature mineral found in sulfide veins with lead and zinc minerals or as a replacement mineral in limestones or shale. Common associates are galena, pyrite, chalcopyrite, calcite, and dolomite.

*Related Minerals*

Pyrite is a more stable polymorph of marcasite. Isostructural minerals include hastite, CoSe<sub>2</sub>; ferroselite, FeSe<sub>2</sub>; frohbergite, FeTe<sub>2</sub>; kullerudite, NiSe<sub>2</sub>; and mattagamite, CoTe<sub>2</sub>.

**Arsenopyrite****FeAsS***Origin of Name*

Named for its composition.

*Hand Specimen Identification*

Metallic luster, silver-white color, and crystal form help identify arsenopyrite. It may be confused with marcasite, pyrite, or skutterudite, but color distinguishes it

from the first two and form from the latter. Arsenopyrite sometimes smells like garlic when struck. Plate 7.2 shows a color photo of arsenopyrite.

*Physical Properties*

hardness	5½ to 6
specific gravity	6.1
cleavage/fracture	good {101}/uneven
luster/transparency	metallic/opaque
color	silver-white
streak	black

*Crystallography*

Monoclinic,  $a = 5.76$ ,  $b = 5.69$ ,  $c = 5.785$ ,  $\beta = 112.2^\circ$ ,  $Z = 4$ ; space group  $P2_1/c$ ; point group  $2/m$ .

*Habit*

Prismatic, striated crystals are typical. Penetration, contact, and cyclic twins are common. It may be disseminated, massive, or granular.

*Structure and Composition*

The structure is similar to that of marcasite with half the S replaced by As. FeAs<sub>3</sub>S<sub>3</sub> octahedra share vertices and edges. As:S ratios vary slightly, but arsenopyrite is always close to FeAsS in composition. Minor Co and Bi may replace Fe and other elements may be present in trace amounts.

*Occurrence and Associations*

Arsenopyrite, the most abundant and widespread arsenic mineral, is found in Fe, Cu, Sn, Co, Ni, Ag, Au, and Pb ores. It occurs in veins, pegmatites, contact aureoles, or as disseminations in low- to medium-grade metamorphic rocks. Common associated minerals include chalcopyrite, pyrite, sphalerite, cassiterite, and gold and silver minerals.

*Related Minerals*

Arsenopyrite forms solid solutions with glaucodot, (Co,Fe)AsS. It is isotypical with marcasite, FeS<sub>2</sub>, and with gudmundite, FeSbS. Other related minerals include lautite, CuAsS; osarsite, (Os,Ru)AsS; and ruarsite, RuAsS.

**Skutterudite****(Co,Ni)As<sub>3</sub>***Origin of Name*

From the type locality at Skutterude, Norway.

*Hand Specimen Identification*

The skutterudite series contains a number of related minerals; they have similar properties and are difficult to tell apart. Density, luster, and color help with identification, but chemical or X-ray analysis may be needed. Skutterudite is sometimes confused with arsenopyrite or cobaltite.

*Physical Properties*

hardness	$5\frac{1}{2}$ to 6
specific gravity	6.1 to 6.8
cleavage/fracture	good (101)/uneven
luster/transparency	metallic/opaque
color	tin-white to silver-gray
streak	black

*Crystallography*

Cubic,  $a = 8.20$ ,  $Z = 8$ ; space group  $I2/m\bar{3}$ ; point group  $2/m\bar{3}$ .

*Habit*

Cubes and octahedra are common forms. Skutterudite usually forms dense to granular aggregates.

*Structure and Composition*

(Co,Ni) in octahedral coordination are linked to square AsS<sub>4</sub> groups. Fe and Bi may substitute for (Co, Ni). Some As may be missing or replaced by S or Sb.

*Occurrence and Associations*

Skutterudite is a vein mineral associated with other Co and Ni minerals such as cobaltite or niccolite. Other associated minerals include arsenopyrite, native silver, silver sulfosalts, native bismuth, calcite, siderite, barite, and quartz.

*Related Minerals*

The three important members of the skutterudite series are skutterudite, (Co,Ni)As<sub>3</sub>; smaltite, (Co,Ni)As<sub>3-x</sub>; and chloanthite, (Ni,Co)As<sub>3-x</sub>. Linnaeite, Co<sub>3</sub>S<sub>4</sub>, is closely related.

**Stibnite****Sb<sub>2</sub>S<sub>3</sub>***Origin of Name*

From the Greek word *stibi*, a name originally used by Pliny, a first-century Greek encyclopedist and scientist.

*Hand Specimen Identification*

Stibnite is characterized by its softness, perfect cleavage in one direction, black streak, bladed habit, and lead-gray color.

*Physical Properties*

hardness	2
specific gravity	4.6
cleavage/fracture	one perfect (010)/subconchoidal
luster/transparency	metallic/opaque
color	lead-gray
streak	lead-gray to black

*Crystallography*

Orthorhombic,  $a = 11.12$ ,  $b = 11.30$ ,  $c = 3.84$ ,  $Z = 4$ ; space group  $P2_1/b2_1/n2_1/m$ ; point group  $2/m2/m2/m$ .

*Habit*

Prismatic striated crystals, often slender, long, and curved, are common. Faces show striations; terminating faces may be steep. Typically, stibnite is found in aggregates containing granular to coarse columns or needles.

*Structure and Composition*

The structure has zigzagging chains of Sb<sub>2</sub>S<sub>3</sub> parallel to the c-axis. Small amounts of other metals may replace Sb. Fe, Pb, and Cu are the most common impurities. Ag, Au, Zn, and Co may also be present in trace amounts.

*Occurrence and Associations*

Stibnite is found in hydrothermal veins, in replacement deposits, and more rarely, in hot spring deposits. Typical associates include orpiment, realgar, cinnabar, galena, sphalerite, pyrite, barite, and sometimes gold.

*Related Minerals*

Bismuthinite, Bi<sub>2</sub>S<sub>3</sub>, and guanajuatite, Bi<sub>2</sub>Se<sub>3</sub>, are isostructural with stibnite.

**Tetrahedrite****Cu<sub>12</sub>Sb<sub>4</sub>S<sub>13</sub>***Origin of Name*

Named for its typical crystal form.

*Hand Specimen Identification*

Tetrahedral crystals, lack of cleavage, and silver to black color help identify members of the tetrahedrite series, Cu<sub>12</sub>(Sb,As)<sub>4</sub>S<sub>13</sub>. They cannot be told apart without chemical analysis or X-ray study.

*Physical Properties*

hardness	3 to $4\frac{1}{2}$
specific gravity	4.5 to 5.1
cleavage/fracture	none/subconchoidal
luster/transparency	metallic/opaque
color	silver or grayish black to black
streak	brown to black

*Crystallography*

Cubic,  $a = 10.34$ ,  $Z = 2$ ; space group  $\bar{I}43m$ ; point group  $\bar{4}3m$ .

*Habit*

Crystals are typically tetrahedra, sometimes with modifying faces. Penetration twins are common. Crystal aggregates may be massive or granular.

*Structure and Composition*

The structure is similar to that of sodalite. CuS<sub>4</sub> tetrahedra share corners. Sb or As occupy openings between the tetrahedra. Fe, Zn, Pb, Ag, and Hg may replace Cu. Complete solid solution exists between end members tetrahedrite, Cu<sub>12</sub>Sb<sub>4</sub>S<sub>13</sub>, and tennantite, Cu<sub>12</sub>As<sub>4</sub>S<sub>13</sub>.

***Occurrence and Associations***

Tetrahedrite, one of the most common sulfosalts, is found in veins and in replacement deposits. Associated minerals include chalcopyrite, sphalerite, galena, pyrite, argentite, and many other minerals.

***Varieties***

Freibergite is a Ag-rich variety. Schwatzite is an Hg-rich variety.

***Related Minerals***

Tennantite,  $\text{Cu}_{12}\text{As}_4\text{S}_{13}$ , is isostructural with tetrahedrite. Other related minerals include germanite,  $\text{Cu}_3(\text{Ge},\text{Fe})\text{S}_4$ ; colusite,  $\text{Cu}_3(\text{As},\text{Sn},\text{Fe})\text{S}_4$ ; and sulvanite,  $\text{Cu}_3\text{VS}_4$ .

**Pyrargyrite (Ruby Silver)** **$\text{Ag}_3\text{SbS}_3$** ***Origin of Name***

From the Greek words meaning “fire” and “silver,” relating to its color and composition.

***Hand Specimen Identification***

Distinctive red color, translucence, and density identify pyrargyrite. It may be confused with proustite but generally has a ruby-red color, while proustite is more vermillion. It is occasionally mistaken for cuprite.

***Physical Properties***

hardness	2
specific gravity	5.85
cleavage/fracture	good {101}/subconchoidal
luster/transparency	adamantine/translucent
color	ruby-red
streak	red to purple

***Optical Properties***

Uniaxial (-),  $\omega = 3.08$ ,  $\epsilon = 2.88$ ,  $\delta = 0.20$ .

***Crystallography***

Hexagonal (trigonal),  $a = 11.06$ ,  $c = 8.73$ ,  $Z = 6$ ; space group  $R\bar{3}c$ ; point group  $3m$ .

***Habit***

Trigonal striated prisms are typical. Simple, repeated, and cyclic twins are common. Aggregates may be massive or granular.

***Structure and Composition***

The structure is composed of  $\text{S}_3$  bonded to Sb to form pyramids. Ag occupies large sites between the pyramids. Cu may replace Ag; As and Bi may replace Sb.

***Occurrence and Associations***

Pyrargyrite is found in low-temperature veins and in replacement deposits. Associated minerals include native silver, argentite, tetrahedrite, galena, sphalerite, carbonates, and quartz.

***Related Minerals***

Pyrargyrite has two polymorphs: pyrostilpnite and xanthoconite. Proustite,  $\text{Ag}_3\text{AsS}_3$ , is isostructural with pyrargyrite, but solid solutions are limited. Both pyrargyrite and proustite are called *ruby silvers*.

**Orpiment** **$\text{As}_2\text{S}_3$** ***Origin of Name***

From the Latin word *aurum* and *pigmentum*, meaning “golden paint,” referring to its color.

***Hand Specimen Identification***

Orpiment is one of the few yellow non-metallic minerals. Its foliated structure and hardness help identify it. When visible, perfect cleavage distinguishes it from sulfur. Plate 7.6 shows a color photo of orpiment.

***Physical Properties***

hardness	$1\frac{1}{2}$ to 2
specific gravity	3.49
cleavage/fracture	one perfect (010)/even or sectile
luster/transparency	resinous, also pearly on cleavage face/translucent
color	lemon-yellow to orange
streak	pale yellow to yellow

***Optical Properties***

Biaxial (-)  $\alpha = 2.40$ ,  $\beta = 2.81$ ,  $\delta = 3.02$ ,  $2V = 76^\circ$ .

***Crystallography***

Monoclinic,  $a = 11.49$ ,  $b = 9.59$ ,  $c = 4.25$ ,  $\beta = 90.45^\circ$ ,  $Z = 4$ ; space group  $P2_1/n$ ; point group  $2/m$ .

***Habit***

Rare crystals are small, tabular, or prismatic, often poorly formed. Columnar or foliated aggregates are common.

***Structure and Composition***

$\text{AsS}_3$  pyramids share edges, producing 6-member rings. Crumpled layers of rings are stacked on top of each other.

***Occurrence and Associations***

Orpiment, a rare mineral found in hot spring deposits and some gold deposits, is commonly associated with realgar. Other associated minerals include stibnite, native arsenic, calcite, barite, and gypsum.

***Related Minerals***

Getchellite,  $\text{AsSbS}_3$ , is similar in structure to orpiment. Realgar,  $\text{AsS}$ , is closely related in composition.

**Realgar** **$\text{AsS}$** ***Origin of Name***

From the Arabic phrase *rahj al-gbar*, meaning “powder of the mine.”

***Hand Specimen Identification***

Association with orpiment, resinous luster, orange-red streak, and red color identify realgar. It is sometimes confused with cinnabar, cuprite, or hematite. Plate 7.6 shows orpiment and realgar.

***Physical Properties***

hardness	1½ to 2
specific gravity	3.56
cleavage/fracture	good {010}/conchoidal
luster/transparency	resinous/transparent to translucent
color	red to orange
streak	red to orange

***Optical Properties***

Biaxial (-),  $\alpha = 2.538$ ,  $\beta = 2.864$ ,  $\gamma = 2.704$ ,  $\delta = 0.166$ ,  $2V = 41^\circ$ .

***Crystallography***

Monoclinic,  $a = 9.29$ ,  $b = 13.53$ ,  $c = 6.57$ ,  $\beta = 106.55^\circ$ ,  $Z = 4$ ; space group  $P2_1/n$ ; point group  $2/m$ .

***Habit***

Realgar may form short prismatic crystals having vertical striations. It is often massive granular or forms as earthy crusts.

***Structure and Composition***

Uneven rings of  $As_4S_4$  form layers in the structure. The As atoms, lying alternately above and below the plane of the S atoms, are covalently bonded to As in adjacent layers.

***Occurrence and Associations***

Realgar is associated with lead, gold, and silver ores. Associated minerals include orpiment, other arsenic minerals, and stibnite.



**FIGURE 24** Halite, NaCl, showing cubic cleavage.

**IV. HALIDES**

halite	NaCl
sylvite	KCl
chlorargyrite	AgCl
atacamite	$Cu_2Cl(OH)_3$
fluorite	$CaF_2$
cryolite	$Na_3AlF_6$

Fluorine and other halogens generally form nearly pure ionic bonds of moderate strength. Consequently, they bond with alkali and alkali earth elements to make chlorides, fluorides, bromides, and other salts referred to collectively as *halides*. Due to the generally large cation size and the nature of the bonding, halide structures tend to be simple with high symmetry. At high temperatures, some halides exhibit mutual solubility, but under normal Earth surface conditions most are usually close to end member composition. Halite and fluorite are the most common halide minerals, but others may be locally abundant.

***Related Minerals***

Orpiment,  $As_2S_3$ , is closely related in composition.

**Halite*****Origin of Name***

From the Greek word *halos*, meaning “salt.”

***Hand Specimen Identification***

Halite is characterized by its softness, often white color, transparency, salty taste, and cubic cleavage. It may be confused with sylvite, but it is distinguished by its less bitter taste. See Figure 24.

***Physical Properties***

hardness	2½
specific gravity	2.16
cleavage/fracture	perfect cubic {100}/conchoidal
luster/transparency	vitreous/transparent to translucent
color	colorless, white, or if impure may contain shades of red, blue, purple, or yellow
streak	white

***Optical Properties***

Halite has low relief, perfect cubic cleavage, and is colorless in thin section. Isotropic,  $n = 1.5446$ .

*Crystallography*

Cubic,  $a = 5.6404$ ,  $Z = 4$ ; space group  $F4/m\bar{3}2/m$ ; point group  $4/m\bar{3}2/m$ .

*Habit*

Cubic crystals, often massive or granular, characterize halite. Cubic cleavage is pronounced (Figure 24).

*Structure and Composition*

Closest packed  $\text{Na}^+$  and  $\text{Cl}^-$  alternate in a face-centered cubic arrangement. Both ions are in perfect octahedral coordination.

*Occurrence and Associations*

Halite, a rock-forming mineral, occurs in salt flats, in sedimentary beds, in salt domes, and as deposits from volcanic gasses. It is the most common evaporite mineral. Associated minerals include many other salts, gypsum, calcite, sylvite, anhydrite, sulfur, and clay.

*Related Minerals*

Galena,  $\text{PbS}$ ; alabandite,  $\text{MnS}$ ; periclase,  $\text{MgO}$ ; sylvite,  $\text{KCl}$ ; carrobbiite,  $\text{KF}$ ; and chlorargyrite,  $\text{AgCl}$  are all isostructural with halite.

**Sylvite****KCl***Origin of Name*

From the old Latin name for the mineral.

*Hand Specimen Identification*

Sylvite is characterized by its softness, generally white color, transparency, taste, and cubic cleavage. It is distinguished from halite by its more bitter taste.

*Physical Properties*

hardness	2
specific gravity	1.99
cleavage/fracture	perfect cubic {100}/uneven
luster/transparency	vitreous/transparent to translucent
color	colorless, white, or shades of yellow, blue, or red caused by impurities
streak	white

*Optical Properties*

Sylvite has low relief, perfect cubic cleavage, and is colorless in thin section. Isotropic,  $n = 1.490$ .

*Crystallography*

Cubic,  $a = 6.29$ ,  $Z = 4$ ; space group  $F4/m\bar{3}2/m$ ; point group  $4/m\bar{3}2/m$ .

*Habit*

Crystals form cubes, often with modifying octahedra. Massive or granular aggregates are typical.

*Structure and Composition*

Sylvite is isostructural with halite.  $\text{K}^+$  and  $\text{Cl}^-$  are arranged in a face centered cubic manner. Only minor solid solution exists between the two salts.

*Occurrence and Associations*

Sylvite is rarer than halite but has the same origin, associates, and occurrences (see **halite**).

*Related Minerals*

Sylvite and halite are isostructural with a number of other minerals (see **halite**). Associated potassium salts include carnallite,  $\text{KMgCl}_3 \cdot 6\text{H}_2\text{O}$ ; kainite,  $\text{KMg}(\text{Cl},\text{SO}_4) \cdot n\text{H}_2\text{O}$ ; and polyhalite,  $\text{K}_2\text{Ca}_2\text{Mg}(\text{SO}_4)_4 \cdot 2\text{H}_2\text{O}$ .

**Chlorargerite****AgCl***Origin of Name*

From the Greek words *chlor* and *argyros*, meaning “green” and “silver.”

*Hand Specimen Identification*

Chlorargerite is characterized by its waxlike appearance and heft.

*Physical Properties*

hardness	$2\frac{1}{2}$
specific gravity	5.55
cleavage/fracture	poor {100}/subconchoidal
luster/transparency	resinous/transparent to translucent
color	colorless, pale green, pearl-gray
streak	white

*Optical Properties*

Isotropic,  $n = 2.071$ .

*Crystallography*

Cubic,  $a = 5.55$ ,  $Z = 4$ ; space group  $F4/m\bar{3}2/m$ ; point group  $4/m\bar{3}2/m$ .

**Habit**

Rare crystals are cubic. Chlorargyrite is usually massive or columnar.

**Structure and Composition**

Chlorargyrite is isostructural with halite. Br, F, and I may substitute for Cl. Hg or Fe may be present in small amounts.

**Occurrence and Associations**

Chlorargyrite is a secondary silver mineral found in the oxidized zones of silver deposits. Associated minerals are many, including native silver.

**Varieties**

Embolite is a Br-rich variety.

**Related Minerals**

Chlorargyrite forms complete solid solutions with bromargyrite, AgBr. It is isostructural with a number of other minerals (see **halite**). Other related minerals include iodargyrite, AgI.

**Atacamite****Origin of Name**

From Atacama, a province in Chile.

**Hand Specimen Identification**

Atacamite is characterized by its granular crystalline aggregates and its bright green to blackish green color.

**Physical Properties**

hardness	3 to $3\frac{1}{2}$
specific gravity	3.76
cleavage/fracture	perfect basal (010), good {101}/conchoidal
luster/transparency	adamantine/transparent to translucent
color	various shades of green
streak	green

**Optical Properties**

Biaxial (-),  $\alpha = 1.831$ ,  $\beta = 1.861$ ,  $\gamma = 1.880$ ,  $\delta = 0.049$ ,  $2V = 75^\circ$ .

**Crystallography**

Orthorhombic,  $a = 6.02$ ,  $b = 9.15$ ,  $c = 6.85$ ,  $Z = 4$ ; space group  $P2_1/n2/a2/m$ ; point group  $2/m2/m2/m$ .

**Habit**

Slender, striated prisms are typical. Massive, granular, or fibrous aggregates are common.

**Structure and Composition**

$\text{CuCl}(\text{OH})_5$  and  $\text{CuCl}_2(\text{OH})_4$  octahedra characterize the structure. Mn commonly substitutes for Cu.

**Occurrence and Associations**

Atacamite occurs in the oxidized zones of copper deposits and in sands. It is associated with malachite, cuprite, and other secondary copper minerals.

**Fluorite****Origin of Name**

From the Latin word *fluere*, meaning "to flow," referring to the ease with which it melts.

**Hand Specimen Identification**

Cubic crystals, octahedral cleavage, hardness, and often purple color characterize fluorite. When uncolored, fluorite is sometimes confused with calcite or quartz, but may be distinguished by hardness and habit. See Figure 25.

**Physical Properties**

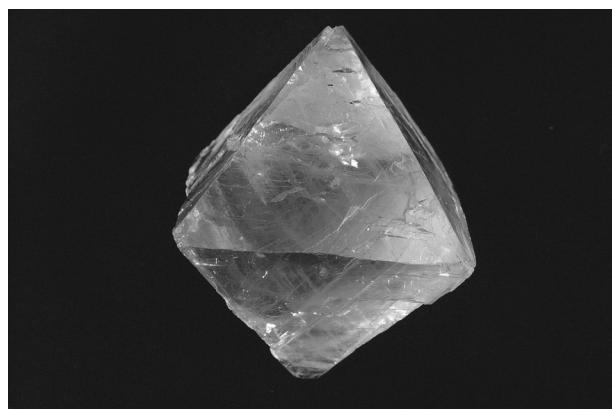
hardness	4
specific gravity	3.18
cleavage/fracture	perfect octahedral {111}/conchoidal and splintery
luster/transparency	vitreous/transparent to translucent
color	colorless to light green, blue-green, yellow, or purple; more rarely can also be white, brown, or rose
streak	white

**Optical Properties**

Fluorite is usually colorless in thin section; occasionally, it is light purple or green. Octahedral cleavage and low RI distinguish it from other clear isotropic minerals. Isotropic,  $n = 1.434$ .

**Crystallography**

Cubic,  $a = 5.463$ ,  $Z = 4$ ; space group  $F4/m\bar{3}2/m$ ; point group  $4/m\bar{3}2/m$ .



**FIGURE 25** This looks like a euhedral crystal, but it is not. Fluorite grows as cubic crystals, not octahedra. However, it has excellent cleavage in four directions. So, when cleaved, it forms nearly perfect octahedra, like the fluorite shown here.

*Habit*

Cubic crystals are common; octahedral cleavage fragments may appear to be crystals (Figure 25). Penetration twins are common. Fluorite may be massive or granular.

*Structure and Composition*

The cubic unit cell has  $\text{Ca}^{2+}$  ions in 8-fold coordination at the corners and in the middle of faces.  $\text{F}^-$  ions are located in tetrahedral coordination within the cell just inside each of the four corners. Fluorite is generally close to end member composition. Minor Y, Ce, and other rare earths may substitute for Ca. Cl, Sr, Ba, Fe, and Na may be present in small amounts.

*Occurrence and Associations*

Fluorite is common and widespread. It is found in veins and associated with quartz, calcite, galena, barite, and a number of other minerals. In some carbonate-hosted ore deposits, it is a replacement or fracture filling mineral associated with pyrrhotite, galena, and pyrite. It is also found as an accessory mineral in limestones and in igneous and metamorphic rocks.

*Related Minerals*

Fluorite is isostructural with thorianite,  $\text{ThO}_2$ ; cerianite,  $(\text{Ce}, \text{Th})\text{O}_2$ ; and uraninite,  $\text{UO}_2$ . It is closely related to sellaite,  $\text{MgF}_2$ , and frankdicksonite,  $\text{BaF}_2$ .

**Cryolite** **$\text{Na}_3\text{AlF}_6$** *Origin of Name*

From the Greek words for “ice” and “stone,” referring to its icy appearance.

*Hand Specimen Identification*

A pearly/greasy luster, white color, habit, and hardness help identify cryolite.

*Physical Properties*

hardness	$2\frac{1}{2}$
specific gravity	2.97
cleavage/fracture	none/uneven; cubic parting
luster/transparency	pearly, greasy, vitreous/transparent to translucent
color	colorless to snow-white
streak	white

*Optical Properties*

Biaxial (+),  $\alpha = 1.3385$ ,  $\beta = 1.3389$ ,  $\gamma = 1.3396$ ,  $\delta = 0.0011$ ,  $2V = 43^\circ$ .

*Crystallography*

Monoclinic,  $a = 5.46$ ,  $b = 5.60$ ,  $c = 7.80$ ,  $\beta = 90.18^\circ$ ,  $Z = 2$ ; space group  $P2_1/n$ ; point group  $2/m$ .

*Habit*

Individual pseudocubic crystals are rare. Aggregates are massive, lamellar, or columnar, often exhibiting pseudocubic parting.

*Structure and Composition*

In cryolite, both Na and Al are coordinated to six F. Na octahedra are distorted. F occupies a tetrahedral site, coordinated to three Na and one Al.

*Occurrence and Associations*

Cryolite is a rare mineral. The most significant samples are from Greenland, where it is in ore deposits hosted by granitic rocks. Associated minerals include quartz, K-feldspar, siderite, galena, sphalerite, and chalcopyrite, and less commonly other sulfides, wolframite, cassiterite, fluorite, and columbite.

*Related Minerals*

Cryolite has a high-temperature cubic polymorph.

**V. OXIDES****Tetrahedral and Octahedral Oxides***Tetrahedral Oxides*

zincite	$\text{ZnO}$
---------	--------------

*Octahedral Oxides*

rutile	$\text{TiO}_2$
periclase	$\text{MgO}$
hematite	$\text{Fe}_2\text{O}_3$
corundum	$\text{Al}_2\text{O}_3$
ilmenite	$\text{FeTiO}_3$
cassiterite	$\text{SnO}_2$
pyrolusite	$\text{MnO}_2$
columbite	$(\text{Fe}, \text{Mn})\text{Nb}_2\text{O}_6$
tantalite	$(\text{Fe}, \text{Mn})\text{Ta}_2\text{O}_6$

Similar to the sulfides, mineralogists divide oxide minerals into those having metal ions only in tetrahedral or only in octahedral coordination, and those in which the ions occupy sites with mixed or unusual coordinations. Zincite, a rare mineral, is the only known example of a purely tetrahedral oxide, but more than a dozen octahedral oxides are known. At high temperatures, Mg-, Fe-, and Ti-oxides form stable solid solutions. At low temperatures, most intermediate compositions are unstable; exsolution is common.

**Zincite** **$\text{ZnO}$** *Origin of Name*

Zincite is named for its composition.

*Hand Specimen Identification*

Zincite is characterized by its association with willemite and franklinite, its orange-yellow streak, and its red color.

*Physical Properties*

hardness	4 to 4½
specific gravity	5.4 to 5.7
cleavage/fracture	perfect basal (001)/ subconchoidal
luster/transparency	subadamantine/translucent
color	orange, yellow to deep red
streak	orange-yellow

*Optical Properties*

Uniaxial (+),  $\omega = 2.013$ ,  $\epsilon = 2.029$ ,  $\delta = 0.016$ .

*Crystallography*

Hexagonal,  $a = 3.25$ ,  $c = 5.19$ ,  $Z = 2$ ; space group  $P6_3mc$ ; point group  $6mm$ .

*Habit*

Zincite is commonly massive, platy, or granular. The rare crystals are hexagonal prisms terminated by pyramids and pedions.

*Structure and Composition*

The structure is identical to that of wurtzite; Zn is hexagonal closest packed. Mn and minor Fe may substitute for Zn.

*Occurrence and Associations*

Zincite is a rare mineral, primarily found at Franklin, New Jersey. Associated minerals include calcite, dolomite, franklinite, and willemite.

*Related Minerals*

Zincite is isostructural with wurtzite, ZnS; enargite,  $Cu_3AsS_4$ ; and greenockite, CdS.

**Rutile****TiO<sub>2</sub>***Origin of Name*

From the Latin word *rutilus*, meaning "red."

*Hand Specimen Identification*

Rutile is characterized by its often red to reddish-black color, adamantine luster, crystal form, and twinning. It sometimes occurs as needles in quartz (Plate 2.1).

*Physical Properties*

hardness	6 to 6½
specific gravity	4.24
cleavage/fracture	good prismatic {100} and {110}/subconchoidal
luster/transparency	adamantine, submetallic/transparent to translucent
color	red, red-brown to black
streak	pale or light brown

*Optical Properties*

Rutile appears deep red, red-brown, or yellow-brown in thin section. The strong color may mask its extreme birefringence. Relief is very high. Uniaxial (+),  $\omega = 2.61$ ,  $\epsilon = 2.90$ ,  $\delta = 0.29$ .

*Crystallography*

Tetragonal,  $a = 4.59$ ,  $c = 2.96$ ,  $Z = 2$ ; space group  $P4_2/m2_1/n2/m$ ; point group  $4/m2/m2/m$ .

*Habit*

Rutile may be massive but more commonly forms stubby to acicular tetragonal crystals. Striated prismatic crystals, terminated by prisms and often twinned, are common.

*Structure and Composition*

Distorted TiO<sub>6</sub> octahedra share edges to form chains. Chains are connected by corner-sharing octahedra. Each O is in triangular coordination, bonded to three Ti. Fe, Ta, Nb, V, Sn, and Cr may be present as substitutions.

*Occurrence and Associations*

Rutile, although not particularly abundant, is widespread. It is found typically as small grains in intermediate to mafic igneous rocks, in some metamorphic rocks, in veins, in pegmatites, and in some sediments. Associated minerals include quartz, feldspar, ilmenite, and hematite.

*Varieties*

Sagenite is the name given to rutile that exists as needled patches within other minerals such as quartz and pyroxene.

*Related Minerals*

Rutile has several polymorphs; most important are anatase and brookite. Minerals with similar structures to rutile include cassiterite, SnO<sub>2</sub>; pyrolusite, MnO<sub>2</sub>; plattnerite, PbO<sub>2</sub>; and stishovite, SiO<sub>2</sub>. Other similar minerals include baddeleyite, ZrO<sub>2</sub>; and paratellurite, TeO<sub>2</sub>.

**Periclase****MgO***Origin of Name*

From the Greek words *peri* and *klasis*, meaning "even" and "fracture," referring to its perfect cubic cleavage.

*Hand Specimen Identification*

Color, crystal form, cubic cleavage, and association help identify periclase.

*Physical Properties*

hardness	5½
specific gravity	3.56
cleavage/fracture	perfect {100}, poor {111}/uneven
luster/transparency	vitreous/transparent to translucent

color	colorless or gray
streak	orange-yellow

*Optical Properties*

Periclase is colorless in thin section, has high relief and cubic cleavage. Isotropic,  $n = 1.736$ .

*Crystallography*

Cubic,  $a = 4.21$ ,  $Z = 4$ ; space group  $F\bar{4}/m\bar{3}2/m$ ; point group  $4/m\bar{3}2/m$ .

*Habit*

Typically periclase crystals are cubes or octahedra. Coarse or granular masses are common.

*Structure and Composition*

Mg and O alternate in a three-dimensional cubic framework. Fe, Zn, and minor Mn may substitute for Mg.

*Occurrence and Associations*

Periclase is a high-temperature mineral found in metamorphosed carbonates. It is typically in contact aureoles, associated with calcite, forsterite, diopside, and a number of other Ca- and Ca-Mg-silicates.

*Related Minerals*

Periclase is isostructural with many other minerals (see **halite**).

**Hematite****Fe<sub>2</sub>O<sub>3</sub>***Origin of Name*

From the Greek word *haimatos*, meaning "blood," a reference to its color when powdered.

*Hand Specimen Identification*

Density and a characteristic red streak identify most hematite. Luster is variable from metallic to earthy. It may be confused with cinnabar.

*Physical Properties*

hardness	5½ – 6½
specific gravity	4.9 to 5.3
cleavage/fracture	none/subconchoidal
luster/transparency	submetallic/translucent to opaque
color	steel-gray, red-brown to black
streak	red

*Optical Properties*

Hematite is usually opaque; when very thin, it may have a deep red color. Uniaxial (-),  $\omega = 3.22$ ,  $\epsilon = 2.96$ ,  $\delta = 0.28$ .

*Crystallography*

Hexagonal (rhombohedral),  $a = 5.04$ ,  $c = 13.76$ ,  $Z = 6$ ; space group  $R\bar{3}2/c$ ; point group  $\bar{3}2/m$ .

*Habit*

Hematite exhibits many habits. Aggregates may be massive, in rosettes, botryoidal, reniform, micaceous and foliated, or earthy. Individual crystals are tabular, with many forms making up the edges. A metallic variety, specularite, may be a massive or fine-grained aggregate. Twins are common.

*Structure and Composition*

Hematite structure is similar to that of corundum. Closest packed O<sup>2-</sup> forms hexagonal layers; Fe<sup>3+</sup> occupies two of the three  $\frac{2}{3}$  interlayer octahedral sites. FeO<sub>6</sub> octahedra, linked by edge sharing, form 6-sided rings. Ti, Fe, Al, and Mn may replace Fe in small amounts.

*Occurrence and Associations*

Hematite is a common mineral in many kinds of rocks. It is found in red sandstones, iron formations, and its metamorphic equivalent; as an accessory in igneous rocks; as coatings and nodules; and in hydrothermal veins. Hematite is also associated with the altered zone of ore deposits. Usually hematite is secondary, forming after magnetite, Fe-sulfides, or Fe-silicates.

*Varieties*

Specularite (specular hematite) is the name given to micaceous hematite exhibiting a splendid metallic luster. Ocher is a red, earthy form of hematite. Martite is the name given to hematite pseudomorphs after magnetite.

*Related Minerals*

Hematite has a rare polymorph, maghemite. Isostructural minerals include corundum, Al<sub>2</sub>O<sub>3</sub>; eskolaite, Cr<sub>2</sub>O<sub>3</sub>; and karelianite, V<sub>2</sub>O<sub>3</sub>. Turgite, 2Fe<sub>2</sub>O<sub>3</sub>·nH<sub>2</sub>O, and limonite, Fe<sub>2</sub>O<sub>3</sub>·nH<sub>2</sub>O, are equivalent to hydrated hematite with variable water content. Other related minerals include goethite and lepidocrocite, both FeO(OH), and bixbyite, Mn<sub>2</sub>O<sub>3</sub>.

**Corundum****Al<sub>2</sub>O<sub>3</sub>***Origin of Name*

Derived from *kauruntaka*, the Indian name for the mineral.

*Hand Specimen Identification*

Corundum is identified primarily by its hardness. Luster, specific gravity, and habit aid identification.

*Physical Properties*

hardness	9
specific gravity	3.9 to 4.1
cleavage/fracture	none/uneven; rectangular parting

luster/transparency	adamantine/transparent to translucent
color	shades of brown, blue, or pink, colorless, variable
streak	white

***Optical Properties***

In thin section, corundum is typically colorless. Some varieties are pale pink, green, blue, or yellow. It has extremely high relief and is weakly birefringent. Uniaxial (-),  $\omega = 1.768$ ,  $\epsilon = 1.760$ ,  $\delta = 0.008$ .

***Crystallography***

Hexagonal (rhombohedral),  $a = 4.95$ ,  $c = 13.78$ ,  $Z = 6$ ; space group  $R\bar{3}2/c$ ; point group  $\bar{3}2/m$ .

***Habit***

Hexagonal crystals may be tabular or prismatic. Multiple pyramidal forms combined with pinacoids give a tapering or barrel-shaped appearance (Figure 3.4). Euhedral individual crystals are rare; corundum is usually massive or granular.

***Structure and Composition***

The corundum structure is identical to that of hematite (see **hematite**). Minor amounts of Fe, Ti, Cr, Ni, and Mn replace Al.

***Occurrence and Associations***

Corundum is an accessory mineral in metamorphosed carbonates and sediments, in some Al-rich igneous rocks, and in placers. Massive corundum, forming emery deposits, is found in carbonate skarns.

***Varieties***

Sapphire (typically blue) and ruby (red) are gem varieties of corundum. Emery refers to hard compact corundum-magnetite-hematite ore.

***Related Minerals***

Corundum is isostructural with hematite,  $Fe_2O_3$ ; ilmenite,  $FeTiO_3$ ; eskolaite,  $Cr_2O_3$ ; and karelianite,  $V_2O_3$ .

**Ilmenite** **$FeTiO_3$** ***Origin of Name***

Named after the Ilmen Mountains in Russia.

***Hand Specimen Identification***

Density and color help identify ilmenite. It is distinguished from magnetite by its lack of strong magnetism and from hematite by its streak. Ilmenite is occasionally confused with chromite.

***Physical Properties***

hardness	$5\frac{1}{2}$ to 6
specific gravity	4.5 to 5
cleavage/fracture	none/subconchoidal

luster/transparency	metallic/opaque
color	iron-black
streak	brownish red to black

***Crystallography***

Hexagonal (trigonal),  $a = 5.08$ ,  $c = 14.08$ ,  $Z = 6$ ; space group  $R\bar{3}$ ; point group 3.

***Habit***

Crystals are tabular or prismatic, often showing rhombohedral forms, and commonly twinned. Most occurrences are massive, granular, compact, scaly, or appearing as skeletal crystals.

***Structure and Composition***

The structure of ilmenite is the same as that of corundum and hematite (see **hematite**). Ilmenite may contain excess Fe replacing Ti, forming limited solid solutions with hematite. Mg and Mn may replace Fe.

***Occurrence and Associations***

Ilmenite, a common vein mineral, is found as masses in igneous rocks, in pegmatites, as an accessory in high-grade metamorphic rocks, and is present in black sands where associated minerals include quartz, hematite, magnetite, rutile, zircon, monazite, and other dense minerals.

***Related Minerals***

Geikielite,  $MgTiO_3$ , and pyrophanite,  $MnTiO_3$ , form complete solid solutions with ilmenite. Several minerals are isostructural with ilmenite (see **hematite**).

**Cassiterite** **$SnO_2$** ***Origin of Name***

From the Greek word *kassiteros*, meaning “tin.”

***Hand Specimen Identification***

Cassiterite is recognized by crystal form, streak, high specific gravity, indistinct prismatic cleavage, and adamantine luster. It may be confused with rutile.

***Physical Properties***

hardness	6 to 7
specific gravity	7.0
cleavage/fracture	good {100}, poor {111}/subconchoidal
luster/transparency	adamantine/transparent to translucent
color	brown or black
streak	white

***Optical Properties***

Cassiterite is yellow, brown, red, or colorless in thin section. Relief and birefringence are high. Uniaxial (+),  $\omega = 2.006$ ,  $\epsilon = 2.097$ ,  $\delta = 0.091$ .

*Crystallography*

Tetragonal,  $a = 4.74$ ,  $c = 3.19$ ,  $Z = 2$ ; space group  $P4_2/m2_1/n2/m$ ; point group  $4/m2/m2/m$ .

*Habit*

Crystals are pyramidal, stubby prismatic, or acicular. Faces may be striated; contact and penetration twins are common; complex multiple twinning is less common. Cassiterite may be massive, colloform, reniform, or fibrous.

*Structure and Composition*

Distorted  $\text{SnO}_6$  octahedra share edges to form chains. Chains are connected by corner-sharing octahedra. Each O is in triangular coordination, bonded to three Sn. Cassiterite may contain minor Fe and Ta substituting for Sn. Mn, W, Nb, and Sc also may be present in trace amounts.

*Occurrence and Associations*

Cassiterite is widespread but rarely concentrated as tin ore. It occurs in pegmatites, veins, contact aureoles, altered zones of ore deposits, and placers. Associated minerals include quartz, topaz, tourmaline, fluorite, muscovite, lepidolite, wolframite, scheelite, and others.

*Related Minerals*

Cassiterite is isostructural with rutile,  $\text{TiO}_2$ ; pyrolusite,  $\text{MnO}_2$ ; plattnerite,  $\text{PbO}_2$ ; and paratellurite,  $\text{TeO}_2$ .

**Pyrolusite** **$\text{MnO}_2$** *Origin of Name*

From the Greek words *pyr* and *louein*, meaning “fire” and “to wash,” referring to its use in glass manufacturing.

*Hand Specimen Identification*

Pyrolusite is characterized by softness and black streak.

*Physical Properties*

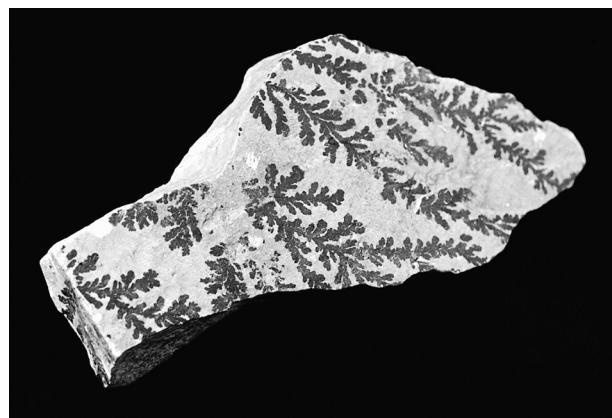
hardness	1 to 2	
specific gravity	4.5 to 5.0	
cleavage/fracture	perfect but rarely seen	
	prismatic {110}/uneven	
luster/transparency	metallic/opaque	
color	black	
streak	black	

*Crystallography*

Tetragonal,  $a = 4.40$ ,  $c = 2.87$ ,  $Z = 2$ ; space group  $P4_2/m2_1/n2/m$ ; point group  $4/m2/m2/m$ .

*Habit*

Rare crystals form perfect tetragonal prisms. More commonly pyrolusite forms orthorhombic pseudomorphs after manganite, or it is dendritic, fibrous, reniform, or columnar (Figure 26).



**FIGURE 26** Dendritic pyrolusite,  $\text{MnO}_2$ , on a slab of sandstone from Spearfish, South Dakota.

*Structure and Composition*

Pyrolusite has the rutile structure (see **rutile**). It is commonly close to pure Mn-oxide, but Mn valence may be slightly variable. Small amounts of  $\text{H}_2\text{O}$  may be present.

*Occurrence and Associations*

Pyrolusite is a secondary mineral found as coatings, nodules, dendrites, and in beds. Associated minerals include barite, limonite, romanechite (psilomelane), hematite, magnetite, and other Mn- and Fe-oxides.

*Varieties*

Wad is the name given to mixtures of Mn-oxides.

*Related Minerals*

Pyrolusite is isostructural with a number of minerals (see **rutile**). It has several polymorphs, including nsutite, ramsdellite, and vernadite. Other related minerals include manganite,  $\text{MnO(OH)}$ ; romanechite (psilomelane),  $\text{BaMn}_9\text{O}_{16}(\text{OH})_4$ ; and birmessite,  $\text{Na}_4\text{Mn}_{14}\text{O}_{27} \cdot 9\text{H}_2\text{O}$ .

**Columbite-Tantalite       $(\text{Fe,Mn})(\text{Nb,Ta})_2\text{O}_6$** *Origin of Name*

Columbium, an early name for the element tantalum, is named after Columbia, where the original samples of this mineral were found. Tantalite refers to the Greek myth of Tantalus.

*Hand Specimen Identification*

Association, color, luster, streak, and density help identify members of the columbite-tantalite series. Crystals often display heart-shaped twins. These minerals may be confused with wolframite or uraninite.

*Physical Properties*

hardness	6
specific gravity	6.0
cleavage/fracture	good (010)/subconchoidal

luster/transparency	submetallic/translucent to opaque
color	iron-black to brown
streak	brown, dark red to black

*Optical Properties*

Biaxial (+),  $\alpha = 2.44$ ,  $\beta = 2.32$ ,  $\gamma = 2.38$ ,  $\delta = 0.12$ ,  $2V = 75^\circ$ .

*Crystallography*

Orthorhombic,  $a = 5.10$ ,  $b = 14.27$ ,  $c = 5.74$ ,  $Z = 4$ ; space group  $P2_1/b2/c2_1/n$ ; point group  $2/m2/m2/m$ .

*Habit*

Short prisms or tabular crystals, sometimes with heart-shaped twins, are typical. Crystal aggregates or masses are common.

*Structure and Composition*

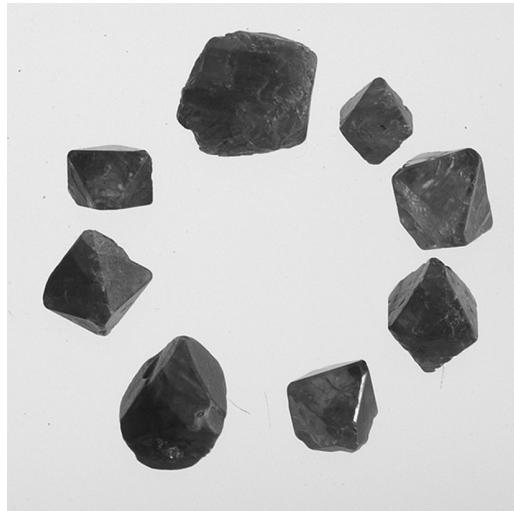
The structure consists of chains of  $(\text{Fe,Mn})\text{O}_6$  and  $(\text{Nb,Ta})\text{O}_6$  octahedra. Edge sharing joins them together. A complete solid solution exists between columbite,  $(\text{Fe,Mn})\text{Nb}_2\text{O}_6$ , and tantalite,  $(\text{Fe,Mn})\text{Ta}_2\text{O}_6$ . Mg may substitute for (Fe,Mn). Sn and W may be present in small amounts.

*Occurrence and Associations*

Members of the columbite-tantalite series are uncommon. They occur in pegmatites with quartz, feldspar, mica, Li-minerals, phosphates, and other typical pegmatite minerals; in carbonatites; and in placer deposits with other dense minerals.

*Varieties*

Tapiolite is a polymorph of columbite-tantalite. Other related minerals include microlite,  $\text{Ca}_2\text{Ta}_2\text{O}_6(\text{O,OH,F})$ ; pyrochlore,  $(\text{Ca,Na})_2(\text{Nb,Ta})_2\text{O}_6(\text{O,OH,F})$ ; and fergusonite,  $(\text{REE})\text{NbO}_4$ .



**FIGURE 27** These spinel crystals from Sri Lanka vary from poor to well-developed octahedra. They are about 1 cm across.

**Spinel and Other Oxides with Mixed or Unusual Coordinations****"Inverse" Spinel**

spinel	$\text{MgAl}_2\text{O}_4$
magnetite	$\text{Fe}_3\text{O}_4$

**"Normal" Spinel**

chromite	$\text{FeCr}_2\text{O}_4$
franklinite	$\text{ZnFe}_2\text{O}_4$

**Others**

perovskite	$\text{CaTiO}_3$
chrysoberyl	$\text{BeAl}_2\text{O}_4$
uraninite	$\text{UO}_2$
thorianite	$\text{ThO}_2$
cuprite	$\text{Cu}_2\text{O}$

In spinel group minerals both tetrahedral and octahedral sites are occupied by metal ions. In "normal" spinel minerals each metal species is found in either tetrahedral or octahedral coordination but not both; their formulas may be written as  $\text{XY}_2\text{O}_4$ , with X representing the tetrahedral cation and Y the octahedral cation. In "inverse" spinels one metal species occupies both coordinations. A general formula might be more appropriately written as  $\text{Y}[\text{XY}] \text{O}_4$ , with the brackets identifying metal ions in octahedral sites.

Mineralogists have identified other oxides that do not fit into the tetrahedral, octahedral, or spinel groups. In uraninite and thorianite, metal atoms occupy cubic sites. In perovskite, Ti and Ca are in 6-fold and 12-fold coordinations, respectively. In cuprite, Cu is in 2-fold coordination and chrysoberyl is isostructural with olivine.

**Spinel***Origin of Name*

From the Latin word *spina*, meaning "thorn," a reference to the sharp crystals.

*Hand Specimen Identification*

The term *spinel* is used in a generic sense to describe any of the many minerals with spinel structure. The specific mineral called *spinel*,  $\text{MgAl}_2\text{O}_4$ , is recognized by association, octahedral crystals, hardness, and sometimes a vitreous luster. See Figure 27.

*Physical Properties*

hardness	8
specific gravity	3.5 to 4.0
cleavage/fracture	none/conchoidal

luster/transparency	vitreous/transparent to translucent
color	variable, red, lavender, blue, green, brown, white, or black
streak	white

*Optical Properties*

Pure Mg spinel is colorless in thin section but is pleochroic green or blue-green if Fe substitutes for Mg. Octahedral shape and high index of refraction aid identification. Isotropic,  $n = 1.74$ .

*Crystallography*

Cubic,  $a = 8.09$ ,  $Z = 8$ ; space group  $F\bar{4}/d\bar{3}2/m$ ; point group  $4/m\bar{3}2/m$ .

*Habit*

Spinel typically forms octahedral crystals (Figure 27); twinning and modifying faces are common. Massive forms and irregular grains are also known.

*Structure and Composition*

Spinel minerals are relatively simple cubic structures.  $MgO_6$  octahedra and  $AlO_4$  tetrahedra share edges and are closest packed.  $Fe^{2+}$ , Zn, and Mn may substitute for Mg.  $Fe^{3+}$  and Cr may substitute for Al.

*Occurrence and Associations*

Spinel is a high-temperature mineral found in metamorphosed carbonates or schists, as an accessory in mafic igneous rocks, and in placers. Associated minerals include calcite, dolomite, garnet, and Ca-Mg silicates in marbles; garnet, corundum, sillimanite, andalusite and cordierite in highly aluminous rocks; diopside, olivine, chondrodite, in mafic ones; and other dense minerals in placers.

*Varieties*

Ruby spinel is the name given to gemmy-red spinel; various other gem names are used to a lesser extent. *Pleonaste* is the name given to intermediate Fe-Mg spinels.

*Related Minerals*

Spinel is isostructural with other members of the spinel group and with bornhardite and linnaeite, both  $Co_3Se_4$ ; polydymite,  $Ni_3S_4$ ; indite,  $FeIn_2S_4$ ; and greigite,  $Fe_3S_4$ . Spinel forms solid solutions with other members of the spinel group, including hercynite,  $FeAl_2O_4$ ; gahnite,

$ZnAl_2O_4$  galaxite,  $MnAl_2O_4$  zincochromite,  $ZnCr_2O_4$  and magnesiochromite,  $MgCr_2O_4$ .

**Magnetite****Fe<sub>3</sub>O<sub>4</sub>***Origin of Name*

Named after Magnesia, near Macedonia in Thessaly, where the Greeks found this mineral.

*Hand Specimen Identification*

Magnetite, a member of the spinel group, is characterized by its strong magnetism, hardness, and black color. Magnetism distinguishes it from ilmenite and chromite.

*Physical Properties*

hardness	6
specific gravity	5.20
cleavage/fracture	none/subconchoidal
luster/transparency	metallic/opaque
color	black
streak	black

*Crystallography*

Cubic,  $a = 8.397$ ,  $Z = 8$ ; space group  $F\bar{4}/d\bar{3}2/m$ ; point group  $4/m\bar{3}2/m$ .

*Habit*

Crystals are typically octahedra, sometimes displaying contact or lamellar twins. Magnetite is also common as massive or granular aggregates or disseminated as fine grains.

*Structure and Composition*

Magnetite has the spinel structure (see **spinel**). Ti is usually present; at high temperature a complete solid solution to  $Fe_2TiO_4$  is possible. Minor amounts of Mg, Mn, Ni, Al, Cr, and V may be present.

*Occurrence and Associations*

Magnetite is common and widespread. It is found as an accessory in many types of igneous, metamorphic, and sedimentary rocks and in unconsolidated sediments. It may be concentrated to form ore bodies by magmatic, metamorphic, or sedimentary processes.

*Related Minerals*

Magnetite forms solid solutions with ulvöspinel,  $Fe_2TiO_4$ ; magnesioferrite,  $MgFe_2O_4$ ; jacobsite,  $MnFe_2O_4$ ; and to a lesser extent with maghemite,  $Fe_2O_3$ .

**Chromite****FeCr<sub>2</sub>O<sub>4</sub>***Origin of Name*

The name *chromite* refers to this mineral's composition.

*Hand Specimen Identification*

Color, density, streak, luster, and association distinguish chromite. It may be slightly magnetic and is sometimes confused with magnetite or ilmenite.

*Physical Properties*

hardness	5½
specific gravity	5.10
cleavage/fracture	none/conchoidal
luster/transparency	metallic/subtranslucent;
color	opaque black, brownish black
streak	brown, dark brown

*Crystallography*

Cubic,  $a = 8.37$ ,  $Z = 8$ ; space group  $F\bar{4}/d\bar{3}2/m$ ; point group  $4/m\bar{3}2/m$ .

*Habit*

Rare euhedral crystals are octahedral; chromite is generally massive or granular.

*Structure and Composition*

The structure of chromite is the same as that of all the spinel minerals (see **spinel**). Mg, Fe, Al, and Zn are typical impurities.

*Occurrence and Associations*

Primary chromite is found with olivine, pyroxene, spinel, magnetite, and sulfides in ultramafic rocks. It is also found in placers and black sands. Chromite is common as an accessory mineral but may be concentrated by gravity or magmatic processes.

*Related Minerals*

Chromite has one polymorph, donathite. It forms solid solutions with magnesiochromite,  $MgCr_2O_4$ , and hercynite,  $FeAl_2O_4$ , and to lesser extent with other spinel minerals.

**Franklinite****ZnFe<sub>2</sub>O<sub>4</sub>***Origin of Name*

Named after Franklin, New Jersey, a classic locality.

*Hand Specimen Identification*

Franklinite resembles other dark-colored spinels and Fe-Ti oxides but has a dark brown streak and is only slightly magnetic.

*Physical Properties*

hardness	6
specific gravity	5.32

cleavage/fracture	none/conchoidal
luster/transparency	metallic/opaque
color	black, iron-black
streak	black, reddish brown to dark brown

cleavage/fracture	none/conchoidal
luster/transparency	metallic/opaque
color	black, iron-black
streak	black, reddish brown to dark brown

*Crystallography*

Cubic,  $a = 8.43$ ,  $Z = 8$ ; space group  $F\bar{4}/d\bar{3}2/m$ ; point group  $4/m\bar{3}2/m$ .

*Habit*

Octahedral crystals, often with modifying faces, are common in Franklin, New Jersey, the only place where it is found in large quantities. It is also found as discrete rounded grains, as granular masses, or in massive lenses.

*Structure and Composition*

The structure is the same as that of other spinel minerals (see **spinel**). Franklinite normally contains substantial Mn substituting for Zn. Mn<sup>3+</sup> may also substitute for Fe<sup>3+</sup>. Mg, Cr, and V also may be present.

*Occurrence and Associations*

Franklinite is associated with zincite and willemite in zinc ore deposits at Franklin, New Jersey. The host rock is a coarse-grained limestone.

*Related Minerals*

Franklinite is similar in many ways to other dark-colored spinel minerals. It forms minor solid solutions with most of them.

**Chrysoberyl****BeAl<sub>2</sub>O<sub>4</sub>***Origin of Name*

From the Greek words meaning "golden beryl."

*Hand Specimen Identification*

Color, luster, hardness, and common twinning characterize chrysoberyl.

*Physical Properties*

hardness	8½
specific gravity	3.7 to 3.8
cleavage/fracture	good but indistinct prismatic {011}, poor (010)/subconchoidal
luster/transparency	vitreous/transparent to translucent
color	yellow, green, or brown
streak	white

*Optical Properties*

Biaxial (+),  $\alpha = 1.747$ ,  $\beta = 1.748$ ,  $\gamma = 1.757$ ,  $\delta = 0.010$ ,  $2V = 45^\circ$ .

*Crystallography*

Orthorhombic,  $a = 4.24$ ,  $b = 9.39$ ,  $c = 5.47$ ,  $Z = 4$ ; space group  $P2_1/b2_1/n2_1/m$ ; point group  $2/m2/m2/m$ .

*Habit*

Chrysoberyl is generally tabular and sometimes heart shaped or pseudohexagonal due to cyclic twinning. Faces are often striated.

*Structure and Composition*

The structure, similar to that of olivine, contains hexagonal closest packed oxygens with Be in tetrahedral sites and Al in octahedral sites.

*Occurrence and Associations*

Chrysoberyl is a rare mineral occurring in granites, pegmatites, mica schists, and some placers.

*Varieties*

Cat's eye (cymophane) is a green chatoyant gem variety. Alexandrite is an emerald-green gem variety that appears red under artificial light. Both are very valuable.

*Related Minerals*

Chrysoberyl is isostructural with olivine minerals. It is chemically similar to spinels but has a different structure.

**Uraninite****UO<sub>2</sub>***Origin of Name*

The name *uraninite* refers to this mineral's composition.

*Hand Specimen Identification*

Uraninite is characterized by its radioactivity, association, high specific gravity, streak, color, and luster.

*Physical Properties*

hardness	$5\frac{1}{2}$
specific gravity	7 to 9.5
cleavage/fracture	none/conchoidal
luster/transparency	pitchy dull to submetallic/opaque
color	black
streak	brown to black

*Crystallography*

Cubic,  $a = 5.4682$ ,  $Z = 4$ ; space group  $F\bar{4}/m\bar{3}2/m$ ; point group  $4/m\bar{3}2/m$ .

*Habit*

Individual crystals are rare; they form cubes, octahedra, or combinations. Massive, colloform, or botryoidal forms are typical.

*Structure and Composition*

Uraninite is isostructural with fluorite (see **fluorite**). U valence and U:O ratios are somewhat

variable; uraninite is really a mixture of  $\text{UO}_2$  and  $\text{U}_3\text{O}_8$ . Th may substitute for U; N, Ar, Fe, Ca, Zr, and rare earths are also commonly present. Pb and Ra are always present as radioactive decay products.

*Occurrence and Associations*

Uraninite occurs in granitic pegmatites, in veins, and in sandstones. Associated minerals include quartz, K-feldspar, zircon, tourmaline, and monazite in pegmatites; cassiterite, galena, sulfides, and arsenides in veins; and quartz and various other secondary minerals in sandstones. Uraninite also concentrates in coal and other organic debris in sediments and related sedimentary rocks.

*Varieties*

Massive forms of uraninite are called *pitchblende*.

*Related Minerals*

Uraninite is isostructural with fluorite,  $\text{CaF}_2$ , and cerianite,  $(\text{Ce}, \text{Th})\text{O}_2$ . It forms complete solid solution with thorianite,  $\text{ThO}_2$ . Other related minerals include baddeleyite,  $\text{ZrO}_2$ .

**Cuprite****Cu<sub>2</sub>O***Origin of Name*

From the Latin word *cuprum*, meaning "copper."

*Hand Specimen Identification*

Red color, form, luster, streak, and association all help identify cuprite. It may be confused with cassiterite, hematite, and cinnabar.

*Physical Properties*

hardness	$3\frac{1}{2}$ to 4
specific gravity	5.9 to 6.1
cleavage/fracture	poor {111}/conchoidal
luster/transparency	submetallic, metallic
color	various shades of red
streak	brownish red

*Crystallography*

Cubic,  $a = 4.27$ ,  $Z = 2$ ; space group  $P4_2/n\bar{3}2/m$ ; point group  $4/m\bar{3}2/m$ .

*Habit*

Octahedral, cubic, and dodecahedral forms, often in combination, are common. Cuprite may occur as elongated capillary crystals called *chalcotrichite*.

*Structure and Composition*

Oxygen, in tetrahedral groups, is arranged in a body centered cubic array. Each Cu is bonded to two O. Cuprite is generally close to end member composition; Fe is a common minor impurity.

*Occurrence and Associations*

Cuprite is a secondary mineral found in the oxidized zones of copper deposits. Native copper, limonite, and secondary copper minerals such as malachite, azurite, and chrysocolla are typically associated minerals.

*Related Minerals*

Tenorite, CuO, is similar in composition and occurrence.

**VI. HYDROXIDES**

gibbsite	$\text{Al(OH)}_3$
brucite	$\text{Mg(OH)}_2$
manganite	$\text{MnO(OH)}$
goethite	$\text{FeO(OH)}$
diaspore	$\text{AlO(OH)}$
romanechite	$\text{BaMn}_9\text{O}_{16}(\text{OH})_4$

The hydroxide minerals all contain  $\text{OH}^-$  as an essential anion. Some, such as diaspore, also contain  $\text{O}^{2-}$ . The structures are all generally simple; brucite and gibbsite have layered structures equivalent to the trioctahedral and dioctahedral layers in micas. Romanechite (also called psilomelane) has a structure related to rutile and spinel. Only limited solid solution occurs between the various hydroxides, but they are often found in intimate mixtures with each other and with oxide minerals. Bauxite refers to a mixture of Al oxides and hydroxides, limonite to a mixture of Fe oxides and hydroxides, and wad to a mixture of Mn oxides and hydroxides.

*Optical Properties*

Gibbsite is usually colorless in thin section; maximum interference colors are upper first order. It is difficult to distinguish from clay minerals. Biaxial (+),  $\alpha = 1.57$ ,  $\beta = 1.57$ ,  $\gamma = 1.59$ ,  $\delta = 0.02$ ,  $2V = 0^\circ$  to  $40^\circ$

*Crystallography*

Monoclinic,  $a = 8.641$ ,  $b = 5.07$ ,  $c = 9.719$ ,  $\beta = 94.57^\circ$ ,  $Z = 8$ ; space group  $P2_1/n$ ; point group  $2/m$ .

*Habit*

Foliated or tabular crystals are typically very small with a pseudohexagonal shape. Granular aggregates, colloform or radiating masses, and coatings are most common.

*Structure and Composition*

In the layered gibbsite structure, octahedral  $\text{Al}^{3+}$  occupies two of the three sites between OH sheets. Small amounts of Fe may replace Al.

*Occurrence and Associations*

Gibbsite is a secondary mineral associated with aluminum deposits, bauxites, and laterites (Figure 28). Diaspore and böhmite, other aluminum hydroxides, are typically intimate associates.

*Related Minerals*

Gibbsite is similar in structure to brucite,  $\text{Mg(OH)}_2$ . It has several polymorphs, including bayierite, doyleite, and nordstrandite. Other related minerals include diaspore and böhmite, both  $\text{AlO(OH)}$ , and bauxite, a mixture of gibbsite, böhmite, and diaspore.

**Gibbsite** **$\text{Al(OH)}_3$** *Origin of Name*

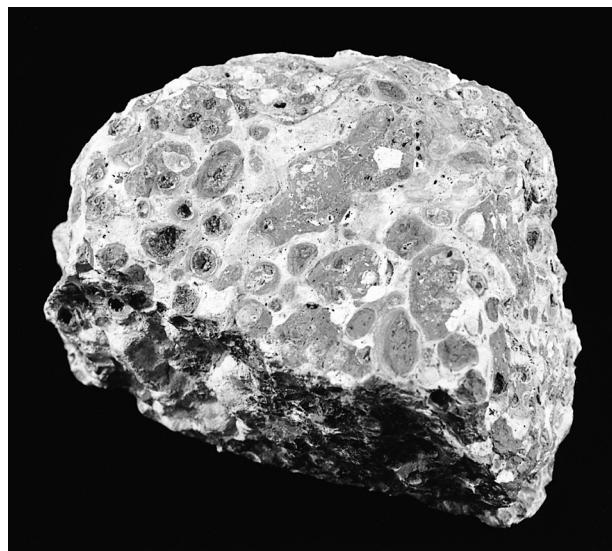
Named after Colonel G. S. Gibbs (1777–1834), a mineral collector.

*Hand Specimen Identification*

Earthy smell and appearance, and color help identify gibbsite. It may be confused with kaolinite, talc, or brucite.

*Physical Properties*

hardness	$2\frac{1}{2}$ to $3\frac{1}{2}$
specific gravity	2.40
cleavage/fracture	perfect (001)/uneven
luster/transparency	vitreous, pearly, earthy/ transparent to translucent
color	white or gray to greenish
streak	white



**FIGURE 28** Bauxite, a mixture of gibbsite and other aluminum hydroxide and oxide minerals, is a product of weathering and leaching.

**Brucite****Mg(OH)<sub>2</sub>****Manganite****MnO(OH)***Origin of Name*

A. Bruce (1777–1818), an early American mineralogist, was the inspiration for this mineral's name.

*Hand Specimen Identification*

Good platy or micaceous cleavage, flexible sheets, color, and luster help identify brucite. It may be confused with gypsum or gibbsite.

*Physical Properties*

hardness	$2\frac{1}{2}$
specific gravity	2.4 to 2.5
cleavage/fracture	perfect basal (001)/sectile
luster/transparency	vitreous, pearly/transparent to translucent
color	white, light green, or gray
streak	white

*Optical Properties*

Brucite is colorless in thin section and displays anomalous second-order red or blue interference colors. Brucite may be mistaken for talc, white mica, or gypsum, but they are all biaxial. Uniaxial (+),  $\omega = 1.57$ ,  $\epsilon = 1.58$ ,  $\delta = 0.02$ .

*Crystallography*

Hexagonal (rhombohedral),  $a = 3.147$ ,  $c = 4.769$ ,  $Z = 1$ ; space group  $P\bar{3}2/m1$ ; point group  $\bar{3}2/m$ .

*Habit*

Broad platy, foliated, or tabular crystals are typical. Massive or fibrous aggregates and foliated masses are common.

*Structure and Composition*

The structure is similar to that of gibbsite: Sheets of OH sandwich Mg in octahedral coordination. Fe, Mn, and Zn may substitute in minor amounts for Mg.

*Occurrence and Associations*

Brucite occurs in veins of mafic rocks, serpentinite, or talc-chlorite schists, and in metamorphosed carbonates or marls. Associated minerals include chlorite and other secondary magnesium minerals in mafic rocks and calcite, dolomite, talc, magnesite, and periclase in carbonates.

*Related Minerals*

Brucite is isostructural with gibbsite,  $Al(OH)_3$ . It is isotypical with pyrochroite,  $Mn(OH)_2$ ; amakinitite,  $(Fe,Mg)(OH)_2$ ; portlandite,  $Ca(OH)_2$ ; and theophrastite,  $Ni(OH)_2$ .

*Origin of Name*

The name *manganite* refers to this mineral's composition.

*Hand Specimen Identification*

Manganite is recognized by its prismatic crystals and black color. It may be confused with pyrolusite, with which it is frequently found, but is harder and has a brown streak.

*Physical Properties*

hardness	4
specific gravity	4.2 to 4.4
cleavage/fracture	perfect basal (010), good {110}/sectile
luster/transparency	submetallic/opaque
color	gray to black
streak	dark to red-brown

*Crystallography*

Monoclinic,  $a = 8.84$ ,  $b = 5.23$ ,  $c = 5.74$ ,  $\beta = 90.0^\circ$ ,  $Z = 8$ ; space group  $B2_1/d$ ; point group  $2/m$ .

*Habit*

Prismatic crystals, sometimes twinned, often show striations and complicated terminations. Bundled, stalactitic, columnar, bladed, or fibrous aggregates are common.

*Structure and Composition*

O and OH are nearly hexagonal closest packed.  $Mn(O,OH)_6$  octahedra share corners to make a three-dimensional framework. Fe and Mg may replace Mn in small amounts.

*Occurrence and Associations*

Manganite is an uncommon secondary mineral found in veins with other Mn oxides or hydroxides, carbonates, limonite, and barite.

*Related Minerals*

A number of manganese oxides and hydroxides are closely related, including pyrolusite,  $MnO_2$ ; partridgeite and bixbyite, both  $Mn_2O_3$ ; hausmannite,  $Mn_3O_4$ ; hollandite,  $Ba_2Mn_8O_{16}$ ; romanechite,  $BaMn_9O_{16}(OH)_4$ ; pyrochroite,  $Mn(OH)_2$ ; vernadite,  $Mn(OH)_4$ ; and takanelite. Wad is a mixture of these manganese minerals.

**Goethite****FeO(OH)***Origin of Name*

Named after J. W. Goethe (1749–1832), a German poet and scientist.

***Hand Specimen Identification***

Brown color, sometimes earthy appearance, habit, and streak identify goethite. It is sometimes confused with hematite but has a brownish yellow streak, in contrast with hematite's red. Figure 29 and Plate 8.6 show goethite crystals that grew in vugs in iron formation.

***Physical Properties***

hardness	5 to $5\frac{1}{2}$
specific gravity	4.3
cleavage/fracture	perfect but rarely seen (010)/uneven
luster/transparency	subadamantine to earthy/subtranslucent to opaque
color	yellow-brown to dark brown or black
streak	brown-yellow

***Optical Properties***

Goethite is pleochroic yellow, orange-red, or various shades of brown in thin section. It has high positive relief and extremely high birefringence that may be masked by its color. Goethite is difficult to distinguish from other Fe oxides. Biaxial (-),  $\alpha = 2.15$  to 2.26,  $\beta = 2.39$  to 2.41,  $\gamma = 2.40$  to 2.52,  $\delta = 0.15$ ,  $2V = 0^\circ$  to  $27^\circ$ .

***Crystallography***

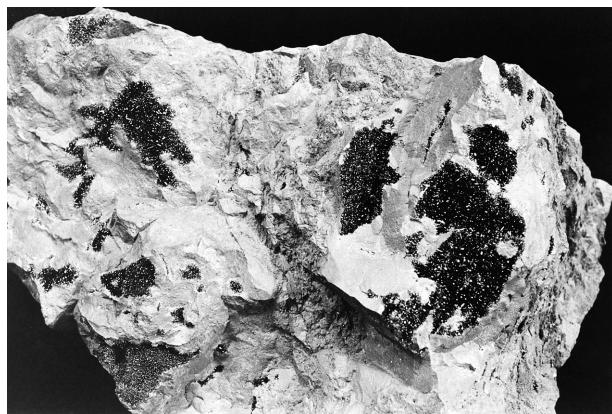
Orthorhombic,  $a = 4.65$ ,  $b = 10.02$ ,  $c = 3.04$ ,  $Z = 4$ ; space group  $P2_1/b2_1/n2_1/m$ ; point group  $2/m2/m2/m$ .

***Habit***

Euhedral goethite crystals are rare; it is usually platy, prismatic, fibrous, botryoidal, or mammillary. Concentric growth bands are common.

***Structure and Composition***

Goethite is isostructural with diaspore. Edge-sharing  $\text{Fe}(\text{O},\text{OH})$  octahedra form bands running parallel to



**FIGURE 29** The black crystals are goethite that crystallized on the sides of vugs in iron formation from Atikokan, Ontario, Canada. See also Plate 8.6.

the c-axis. Perpendicular to c, the bands form a checkerboard pattern, leaving empty channels between them. Up to several weight percent of Mn and absorbed water are often present.

***Occurrence and Associations***

Goethite is a widely distributed secondary mineral formed by the weathering of Fe-rich compounds (Figure 29). It concentrates in sediments, gossans, and laterites. Common associated minerals include siderite, pyrite, magnetite, and many residual weathering products.

***Varieties***

*Bog ore* is a porous, poorly consolidated form of goethite. *Limonite* refers to a mixture of hydrous iron oxides of variable chemistry and crystallinity.

***Related Minerals***

Lepidocrocite, akaganeite, and feroxyhyte are all rare polymorphs of goethite. Diaspore has the same structure except that Al replaces two-thirds of the Fe. Other related minerals are manganite,  $\text{MnO(OH)}$ ; heterogenite,  $\text{CoO(OH)}$ ; and montroseite,  $(\text{V}, \text{Fe})\text{O(OH)}$ .

**Diaspore*****Origin of Name***

From the Greek word *diaspora*, meaning "to scatter," referring to its decrepitation when heated.

***Hand Specimen Identification***

Bladed habit, hardness, good cleavage, and luster identify diaspore. It is occasionally confused with brucite, but brucite is much softer.

***Physical Properties***

hardness	$6\frac{1}{2}$ to 7
specific gravity	3.2 to 3.5
cleavage/fracture	one perfect (010), poor (210)/conchoidal
luster/transparency	pearly, vitreous/translucent
color	colorless, yellow, gray, white or green
streak	white-yellow

***Optical Properties***

Diaspore has high relief, is colorless or pale, displays parallel extinction, and shows up to third-order interference colors. It may be confused with gibbsite or sillimanite, but gibbsite has lower relief and inclined extinction, and sillimanite has lower relief and birefringence. Biaxial (+),  $\alpha = 1.68$  to 1.71,  $\beta = 1.71$  to 1.72,  $\gamma = 1.73$  to 1.75,  $\delta = 0.04$ ,  $2V = 85^\circ$ .

***Crystallography***

Orthorhombic,  $a = 4.42$ ,  $b = 9.40$ ,  $c = 2.84$ ,  $Z = 4$ ; space group  $P2_1/b2_1/n2_1/m$ ; point group  $2/m2/m2/m$ .

**Habit**

Platy, tabular, or acicular crystals are common. Massive forms or foliated aggregates are common.

**Structure and Composition**

Diaspore structure is the same as that of goethite, except that Al replaces two-thirds of the Fe (see **goethite**). It is generally close to end member composition. Minor Fe or Mn may replace Al.

**Occurrence and Associations**

Diaspore is found in emery deposits with corundum, magnetite, spinel, and chlorite; in bauxites with other aluminum oxides and hydroxides; and as a rare mineral in some pegmatites.

**Related Minerals**

Böhmite is a polymorph of diaspore. Diaspore is isostructural with goethite and close in composition to gibbsite,  $\text{Al}(\text{OH})_3$ . Bauxite is a mixture of gibbsite, böhmite, and diaspore.

## Romanechite (Psilomelane)

**Origin of Name**

From the original locality in Romaneche, France.

**Hand Specimen Identification**

Color, luster, and habit identify romanechite. It is sometimes confused with pyrolusite, but is harder. A brown-black streak separates it from limonite and other hydrous iron oxides.

**Physical Properties**

hardness	5 to 6
specific gravity	3.5 to 4.7
luster/transparency	submetallic, dull/opaque
color	black
streak	brown-black

**Crystallography**

Monoclinic,  $a = 9.56$ ,  $b = 2.88$ ,  $c = 13.85$ ,  $\beta = 90.5^\circ$ ,  $Z = 2$ ; space group  $A2/m$ ; point group  $2/m$ .

**Habit**

Reniform, botryoidal, or dendritic masses are typical. Distinct crystals are not known.

**Structure and Composition**

Structure is related to those of rutile and spinel.  $\text{Mn}(\text{O},\text{OH})_4$  octahedra form distorted chains; Ba and  $\text{H}_2\text{O}$  occupy holes between the chains. Many other elements, including As, V, W, Co, Cu, Ni, Mg, Ca, and alkalis may be present in small or trace amounts.

**Occurrence and Associations**

Romanechite is a rare secondary mineral associated with pyrolusite, manganite, calcite, and hematite.

**Related Minerals**

Related minerals include pyrolusite,  $\text{MnO}_2$ ; manganite,  $\text{MnO}(\text{OH})$ ; cryptomelane,  $\text{KMn}_8\text{O}_{16}$ ; hollandite,  $\text{BaMn}_8\text{O}_{16}$ ; and wad, a mixture of manganese oxides and hydroxides.

## VII. CARBONATES AND NITRATES

**Calcite Group**

calcite	$\text{CaCO}_3$
magnesite	$\text{MgCO}_3$
siderite	$\text{FeCO}_3$
rhodochrosite	$\text{MnCO}_3$
smithsonite	$\text{ZnCO}_3$

**Dolomite Group**

dolomite	$\text{CaMg}(\text{CO}_3)_2$
ankerite	$\text{CaFe}(\text{CO}_3)_2$
kutnahorite	$\text{CaMn}(\text{CO}_3)_2$

**Aragonite Group**

aragonite	$\text{CaCO}_3$
witherite	$\text{BaCO}_3$
strontianite	$\text{SrCO}_3$
cerussite	$\text{PbCO}_3$

**Other Carbonates**

malachite	$\text{Cu}_2\text{CO}_3(\text{OH})_2$
azurite	$\text{Cu}_3(\text{CO}_3)_2(\text{OH})_2$

**Nitrate Group**

nitratite	$\text{NaNO}_3$
niter (saltpeter)	$\text{KNO}_3$

Mineralogists divide carbonate minerals into three main groups based on atomic arrangement: the calcite group, dolomite group, and aragonite group. Several other species that have more complex structures and chemistries are classified separately. Calcite group minerals have hexagonal structures related to the structures of halite and galena: six Ca, Mg, Fe, Mn, or Zn surround anionic  $(\text{CO}_3)^{2-}$  groups and each metal atom is surrounded by six carbonate groups. Dolomite group minerals have structures similar to calcite's, but Ca and Mg, Fe, or Mn occupy alternate layers. Aragonite group minerals are orthorhombic. Solid solutions are common within a structural group, although some carbonates, such as aragonite, are almost always close to end member composition.

Due to very high solubility in water, nitrate minerals are rare. They have structures similar to carbonates, but contain monovalent rather than divalent cations because the  $\text{NO}_3^-$  anionic group is monovalent. Over half a dozen nitrates are known, but nitratite and niter are the only common ones in more than just a few localities.

**Calcite****CaCO<sub>3</sub>***Origin of Name*

From the Latin word *calx*, meaning “burnt lime.”

*Hand Specimen Identification*

Calcite is identified by its hardness, rhombohedral cleavage, and effervescence in cold dilute HCl. It may be confused with dolomite or aragonite. Plate 3.8 shows euhedral calcite crystals and Figure 30 shows “sandy” calcite.

*Physical Properties*

hardness	3
specific gravity	2.71
cleavage/fracture	perfect rhombohedral {101}/conchoidal
luster/transparency	vitreous/transparent to translucent
color	colorless to white; may also be tinted gray, red, blue, yellow, or green; brown to black when impure
streak	white

*Optical Properties*

Calcite is colorless in thin section and has extremely high birefringence, resulting in pale, washed out, or white interference colors. Polysynthetic twinning is nearly always visible. It shows variable relief upon stage rotation. Calcite may be confused with other hexagonal carbonates. Orthorhombic carbonates have parallel extinction and are biaxial. Uniaxial (−),  $\omega = 1.658$ ,  $\epsilon = 1.486$ ,  $\delta = 0.172$ . Plates 5.1 and 5.2 show calcite in thin section.

*Crystallography*

Hexagonal (rhombohedral),  $a = 4.99$ ,  $c = 17.04$ ,  $Z = 6$ ; space group  $R\bar{3}2/c$ ; point group  $\bar{3}2/m$ .



**FIGURE 30** Calcite crystals encrusted with sand. The field of view is about 20 cm across.

*Habit*

Calcite has many habits. The most common are hexagonal prisms with simple to complex terminations; scalenohedra, often with combinations of other forms; rhombohedra, either acute or flattened; and tabs with well-developed basal faces. Polysynthetic twinning is common but usually requires a microscope to detect. Calcite is also found as a massive rock-forming mineral, as nodules or crusts, in speleothems, and as fine to coarse granular aggregates.

*Structure and Composition*

In calcite, Ca<sup>2+</sup> ions alternate with (CO<sub>3</sub>)<sup>2-</sup> groups in a three-dimensional array. The structure is similar to that of cubic salts, such as halite or periclase, but is not cubic because the structure has been squashed along the equivalent of a main diagonal of the cube. The shortened direction is the c-axis in calcite; planar (CO<sub>3</sub>) groups are perpendicular to c, giving the structure a 3-fold axis of symmetry in that direction only. Mg, Fe, Mn, Zn, and a number of others may substitute for some of the Ca; except for Mn, most solid solutions are quite limited.

*Occurrence and Associations*

Calcite is a common and widespread mineral. It is an essential and major mineral in limestones and marbles, occurs in cave deposits, and occurs as a vein mineral with other carbonates, sulfides, barite, fluorite, and quartz. Calcite also occurs in some rare carbonate-rich igneous rocks and is a common cement in some sandstones. Calcite is common as a weathering product. Organic calcite is common in shells and skeletal material.

*Varieties*

*Iceland spar* refers to clear calcite, usually in rhombohedral cleavage fragments; *dogtooth spar* refers to crystals with steep scalenohedral forms; and *nail-head spar* refers to flat rhombs or stubby prismatic crystals.

*Related Minerals*

Calcite has two polymorphs, aragonite and vaterite. It is isostructural with magnesite, MgCO<sub>3</sub>; siderite, FeCO<sub>3</sub>; sphalerocobaltite, CoCO<sub>3</sub>; smithsonite, ZnCO<sub>3</sub>; nitratite, Na(NO<sub>3</sub>); dolomite, CaMg(CO<sub>3</sub>)<sub>2</sub>; and gaspeite, (Ni,Mg,Fe)(CO<sub>3</sub>). Calcite and rhodochrosite form extensive solid solutions at room temperature and a complete solid solution above about 550°C (1,020°F). Calcite forms limited solid solutions with ankerite, CaFe(CO<sub>3</sub>)<sub>2</sub>; dolomite, CaMg(CO<sub>3</sub>)<sub>2</sub>; and kutnohorite, CaMn(CO<sub>3</sub>)<sub>2</sub>, at all temperatures.

**Magnesite****MgCO<sub>3</sub>***Origin of Name*

The name refers to its composition.

*Hand Specimen Identification*

Massive forms may be chalky or porcelainlike. They are occasionally confused with chert but have inferior hardness. Coarse crystals of magnesite may be difficult to tell from other carbonates, but magnesite is denser than dolomite and does not react to cold HCl like calcite.

*Physical Properties*

hardness	$3\frac{1}{2}$ to 5
specific gravity	3.00
cleavage/fracture	perfect rhombohedral {101}/conchoidal
luster/transparency	porcelainous/transparent to translucent
color	white, gray, brown, or yellow
streak	white

*Optical Properties*

Magnesite is similar to calcite in thin section but has higher index of refraction (see **calcite**). Uniaxial (−),  $\omega = 1.700$ ,  $\epsilon = 1.509$ ,  $\delta = 0.191$ .

*Crystallography*

Hexagonal (rhombohedral),  $a = 4.59$ ,  $c = 14.87$ ,  $Z = 6$ ; space group  $R\bar{3}2/c$ ; point group  $\bar{3}2/m$ .

*Habit*

Crystals are rare; magnesite is usually massive, granular, fibrous, or earthy.

*Structure and Composition*

Magnesite is isostructural with calcite (see **calcite**). Large amounts of Fe commonly substitute for Mg. Mn, Ca, Ni, and Zn may also be present in small amounts.

*Occurrence and Associations*

Magnesite is most common in veins or masses as an alteration product of mafic minerals. It also occurs in some Mg-rich schists and as a primary mineral in some rare chemical sediments and is found as a replacement for calcite or dolomite in limestone.

*Varieties*

Breunnerite is a Fe-rich variety of magnesite; hoshite is an Ni-rich variety.

*Related Minerals*

Magnesite is isostructural with calcite and many other minerals (see **calcite**). It forms complete solid solutions with siderite,  $FeCO_3$ , and with gaspeite,  $(Ni,Mg,Fe)CO_3$ . Related minerals include hydromagnesite,  $Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$ .

**Siderite****FeCO<sub>3</sub>***Origin of Name*

From the Greek word *sideros*, meaning “iron.”

*Hand Specimen Identification*

Siderite is distinguished from other carbonates by its high specific gravity and brownish color. It effervesces in warm HCl. It may be confused with sphalerite.

*Physical Properties*

hardness	$3\frac{1}{2}$ to 4
specific gravity	3.96
cleavage/fracture	perfect rhombohedral {101}/subconchoidal
luster/transparency	vitreous/translucent
color	light to dark brown
streak	white

*Optical Properties*

Siderite is colorless to pale yellow-brown in thin section. It is similar to calcite and other carbonates, but they have lower index of refraction and lack color (see **calcite**). Uniaxial (−),  $\omega = 1.875$ ,  $\epsilon = 1.633$ ,  $\delta = 0.242$ .

Hexagonal (rhombohedral),  $a = 4.72$ ,  $c = 15.46$ ,  $Z = 6$ ; space group  $R\bar{3}2/c$ ; point group  $\bar{3}2/m$ .

*Habit*

Crystals are typically rhombohedra, often with curved faces. Fine- to coarse-grained aggregates and colloform, globular, botryoidal, fibrous, and earthy forms are common.

*Structure and Composition*

Siderite is isostructural with calcite (see **calcite**). Mn and Mg often substitute for Fe. Small amounts of Ca, Zn, and Co may be present.

*Occurrence and Associations*

Siderite is a relatively common mineral found in veins with galena, pyrite, chalcopyrite, and tetrahedrite; as a rock-forming mineral associated with limestone, clay, shale, coal or ironstone; as a replacement mineral in limestone; and less commonly in metamorphic rocks.

*Related Minerals*

Siderite is isostructural with calcite and a number of other minerals (see **calcite**). It forms complete solid solutions with rhodochrosite,  $MnCO_3$ , and magnesite,  $MgCO_3$ .

**Rhodochrosite****MnCO<sub>3</sub>***Origin of Name*

From the Greek words meaning “rose” and “color,” referring to its rose-pink color.

*Hand Specimen Identification*

Pink color and rhombohedral carbonate morphology identify rhodochrosite. It may be confused with

rhodonite, but rhodonite is harder and does not effervesce in HCl.

#### *Physical Properties*

hardness	3½ to 4
specific gravity	3.70
cleavage/fracture	perfect rhombohedral {101}/uneven
luster/transparency	vitreous, pearly/transparent to translucent
color	rose-red, light pink to dark brown
streak	white

#### *Optical Properties*

Rhodochrosite is colorless or pale pink in thin section, has extremely high birefringence, and three perfect cleavage directions. It may be confused with calcite and other carbonates (see **calcite**). Uniaxial (−),  $\omega = 1.816$ ,  $\epsilon = 1.597$ ,  $\delta = 0.219$ .

#### *Crystallography*

Hexagonal (rhombohedral),  $a = 4.74$ ,  $c = 15.51$ ,  $Z = 6$ ; space group  $R\bar{3}2/m$ ; point group  $\bar{3}2/m$ .

#### *Habit*

Rhodochrosite forms rare rhombohedral crystals. It is usually massive, sometimes granular, botryoidal, columnar, or crusty.

#### *Structure and Composition*

Rhodochrosite is isostructural with calcite (see **calcite**). Zn commonly replaces some Mn; Ca, Mg, Cd, and Co may be present in limited amounts.

#### *Occurrence and Associations*

Rhodochrosite is uncommon. It is found with other manganese minerals in Mn-rich metamorphic rocks, as a primary mineral in sulfide veins and some replacement bodies, and as a secondary mineral in residual deposits.

#### *Related Minerals*

Rhodochrosite has the same structure as calcite and number of other minerals (see **calcite**). It forms solid solutions with calcite,  $\text{CaCO}_3$ ; siderite,  $\text{FeCO}_3$ ; and kutnohorite,  $\text{CaMn}(\text{CO}_3)_2$ .

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## Smithsonite

## $\text{ZnCO}_3$

#### *Origin of Name*

Named after J. Smithson (1754–1829), founder of the Smithsonian Institute.

#### *Hand Specimen Identification*

Rhombohedral carbonate habit, color (if green or purplish), density, and association identify smithsonite. If not distinctly colored, it may be difficult to tell from other dense carbonates. It is occasionally confused

with hemimorphite. Plates 1.2 and 1.8 show color photos of smithsonite.

#### *Physical Properties*

hardness	4 to 4½
specific gravity	4.43
cleavage/fracture	perfect rhombohedral {101}/subconchoidal
luster/transparency	pearly, vitreous/transparent to translucent
color	typically green; also purple, lilac, pink, and other colors
streak	white

#### *Optical Properties*

Uniaxial (−),  $\omega = 1.850$ ,  $\epsilon = 1.625$ ,  $\delta = 0.225$ .

#### *Crystallography*

Hexagonal (rhombohedral),  $a = 4.61$ ,  $c = 14.88$ ,  $Z = 6$ ; space group  $R\bar{3}2/m$ ; point group  $\bar{3}2/m$ .

#### *Habit*

Crystals, when they are euhedral or subhedral, show rhombohedral form and cleavage. More typical smithsonite is massive, colloform, earthy, stalactitic, or forms crusts.

#### *Structure and Composition*

Smithsonite is isostructural with calcite (see **calcite**). It typically contains substantial amounts of Fe; smaller amounts of Ca, Co, Cu, Cd, Mg, or Mn; and traces of Ge or Pb.

#### *Occurrence and Associations*

Smithsonite is a secondary mineral found in zinc deposits. Associated minerals include sphalerite, hemimorphite, cerussite, malachite, azurite, and anglesite.

#### *Related Minerals*

Smithsonite is isostructural with many other minerals (see **calcite**). It forms limited solid solutions with most other carbonates, including otavite,  $\text{CdCO}_3$ .

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## Dolomite

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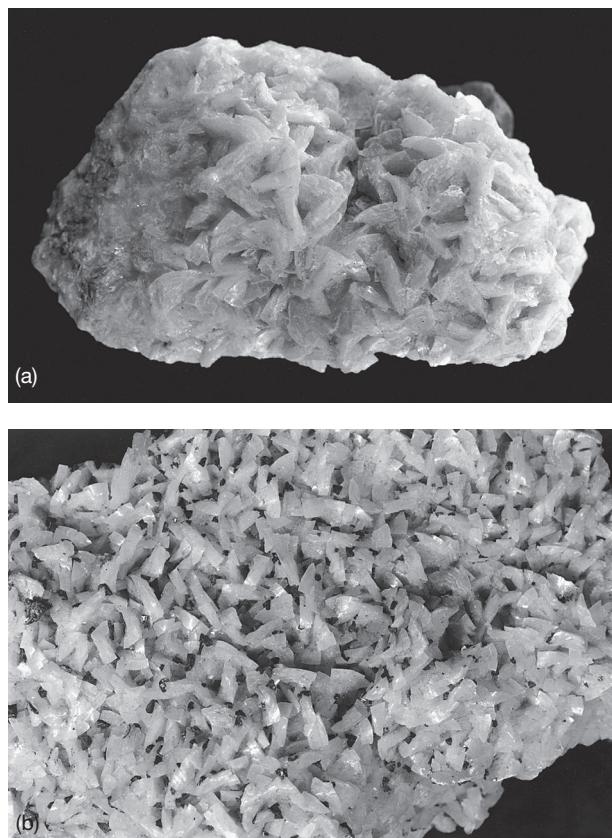
## $\text{CaMg}(\text{CO}_3)_2$

#### *Origin of Name*

Named after D. de Dolomieu (1750–1801), a French chemist and geologist.

#### *Hand Specimen Identification*

Dolomite is characterized by typical rhombohedral carbonate habit and cleavage and effervescence by cold dilute HCl only when powdered. It is sometimes confused with calcite or ankerite. Figure 31.



**FIGURE 31** (a) Dolomite crystals from West Virginia; (b) dolomite crystals dusted with drusy chalcopyrite from Joplin, Missouri.

#### Physical Properties

hardness	$3\frac{1}{2}$ to 4
specific gravity	2.85
cleavage/fracture	perfect rhombohedral $\{101\}$ /subconchoidal
luster/transparency	vitreous/transparent to translucent
color	usually a shade of pink, can be white, colorless, brown, black, green, or gray
streak	white

#### Optical Properties

Dolomite is similar to calcite in thin section, but has lower RI and two possible orientations of polysynthetic twins (see **calcite**). Uniaxial (-),  $\omega = 1.679$ ,  $\epsilon = 1.500$ ,  $\delta = 0.179$ .

#### Crystallography

Hexagonal (rhombohedral),  $a = 4.84$ ,  $c = 15.96$ ,  $Z = 3$ ; space group  $R\bar{3}$ ; point group  $\bar{3}$ .

#### Habit

Crystals are typically rhombohedral, having the shape of cleavage fragments, often with curved faces (Figure 31). Less commonly they are prismatic or steep

rhombohedra. Lamellar twinning is nearly always present but may be hard to see. Massive dolomite, showing rhombohedral cleavage, is common.

#### Structure and Composition

Dolomite is isostructural with calcite (see **calcite**). Fe and Mn may substitute for Mg in substantial amounts. Co, Pb, Zn, Ce, or excess Ca may also be present.

#### Occurrence and Associations

Dolomite is a common mineral, found in massive carbonate sediments and in marbles, often with calcite. It also occurs in hydrothermal veins with fluorite, barite, other carbonates, and quartz, and as a secondary mineral or alteration product in limestone.

#### Related Minerals

Dolomite is isostructural with calcite,  $\text{CaCO}_3$ , norden-skiöldine,  $\text{CaSnB}_2\text{O}_6$ ; and a number of other minerals (see **calcite**). Huntite,  $\text{CaMg}_3(\text{CO}_3)_4$ , is quite similar. Dolomite forms solid solutions with ankerite,  $\text{CaFe}(\text{CO}_3)_2$ ; kutnohorite,  $\text{CaMn}(\text{CO}_3)_2$ ; minrecordite,  $\text{CaZn}(\text{CO}_3)_2$ ; and norsethite,  $\text{BaMg}(\text{CO}_3)_2$ .

## Ankerite



#### Origin of Name

Named after M. J. Anker (1772–1843), an Austrian mineralogist.

#### Hand Specimen Identification

Typical rhombohedral carbonate habit and cleavage, effervescence by cold dilute HCl when powdered, and yellow-brown to brown color usually identify ankerite. It is sometimes confused with calcite or dolomite.

#### Physical Properties

hardness	$3\frac{1}{2}$
specific gravity	3.10
cleavage/fracture	perfect rhombohedral $\{101\}$ /subconchoidal
luster/transparency	vitreous/transparent to translucent
color	white, yellow-brown
streak	white

#### Optical Properties

Ankerite is similar to dolomite in thin section (see **dolomite**), but tends to be stained red or brown by iron oxidation. Uniaxial (-),  $\omega = 1.750$ ,  $\epsilon = 1.548$ ,  $\delta = 0.202$ .

#### Crystallography

Hexagonal (rhombohedral),  $a = 4.82$ ,  $c = 16.14$ ,  $Z = 3$ ; space group  $R\bar{3}$ ; point group  $\bar{3}$ .

**Habit**

Rare crystals are usually rhombohedral, often with curved faces, or prisms. Lamellar twinning is nearly always present but may be hard to see. Granular ankerite is sometimes found. Massive ankerite showing rhombohedral cleavage is most typical.

**Structure and Composition**

Ankerite is isostructural with calcite, dolomite, and many other minerals (see **calcite**). It may contain substantial Mg replacing Fe. Minor amounts of Mn, Co, Pb, Zn, Ce, or excess Ca may also be present.

**Occurrence and Associations**

Ankerite is most common in Precambrian iron formations. It is also found in veins and as replacements in limestones.

**Related Minerals**

Ankerite is isostructural with calcite,  $\text{CaCO}_3$ , dolomite,  $\text{CaMg}(\text{CO}_3)_2$ , and a number of other minerals (see **calcite** and **dolomite**).

**Aragonite** **$\text{CaCO}_3$** **Origin of Name**

Named after the original locality in Aragon, Spain.

**Hand Specimen Identification**

Aragonite's softness, color, and association help identify it. Like calcite, it effervesces in cold dilute HCl. However, it does not have rhombohedral cleavage. If not well crystallized or showing cleavage, it may be difficult to distinguish from calcite. Aragonite is also sometimes confused with strontianite.

**Physical Properties**

hardness	$3\frac{1}{2}$ to 4
specific gravity	2.94
cleavage/fracture	good {010}, poor {110}/subconchoidal
luster/transparency	vitreous/transparent to translucent
color	colorless to white, and pale yellow
streak	white

**Optical Properties**

Aragonite is similar to calcite (see **calcite**) in thin section but displays parallel extinction and is biaxial (−) with a small  $2V$ . Biaxial (−),  $\alpha = 1.530$ ,  $\beta = 1.681$ ,  $\gamma = 1.685$ ,  $\delta = 0.155$ ,  $2V = 18^\circ$ .

**Crystallography**

Orthorhombic,  $a = 4.95$ ,  $b = 7.96$ ,  $c = 5.73$ ,  $Z = 4$ ; space group  $P2_1/m2_1/c2_1/n$ ; point group  $2/m2/m2/m$ .

**Habit**

Aragonite crystals are acicular, tabular, prismatic, or fibrous. Crystals may form radiating splays, crusts, or masses of many different morphologies. Contact and cyclic twins are common, sometimes giving it a pseudohexagonal appearance.

**Structure and Composition**

In aragonite, triangular  $(\text{CO}_3)^{2-}$  groups are in layers perpendicular to the c-axis, as in calcite. Alternate layers, however, have their  $(\text{CO}_3)^{2-}$  groups pointing in opposite directions. Ca is coordinated to nine oxygens in six surrounding  $(\text{CO}_3)^{2-}$  groups, giving orthorhombic (pseudohexagonal) symmetry. Solid solutions are much more restricted than for calcite. Aragonite is usually near end member composition, with only minor amounts of Sr, Pb, or Zn substituting for Ca.

**Occurrence and Associations**

Aragonite is found as disseminated carbonate in gypsum beds, as hot spring deposits, as precipitates from Ca-oversaturated waters, associated with sedimentary iron ores, in oxidized zones of ore deposits, in some cave formations, and in blueschist facies metamorphic rocks. It also occurs in shells and other organic carbonate material. Associated minerals typically include gypsum, siderite, celestite, sulphur, limonite, calcite, malachite, azurite, smithsonite, and cerussite.

**Varieties**

Flos ferri is a corallike form of aragonite associated with iron deposits.

**Related Minerals**

Aragonite has two significant polymorphs, calcite and vaterite. Strontianite,  $\text{SrCO}_3$ ; witherite,  $\text{BaCO}_3$ ; cerussite,  $\text{PbCO}_3$ ; and niter,  $\text{KNO}_3$ , are all isostructural with aragonite.

**Witherite** **$\text{BaCO}_3$** **Origin of Name**

Named after D. W. Withering (1741–1799), who first demonstrated that witherite was different from barite.

**Hand Specimen Identification**

Density, effervescence with dilute HCl, and hardness identify witherite. It is occasionally confused with barite, but barite does not react with HCl.

**Physical Properties**

hardness	$3\frac{1}{2}$
specific gravity	4.29
cleavage/fracture	good basal {010}, poor {110} and {012}/uneven

luster/transparency	resinous/transparent to translucent
color streak	gray, white, or colorless white

*Optical Properties*

Witherite is similar to aragonite and other orthorhombic carbonates (see **aragonite**) in thin section. It may be confused with strontianite, but the latter has lower RI and two good cleavages. Biaxial (-),  $\alpha = 1.529$ ,  $\beta = 1.676$ ,  $\gamma = 1.677$ ,  $\delta = 0.148$ ,  $2V = 16^\circ$ .

*Crystallography*

Orthorhombic,  $a = 5.26$ ,  $b = 8.85$ ,  $c = 6.55$ ,  $Z = 4$ ; space group  $P2_1/m2_1/c2_1/n$ ; point group  $2/m2/m2/m$ .

*Habit*

Crystals are orthorhombic, but multiple twinning yields pseudohexagonal pyramids. Columnar, globular, and botryoidal aggregates are common.

*Structure and Composition*

The structure of witherite is the same as that of aragonite. Minor Sr, Mg, and Ca may substitute for Ba.

*Occurrence and Associations*

Witherite is a rare low-temperature vein mineral, usually associated with galena and barite.

*Related Minerals*

Witherite has two high-temperature polymorphs. Strontianite,  $\text{SrCO}_3$ ; aragonite,  $\text{CaCO}_3$ ; cerussite,  $\text{PbCO}_3$ ; and niter,  $\text{KNO}_3$ , are all isostructural with witherite.

**Strontianite** **$\text{SrCO}_3$** *Origin of Name*

Named after the first known locality at Strontian, Scotland.

*Hand Specimen Identification*

Form, hardness, color, density, and reaction to cold dilute HCl help identify strontianite. It may be confused with aragonite but has different cleavage.

*Physical Properties*

hardness	$3\frac{1}{2}$ to 4
specific gravity	3.72
cleavage/fracture	good prismatic {110}, poor {010}/uneven
luster/transparency	vitreous/transparent to translucent
color	white, pale green, yellow, gray
streak	white

*Optical Properties*

Strontianite is similar to aragonite and other orthorhombic carbonates in thin section. Aragonite and witherite both have higher indices of refraction, aragonite has only one well-developed cleavage, and witherite has a larger  $2V$ . Biaxial (-),  $\alpha = 1.520$ ,  $\beta = 1.667$ ,  $\gamma = 1.668$ ,  $\delta = 0.148$ ,  $2V = 7^\circ$ .

*Crystallography*

Orthorhombic,  $a = 5.13$ ,  $b = 8.42$ ,  $c = 6.09$ ,  $Z = 4$ ; space group  $P2_1/m2_1/c2_1/n$ ; point group  $2/m2/m2/m$ .

*Habit*

Strontianite is typically acicular but may be prismatic, fibrous, granular, or massive. Twins, creating pseudo-hexagonal or lamellar habits, are common.

*Structure and Composition*

Strontianite has the same structure as aragonite and a number of other minerals (see **aragonite**). Substantial replacement of Sr by Ca or Ba is common; Pb may also be present.

*Occurrence and Associations*

Strontianite is an uncommon mineral. It occurs in hydrothermal veins with barite, celestite, and calcite. Hosts include limestones, sulfide veins, vugs, and concretions.

*Related Minerals*

Strontianite has one high-temperature polymorph. Aragonite,  $\text{CaCO}_3$ ; witherite,  $\text{BaCO}_3$ ; cerussite,  $\text{PbCO}_3$ ; and niter,  $\text{KNO}_3$ , are all isostructural with strontianite.

**Cerussite** **$\text{PbCO}_3$** *Origin of Name*

From the Latin word *cerussa*, meaning “white lead.”

*Hand Specimen Identification*

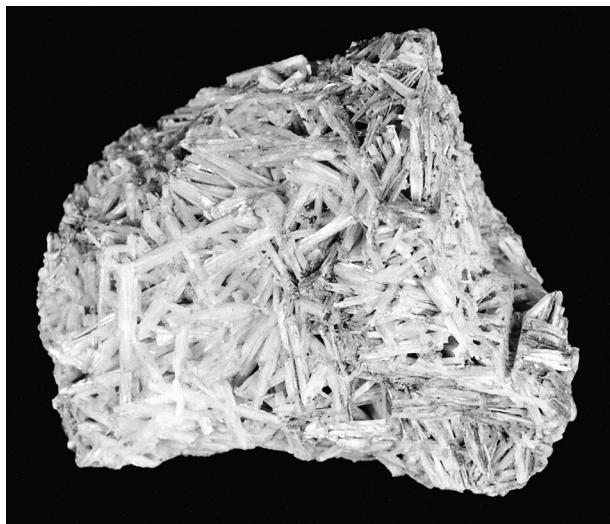
High density, color, and luster identify cerussite. It may be confused with anglesite, but it has a different habit and effervesces in cold dilute HCl, while anglesite does not.

*Physical Properties*

hardness	3 to $3\frac{1}{2}$
specific gravity	6.55
cleavage/fracture	good prismatic {110}, poor {021}/conchoidal
luster/transparency	adamantine/transparent to translucent
color	colorless, gray, or white
streak	white

*Optical Properties*

Biaxial (-),  $\alpha = 1.804$ ,  $\beta = 2.076$ ,  $\gamma = 2.078$ ,  $\delta = 0.274$ ,  $2V = 9^\circ$ .



**FIGURE 32** Cerussite,  $\text{PbCO}_3$ , is a rare carbonate mineral. This sample is from Whim Creek, Australia.

#### Crystallography

Orthorhombic,  $a = 5.15$ ,  $b = 8.47$ ,  $c = 6.11$ ,  $Z = 4$ ; space group  $P2_1/m2_1/c2_1/n$ ; point group  $2/m2/m2/m$ .

#### Habit

Crystals are variable but most commonly tabular, with twinning giving a pseudohexagonal appearance. Cerussite may also appear prismatic, acicular, granular, and massive. Coarse intergrowths with platy fabric are typical (Figure 32).

#### Structure and Composition

Cerussite has the same structure as aragonite and a number of other minerals (see **aragonite**). It is generally quite close to end member composition, although minor amounts of Ba, Sr, Ag, or Zn are sometimes present.

#### Occurrence and Associations

Cerussite is a common secondary lead mineral found in altered ore deposits. Typical associated minerals include galena, anglesite, limonite, and pyromorphite. It occurs in both veins and bedded deposits.

#### Related Minerals

Strontianite,  $\text{SrCO}_3$ ; aragonite,  $\text{CaCO}_3$ ; witherite,  $\text{BaCO}_3$ ; and niter,  $\text{KNO}_3$ , are all isostructural with cerussite. Hydrocerussite,  $\text{Pb}_3(\text{CO}_3)_2(\text{OH})_2$ , is a closely related mineral.

## Malachite

## $\text{Cu}_2\text{CO}_3(\text{OH})_2$

#### Origin of Name

From the Greek word *moloche*, meaning “mallows,” referring to the green color of mallow leaves.

#### Hand Specimen Identification

Distinctive green color, habit, and association help identify malachite. It may be confused with other secondary copper minerals but effervesces in cold dilute HCl.

#### Physical Properties

hardness	$3\frac{1}{2}$ to 4
specific gravity	3.7 to 4.0
cleavage/fracture	perfect (201)/subconchoidal
luster/transparency	adamantine/transparent to translucent
color	bright green
streak	pale green

#### Optical Properties

Biaxial  $(-)$ ,  $\alpha = 1.655$ ,  $\beta = 1.875$ ,  $\gamma = 1.909$ ,  $\delta = 0.254$ ,  $2V = 43^\circ$ .

#### Crystallography

Monoclinic,  $a = 9.48$ ,  $b = 12.03$ ,  $c = 3.21$ ,  $\beta = 98.0^\circ$ ,  $Z = 4$ ; space group  $P2_1/a$ ; point group  $2/m$ .

#### Habit

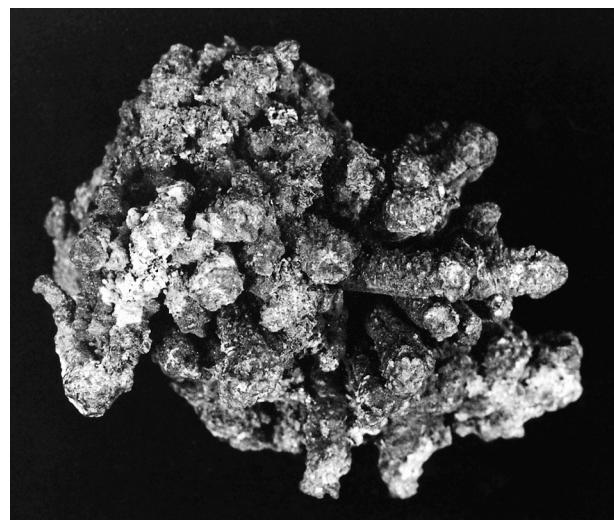
Crystals are rare. Malachite is usually massive; frequently colloform or banded, and often intergrown with other secondary copper minerals.

#### Structure and Composition

The structure resembles those of other carbonates. Triangular  $(\text{CO}_3)^{2-}$  groups are surrounded by three  $\text{Cu}(\text{O},\text{OH})_6$  octahedra. The octahedra share edges to form chains. Zn and Co are commonly present in small amounts.

#### Occurrence and Associations

Malachite is a secondary copper mineral typically found in carbonate rocks with azurite, cuprite, native copper, limonite, and chrysocolla (Figure 33).



**FIGURE 33** Malachite,  $\text{Cu}_2\text{CO}_3(\text{OH})_2$ , and limonite (Fe-hydroxide) are often found together. This sample is from Tooele County, Utah.

**Related Minerals**

Similar minerals include azurite,  $\text{Cu}_3(\text{CO}_3)_2(\text{OH})_2$ ; hydrozincite,  $\text{Zn}_5(\text{CO}_3)_2(\text{OH})_6$ ; aurichalcite,  $(\text{Zn}, \text{Cu})_5(\text{CO}_3)_2(\text{OH})_6$ ; and a number of other rare hydrated Cu and Zn carbonates.

**Azurite** **$\text{Cu}_3(\text{CO}_3)_2(\text{OH})_2$** *Origin of Name*

From the French word *azur*, meaning “sky-blue color.”

*Hand Specimen Identification*

Azurite’s softness, characteristic blue color, association with malachite, effervescence in cold HCl, and habit are distinctive.

*Physical Properties*

hardness	$3\frac{1}{2}$ to 4
specific gravity	3.77
cleavage/fracture	brittle, perfect {011}, good {100}/conchoidal
luster/transparency	normally dull and earthy/transparent to translucent
color	blue
streak	blue

*Optical Properties*

Biaxial (+),  $\alpha = 1.730$ ,  $\beta = 1.756$ ,  $\gamma = 1.836$ ,  $\delta = 0.106$ ,  $2V = 68^\circ$ .

*Crystallography*

Monoclinic,  $a = 4.97$ ,  $b = 5.84$ ,  $c = 10.29$ ,  $\beta = 92.4^\circ$ ,  $Z = 2$ ; space group  $P2_1/c$ ; point group  $2/m$ .

*Habit*

Azurite is typically massive and earthy. It may form as a crust on other copper minerals. Rarer individual crystals are tabular or prismatic.

*Structure and Composition*

Usually nearly pure copper carbonate, azurite has a complex structure consisting of  $\text{Cu}^{2+}$  ions coordinated to two oxygens of adjacent  $\text{CO}_3$  groups and to two OH radicals, making a square planar group. The square groups are linked to form chains.

*Occurrence and Associations*

Azurite, like malachite, is a secondary copper mineral formed by alteration of copper oxides and sulfides. It is less common than malachite.

**Related Minerals**

Chemically similar minerals include malachite,  $\text{Cu}_2\text{CO}_3(\text{OH})_2$ ; hydrocerussite,  $\text{Pb}_3(\text{CO}_3)_2(\text{OH})_2$ ; hydromagnesite,  $\text{Mg}_5(\text{CO}_3)_4(\text{OH})_2$ ; and aurichalcite,  $(\text{Zn}, \text{Cu})_5(\text{CO}_3)_2(\text{OH})_3$ .

**Nitratite (Soda Niter)** **$\text{NaNO}_3$** *Origin of Name*

Nitratite is one of the two more common nitrate minerals.

*Hand Specimen Identification*

Softness, distinctive “cooling” taste, habit, and solubility help identify nitratite.

*Physical Properties*

hardness	1 to 2
specific gravity	2.29
cleavage/fracture	perfect but rarely seen rhombohedral {104}/conchoidal
luster/transparency	vitreous/transparent to translucent
color	colorless
streak	white

*Optical Properties*

Uniaxial (-),  $\omega = 1.587$ ,  $\epsilon = 1.336$ ,  $\delta = 0.251$ .

*Crystallography*

Hexagonal (rhombohedral),  $a = 5.07$ ,  $c = 16.82$ ,  $Z = 6$ ; space group  $R\bar{3}2/c$ ; point group  $\bar{3}2/m$ .

*Habit*

Individual crystals have a rhombohedral habit, but nitratite is often too fine grained or too massive for crystals to be easily seen. It sometimes forms as a crust.

*Structure and Composition*

Nitratite is isostructural with calcite;  $\text{Na}^+$  and  $\text{NO}_3^-$  take the place of  $\text{Ca}^{2+}$  and  $\text{CO}_3^{2-}$ , respectively. It is always nearly pure, forming very limited solid solution with niter (saltpeter).

*Occurrence and Associations*

Because nitratite is highly soluble in water, it is only found in arid regions where it may be associated with other evaporite minerals.

**Related Minerals**

The only other common nitrate is niter (saltpeter).

**Niter (Saltpeter)** **$\text{KNO}_3$** *Origin of Name*

Niter is the second most common nitrate mineral.

*Hand Specimen Identification*

Softness, salty taste, habit, and high solubility in water help identify this mineral.

*Physical Properties*

hardness	2
specific gravity	2.10

cleavage/fracture	perfect but rarely seen
luster/transparency	rhombohedral {011}/uneven
color	vitreous/translucent
streak	white

*Optical Properties*

Biaxial (-),  $\alpha = 1.333$ ,  $\beta = 1.505$ ,  $\gamma = 1.505$ ,  $\delta = 0.172$ ,  $2V = 7^\circ$ .

*Crystallography*

Orthorhombic,  $a = 5.43$ ,  $b = 9.19$ ,  $c = 6.46$ ,  $Z = 4$ ; space group  $P2_1/c2_1/m2_1/n$ ; point group  $2/m2/m2/m$ .

*Habit*

When visible, crystals are typically acicular. Niter is common as crusts and coatings or fine dusty aggregates.

*Structure and Composition*

Niter is isostructural with aragonite. It forms minor solid solutions with nitratite.

*Occurrence and Associations*

Niter is found in arid-region soils and unconsolidated sediments in caves.

*Related Minerals*

Eight or nine nitrate minerals are known, but all except niter and nitratite are extremely rare.

Borax can be confused with other borates, especially kernite,  $\text{Na}_2\text{B}_4\text{O}_6(\text{OH})_2 \cdot 3\text{H}_2\text{O}$ .

*Physical Properties*

hardness	2 to $2\frac{1}{2}$
specific gravity	1.7 to 1.9
cleavage/fracture	perfect {100}, good {110}/conchoidal
luster/transparency	vitreous, resinous/translucent
color	white, gray, rarely light blue or green
streak	white

*Optical Properties*

Borax is colorless in thin section, has three distinct cleavages, displays second-order interference colors, and shows anomalous interference colors in some orientations. Biaxial (-),  $\alpha = 1.447$ ,  $\beta = 1.469$ ,  $\gamma = 1.472$ ,  $\delta = 0.025$ ,  $2V = 40^\circ$ .

*Crystallography*

Monoclinic,  $a = 11.84$ ,  $b = 10.63$ ,  $c = 12.32$ ,  $\beta = 106.58^\circ$ ,  $Z = 4$ ; space group  $C2/c$ ; point group  $2/m$ .

*Habit*

Euhedral crystals are stubby prisms with complex combinations of terminating faces. Borax is common in massive or granular aggregates.

*Structure and Composition*

Although the Na:B ratio is fixed, the amounts of  $(\text{OH})^-$  and  $\text{H}_2\text{O}$  in borax are variable. The structure consists of chains of  $\text{Na}(\text{H}_2\text{O})_6$  octahedra connected to isolated groups of boron tetrahedra and double boron triangles. Weak van der Waals and hydrogen bonds link the octahedral chains to the boron groups, resulting in perfect prismatic cleavage.

*Occurrence and Associations*

Borax, associated with evaporite deposits in volcanic terranes, is the most common of the hydrous borate minerals. It is found in thick beds, similar to other salts, and as crusts and surface coatings. Common associated minerals are halite,  $\text{NaCl}$ ; colemanite,  $\text{CaB}_3\text{O}_4(\text{OH})_3 \cdot \text{H}_2\text{O}$ ; ulexite,  $\text{NaCaB}_5\text{O}_6(\text{OH})_6 \cdot 5\text{H}_2\text{O}$ ; and gypsum,  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ .

*Related Minerals*

Borax dehydrates easily to tincalconite,  $\text{Na}_2\text{B}_4\text{O}_5(\text{OH})_4 \cdot 3\text{H}_2\text{O}$ .

**VIII. BORATES****Anhydrous Borate Group**

boracite	$\text{Mg}_3\text{ClB}_7\text{O}_{13}$
sinhalite	$\text{MgAlBO}_4$

**Hydrous Borate Group**

borax	$\text{Na}_2\text{B}_4\text{O}_5(\text{OH})_4 \cdot 8\text{H}_2\text{O}$
kernite	$\text{Na}_2\text{B}_4\text{O}_6(\text{OH})_2 \cdot 3\text{H}_2\text{O}$
ulexite	$\text{NaCaB}_5\text{O}_6(\text{OH})_6 \cdot 5\text{H}_2\text{O}$
colemanite	$\text{CaB}_3\text{O}_4(\text{OH})_3 \cdot \text{H}_2\text{O}$
dumortierite	$\text{Al}_{6\frac{1}{2}-7}\text{BSi}_3\text{O}_{15}(\text{O},\text{OH})_3$

Mineralogists have identified many borate minerals. Most, especially the anhydrous borates, are very rare. Borate minerals have complex structures and chemistries, due in large part to the small size and trivalent nature of ionic boron. They have structural similarity to carbonates and nitrates because boron combines with oxygen to form anionic groups:  $(\text{BO}_3)^{3-}$  or  $(\text{BO}_4)^{5-}$ .

**Borax***Origin of Name*

From the Persian word *burah*, meaning "white."

*Hand Specimen Identification*

Low specific gravity, softness, prismatic habit, solubility in water, and association help identify borax.

**Kernite***Origin of Name*

Named after its only major occurrence, in Kern County, California.

## Descriptions of Mineral

### *Hand Specimen Identification*

Kernite resembles borax but is characterized by long, splintery cleavage fragments.

### *Physical Properties*

hardness	3
specific gravity	1.90
cleavage/fracture	prismatic, perfect (100) and (001), poor (010)/uneven
luster/transparency	vitreous, pearly/transparent
color	colorless, white
streak	white

### *Optical Properties*

Kernite is colorless in thin section and has negative relief and two perfect cleavages. Interference colors range up to second-order red or orange. Borax has a moderate  $2V$  and lower birefringence; ulexite and colemanite have only one cleavage and are biaxial (+). Biaxial (-),  $\alpha = 1.454$ ,  $\beta = 1.472$ ,  $\gamma = 1.488$ ,  $\delta = 0.034$ ,  $2V = 80^\circ$ .

### *Crystallography*

Monoclinic,  $a = 15.68$ ,  $b = 9.09$ ,  $c = 7.02$ ,  $\beta = 108.87^\circ$ ,  $Z = 4$ ; space group  $P2/a$ ; point group  $2/m$ .

### *Habit*

Kernite typically is in massive or coarse aggregates that cleave into long splintery fragments.

### *Structure and Composition*

The structure is complex, consisting of mixed chains of  $(BO_4)^{5-}$  tetrahedra and  $(BO_3)^{3-}$  triangles. The chains are linked by bonds to  $Na^+$  ions.

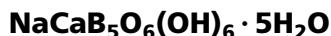
### *Occurrence and Associations*

The only major deposit known is in Kern County, California, where it occurs with borax and ulexite.

### *Related Minerals*

Kernite is similar to other borates in composition but, being identified by its distinctive cleavage, is rarely misidentified.

## **Ulexite**



### *Origin of Name*

Named for German chemist G. L. Ulex (1811–1883), who discovered it.

### *Hand Specimen Identification*

Soft, rounded masses with a loose, “cottonball” appearance are common. Ulexite is similar to, and may be confused with, other borates.

### *Physical Properties*

hardness	1 to $2\frac{1}{2}$
specific gravity	1.96

cleavage/fracture

luster/transparency

color

streak

perfect but rarely seen

{010}/uneven

silky/transparent to  
translucent

white

white

### *Optical Properties*

Biaxial (+),  $\alpha = 1.491$ ,  $\beta = 1.505$ ,  $\gamma = 1.520$ ,  $\delta = 0.029$ ,  $2V = 73^\circ$ .

### *Crystallography*

Triclinic,  $a = 8.73$ ,  $b = 12.75$ ,  $c = 6.70$ ,  $\alpha = 90.27^\circ$ ,  $\beta = 109.13^\circ$ ,  $\gamma = 105.12^\circ$ ,  $Z = 2$ ; space group  $P\bar{1}$ ; point group  $\bar{1}$ .

### *Habit*

Acicular and fibrous crystals are typical; crystal aggregates may form rounded masses with a “cottonball” appearance. A variety called *television rock* has massive, closely packed fibers, resulting in fiberopticlike properties (Figure 34).

### *Structure and Composition*

The structure is complex, consisting of large  $B(O,OH)_3$  and  $B(O,OH)_4$  anionic groups,  $Ca^{2+}$  in 8- to 10-fold coordination, and  $Na^+$  in 6-fold coordination.

### *Occurrence and Associations*

Similar to other borate minerals, ulexite forms in arid regions from evaporating water. It is commonly associated with borax, kernite, and colemanite.



**FIGURE 34** Ulexite, a fibrous borate mineral, from Boron, California. Some varieties of ulexite are called *television rock* because of their fiberopticlike properties.

**Colemanite***Origin of Name*

Named after W. T. Coleman (1824–1893), the Californian who founded the California borax industry.

*Hand Specimen Identification*

Colemanite is similar in chemistry and properties to other borates. Excellent cleavage in one direction, color, transparency, and association help identify it.

*Physical Properties*

hardness	4 to $4\frac{1}{2}$
specific gravity	2.42
cleavage/fracture	one perfect (010)/subconchoidal
luster/transparency	vitreous/transparent to translucent
color	colorless, white, gray
streak	white

*Optical Properties*

Colemanite is colorless in thin section, appearing similar to other borates (see **borax**) but having a higher index of refraction. Biaxial (+),  $\alpha = 1.586$ ,  $\beta = 1.592$ ,  $\gamma = 1.614$ ,  $\delta = 0.028$ ,  $2V = 56^\circ$ .

*Crystallography*

Monoclinic,  $a = 8.74$ ,  $b = 11.26$ ,  $c = 6.10$ ,  $\beta = 110.12^\circ$ ,  $Z = 4$ ; space group  $P2_1/a$ ; point group  $2/m$ .

*Habit*

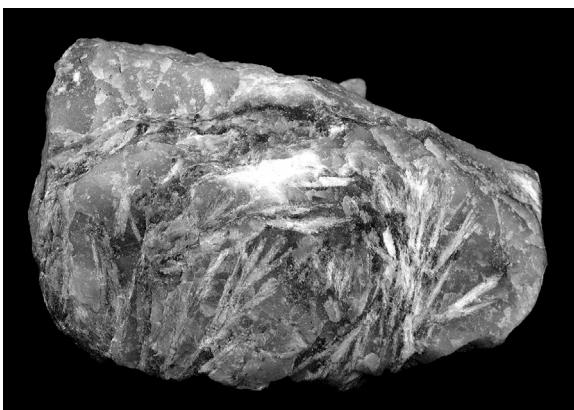
Crystals vary, usually being short and prismatic but sometimes massive or granular.

*Structure and Composition*

The structure consists of uneven sheets containing rings of  $(\text{BO}_4)^{5-}$  tetrahedra and  $(\text{BO}_3)^{3-}$  triangles.

*Occurrence and Associations*

Usually associated with ulexite, kernite, and borax, colemanite deposits form thick layers in ancient lake beds.



**FIGURE 35** Massive anhydrite with thin sheaves of gypsum (from Wyoming).

**IX. SULFATES****Anhydrous Sulfate Group**

anhydrite	$\text{CaSO}_4$
barite	$\text{BaSO}_4$
celestite	$\text{SrSO}_4$
anglesite	$\text{PbSO}_4$

**Hydrous Sulfate Group**

gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$
chalcanthite	$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$
epsomite	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$
antlerite	$\text{Cu}_3\text{SO}_4(\text{OH})_4$
alunite	$\text{KAl}_3(\text{SO}_4)_2(\text{OH})_6$

Mineralogists divide sulfate minerals into two groups: the anhydrous sulfates and the hydrous sulfates. Chemistries and structures of the anhydrous sulfates are related to the carbonates, with  $\text{SO}_4$  replacing  $\text{CO}_3$ . More than 100 sulfate minerals are known, and most are rare. Gypsum and anhydrite are the only rock-forming sulfates.

**Anhydrite***Origin of Name*

From the Greek word *anhydros*, because it lacks water (compared to gypsum).

*Hand Specimen Identification*

Anhydrite has three cleavages at  $90^\circ$  to each other. It is distinguished from calcite by its higher specific gravity and from gypsum by its hardness.

*Physical Properties*

hardness	3 to $3\frac{1}{2}$
specific gravity	2.98
cleavage/fracture	perfect cubic (010), good (100) and (001)/uneven, splintery
luster/transparency	vitreous, pearly/transparent
color	colorless
streak	white

*Optical Properties*

Anhydrite is colorless in thin section, displays up to third-order green interference colors, has pseudocubic cleavage, and displays parallel extinction. Gypsum has lower relief and birefringence; barite and celestite have higher indices of refraction and low birefringence. Biaxial (+),  $\alpha = 1.570$ ,  $\beta = 1.575$ ,  $\gamma = 1.614$ ,  $\delta = 0.044$ ,  $2V = 44^\circ$ .

*Crystallography*

Orthorhombic,  $a = 6.22$ ,  $b = 6.97$ ,  $c = 6.96$ ,  $Z = 4$ ; space group  $C2/c2/m2_1/m$ ; point group  $2/m2/m2/m$ .

*Habit*

Anhydrite is usually massive, granular, or fibrous; individual crystals, typically tabular or prismatic, are rare (Figure 35).

*Structure and Composition*

The structure is similar to zircon's;  $(SO_4)^{2-}$  tetrahedra share edges and are linked by  $(CaO_8)$  polyhedra. Anhydrite is generally close to  $CaSO_4$  in composition but may be partially hydrated (tending toward gypsum).

*Occurrence and Associations*

Anhydrite is typically an evaporite mineral associated with gypsum, sulfur, halite, calcite, or dolomite. Thick anhydrite beds are well known. It is also found in amygdules or cracks in basalt, as a gangue mineral in hydrothermal ore deposits, as a component of soils, or as a hot spring deposit.

*Related Minerals*

Anhydrite is chemically related to other anhydrous sulfates, including barite ( $BaSO_4$ ); celestite ( $SrSO_4$ ); and anglesite ( $PbSO_4$ ), but has a different structure. A polymorph of anhydrite,  $\gamma$ - $CaSO_4$ , forms when gypsum ( $CaSO_4 \cdot 2H_2O$ ) is dehydrated.

**Barite** **$BaSO_4$** *Origin of Name*

From the Greek word *barys*, meaning "heavy."

*Hand Specimen Identification*

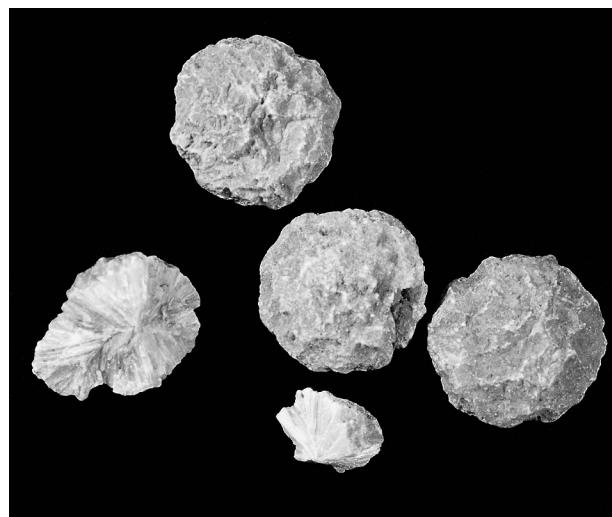
High specific gravity, white or light color, distinctive crystal habit, and two principle cleavages at  $90^\circ$  all help identify barite (Figure 36).

*Physical Properties*

hardness	3 to $3\frac{1}{2}$
specific gravity	4.5
cleavage/fracture	perfect (001), good (010) and {210}/uneven
luster/transparency	vitreous, pearly/transparent to translucent
color	white, gray, or colorless
streak	white

*Optical Properties*

Barite is colorless in thin section and displays up to second-order yellow interference colors. Biaxial (+),  $\alpha = 1.636$ ,  $\beta = 1.637$ ,  $\gamma = 1.648$ ,  $\delta = 0.012$ ,  $2V = 37^\circ$ .



**FIGURE 36** Typical rosettes of barite, about 3 cm across.

*Crystallography*

Orthorhombic,  $a = 8.87$ ,  $b = 5.45$ ,  $c = 7.14$ ,  $Z = 4$ ; space group  $P2_1/n2_1/m2_1/a$ ; point group  $2/m2/m2/m$ .

*Habit*

Barite's crystal habit is complex and variable. Tabular crystals may combine to form cockscomb aggregates called "barite roses" or "crested barite." Individual rosettes are common (Figure 36). Barite is also common as massive concretions, veins, or beds.

*Structure and Composition*

Barite contains  $(SO_4)^{2-}$  tetrahedra linked by  $(BaO_{12})$  polyhedra. Each  $(BaO_{12})$  group is bonded to seven individual  $(SO_4)^{2-}$  tetrahedra. The structure differs from anhydrite's.

*Occurrence and Associations*

Barite is a common gangue mineral in hydrothermal veins, associated with fluorite, galena, quartz, calcite, or dolomite. It is also found in veins in limestone, and as residual masses in clays.

*Related Minerals*

Barite is chemically and structurally similar to celestite,  $SrSO_4$ , and anglesite,  $PbSO_4$ , although solid solutions between the three are limited in nature.

**Celestite** **$SrSO_4$** *Origin of Name*

From the Latin word *caelensis*, meaning "celestial," in reference to the sky-blue color of some celestite.

*Hand Specimen Identification*

The light blue color is distinctive, if present. Celestite may resemble barite, but has a lower specific gravity.

Crystal form and 90° cleavage angle also aid identification. Plate 1.6 shows a color photograph of celestite with a hint of light blue color.

#### *Physical Properties*

hardness	3 to 3½
specific gravity	3.97
cleavage/fracture	perfect basal (001), good prismatic {210}, poor (011)/uneven
luster/transparency	vitreous, pearly/transparent to translucent
color	colorless, blue, rarely light red
streak	white

#### *Optical Properties*

Celestite is similar to barite in thin section but may have a light blue color. Biaxial (+),  $\alpha = 1.622$ ,  $\beta = 1.624$ ,  $\gamma = 1.631$ ,  $\delta = 0.009$ ,  $2V = 51^\circ$ .

#### *Crystallography*

Orthorhombic,  $a = 8.38$ ,  $b = 5.37$ ,  $c = 6.85$ ,  $Z = 4$ ; space group  $P2_1/n2_1/m2_1/a$ ; point group  $2/m2/m2/m$ .

#### *Habit*

Tabular crystals, similar to those of barite, are typical. Acicular, fibrous, reniform, or granular crystals are also common.

#### *Structure and Composition*

Although in principal a complete solid solution exists between celestite ( $\text{SrSO}_4$ ) and barite ( $\text{BaSO}_4$ ), most celestite is close to end member  $\text{SrSO}_4$ . Small amounts of Pb may substitute for Sr.

#### *Occurrence and Associations*

Celestite is a rare mineral found in sedimentary rocks and in veins. Associated minerals often include dolomite, gypsum, halite, calcite, fluorite, or barite.

#### *Related Minerals*

Celestite is isostructural with barite,  $\text{BaSO}_4$ , and anglesite,  $\text{PbSO}_4$ . It may alter to strontianite,  $\text{SrCO}_3$ , the only other Sr end member mineral of significance.

## **Anglesite**

## **$\text{PbSO}_4$**

#### *Origin of Name*

Named after the Welsh island of Anglesey, where it was discovered.

#### *Hand Specimen Identification*

Adamantine luster, high specific gravity, and association with galena distinguish anglesite.

#### *Physical Properties*

hardness	2½ to 3
specific gravity	6.38
cleavage/fracture	perfect (001), good {210}/conchoidal
luster/transparency	adamantine/translucent
color	white
streak	white

#### *Optical Properties*

Biaxial (+),  $\alpha = 1.877$ ,  $\beta = 1.883$ ,  $\gamma = 1.894$ ,  $\delta = 0.017$ ,  $2V = 75^\circ$ .

#### *Crystallography*

Orthorhombic,  $a = 8.47$ ,  $b = 5.39$ ,  $c = 6.94$ ,  $Z = 4$ ; space group  $P2_1/n2_1/m2_1/a$ ; point group  $2/m2/m2/m$ .

#### *Habit*

Anglesite is normally blocky massive or in granular aggregates; individual crystals may be tabular, prismatic, bipyramidal, or nearly equant.

#### *Structure and Composition*

Anglesite, being isostructural with barite and celestite, may contain significant amounts of Ba or Sr.

#### *Occurrence and Associations*

Anglesite, a common alteration product of galena,  $\text{PbS}$ , is found in oxidized portions of Pb deposits. Associated minerals include cerussite,  $\text{SrSO}_4$ ; wulfenite,  $(\text{PbMoO}_4)$ ; smithsonite,  $\text{ZnCO}_3$ ; hemimorphite,  $\text{Zn}_4(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$ ; and pyromorphite,  $\text{Pb}_5(\text{PO}_4)_3\text{Cl}$ .

#### *Related Minerals*

Anglesite is isostructural with barite,  $\text{BaSO}_4$ , and celestite,  $\text{SrSO}_4$ , and is one of only a few common Pb minerals.

## **Gypsum**

## **$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$**

#### *Origin of Name*

From the Arabic word *jibs*, meaning “plaster.”

#### *Hand Specimen Identification*

Softness and three cleavages, tabular or platy crystals, and gray or white color distinguish gypsum. It is sometimes confused with anhydrite. See Plate 3.5 and Figure 37.

#### *Physical Properties*

hardness	2
specific gravity	2.32
cleavage/fracture	perfect basal (010), good (100) and {011}/conchoidal
luster/transparency	vitreous, pearly/transparent to translucent
color	colorless, white, variable
streak	white

*Optical Properties*

Gypsum is colorless in thin section and displays up to first-order yellow interference colors. It may be confused with anhydrite or barite, but anhydrite has higher relief and birefringence, and barite has higher relief and parallel extinction. Biaxial (+),  $\alpha = 1.520$ ,  $\beta = 1.523$ ,  $\gamma = 1.529$ ,  $\delta = 0.009$ ,  $2V = 58^\circ$ .

*Crystallography*

Monoclinic,  $a = 5.68$ ,  $b = 15.518$ ,  $c = 6.29$ ,  $\beta = 113.83^\circ$ ,  $Z = 4$ ; space group  $A2/n$ ; point group  $2/m$ .

*Habit*

Typical crystals are tabular, thick to thin, often forming as elongated masses or rosettes. Gypsum also forms acicular splays and may be massive or granular. Twinning and crystal intergrowths are common (Figure 37).

*Structure and Composition*

In gypsum, layers of  $\text{H}_2\text{O}$  alternate with layers containing  $\text{Ca}^{2+}$  and  $\text{SO}_4$ .  $\text{Ca}^{2+}$  is bonded to six O and two  $\text{H}_2\text{O}$ . The  $\text{Ca}^{2+}$  polyhedra link isolated  $\text{SO}_4$  tetrahedra. Gypsum rarely contains significant impurities.

*Occurrence and Associations*

Gypsum, the most common sulfate mineral, is a rock-forming mineral of many evaporite deposits where it may be associated with other bedded salts. It is also found interlayered with limestones or shales and may be found in fractures or cracks in a variety of sedimentary rocks. It is a gangue mineral or alteration product in some ore deposits and is occasionally found around fumaroles.



**FIGURE 37** Gypsum,  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ , is the most common of the sulfate minerals. Here it is showing asymmetrical "swallow tail" twinning.

*Varieties*

Well-known varieties of gypsum include selenite (clear, often needlelike, crystals), alabaster (compact white masses), and satin spar (fibrous deposits in veins).

*Related Minerals*

Other hydrous sulfates include chalcanthite,  $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ ; epsomite,  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ ; antlerite,  $\text{Cu}_3\text{SO}_4(\text{OH})_4$ ; and alunite,  $\text{KAl}_3(\text{SO}_4)_2(\text{OH})_6$ . Gypsum forms from, or alters to, anhydrite,  $\text{CaSO}_4$ .

**Epsomite** **$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$** *Origin of Name*

Derived from Epsom, England, where epsom salts were first precipitated from mineral waters.

*Hand Specimen Identification*

Typical crusty habit, low specific gravity, and salty taste are characteristic of epsomite.

*Physical Properties*

hardness	2 to $2\frac{1}{2}$
specific gravity	1.68
cleavage/fracture	perfect (010), good {011}/conchoidal
luster/transparency	vitreous/transparent to translucent
color	colorless
streak	white

*Optical Properties*

Biaxial (+),  $\alpha = 1.433$ ,  $\beta = 1.455$ ,  $\gamma = 1.461$ ,  $\delta = 0.028$ ,  $2V = 52^\circ$ .

*Crystallography*

Orthorhombic,  $a = 11.96$ ,  $b = 12.05$ ,  $c = 6.88$ ,  $Z = 4$ ; space group  $P2_12_12_1$ ; point group 222.

*Habit*

Epsomite may be botryoidal, fibrous, or colloform, and typically forms as crusts. Large crystals are rare.

*Structure and Composition*

Epsomite contains two types of  $\text{H}_2\text{O}$  molecules; some are coordinated with Mg and some are not.

*Occurrence and Associations*

Epsomite is uncommon but occurs in caves or mine adits as encrustations, as precipitates on carbonate or mafic igneous rocks, as an evaporite mineral, or as gangue in ore deposits. It is usually associated with other sulfates.

**Antlerite** **$\text{Cu}_3\text{SO}_4(\text{OH})_4$** *Origin of Name*

Derived from the Antler Mine, Arizona, where it was first described.

*Hand Specimen Identification*

Antlerite has a characteristic green color and one good cleavage. It is frequently best identified by association with other Cu minerals.

*Physical Properties*

hardness	$3\frac{1}{2}$ to 4
specific gravity	3.9
cleavage/fracture	perfect (010)/uneven
luster/transparency	vitreous/transparent to translucent
color	green, white, gray
streak	green, gray

*Optical Properties*

Biaxial (+),  $\alpha = 1.726$ ,  $\beta = 1.738$ ,  $\gamma = 1.789$ ,  $\delta = 0.063$ ,  $2V = 53^\circ$ .

*Crystallography*

Orthorhombic,  $a = 8.24$ ,  $b = 11.99$ ,  $c = 6.03$ ,  $Z = 4$ ; space group  $P2_1/a2_1/a2_1/m$ ; point group  $2/m2/m2/m$ .

*Habit*

Individual prismatic crystals, often showing striae, are common. Massive forms or fibrous aggregates are also typical (Figure 38).

*Structure and Composition*

$\text{CuO}(\text{OH})_5$  and  $\text{CuO}_3(\text{OH})_3$  octahedra are linked by  $(\text{SO}_4)^{2-}$  tetrahedra.

*Occurrence and Associations*

Antlerite is a rare mineral associated with Cu mineralization, forming either as a primary or a secondary mineral. It may be locally abundant, and is sometimes mined as a Cu ore mineral.

*Related Minerals*

Chalcanthite,  $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ , is another rare hydrous copper sulfate.

**Alunite** **$\text{KAl}_3(\text{SO}_4)_2(\text{OH})_6$** *Origin of Name*

From the Latin word *alumen*, meaning “alum.” The element aluminum was named for its presence in this mineral.

*Hand Specimen Identification*

Alunite’s association helps identify it, but it can be difficult to tell from other massive minerals or from limestone and dolomite.

*Physical Properties*

hardness	4
specific gravity	2.6 to 2.9

cleavage/fracture	good (001), poor (101)/conchoidal
luster/transparency	vitreous, pearly/transparent to translucent
color	white, gray, red
streak	white, gray

*Optical Properties*

In thin section, alunite is clear and displays up to second-order interference colors. It may be confused with brucite but has different associations. Uniaxial (+),  $\omega = 1.572$ ,  $\epsilon = 1.592$ ,  $\delta = 0.020$ .

*Crystallography*

Hexagonal (rhombohedral),  $a = 6.97$ ,  $c = 17.38$ ,  $Z = 3$ ; space group  $R\bar{3}m$ ; point group  $3m$ .

*Habit*

Alunite forms as crusts and coatings and is usually massive. Fibrous, columnar, and granular occurrences are known.

*Structure and Composition*

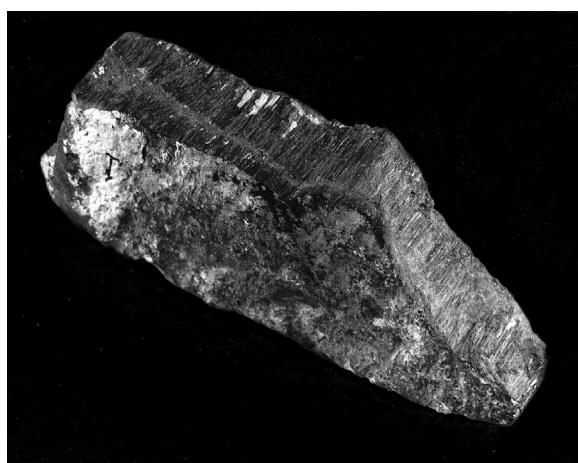
Alunite consists of layers of isolated  $(\text{SO}_4)^{2-}$  tetrahedra alternating with  $\text{Al}(\text{OH})_6$  octahedra. The two polyhedra share oxygens at their corners. Distorted  $\text{K}(\text{O},\text{OH})_6$  octahedra also share oxygen with the  $(\text{SO}_4)^{2-}$  groups. Na may substitute for K; minor amounts of Fe and P may substitute for Al and S.

*Occurrence and Associations*

A rare mineral, alunite is associated with fumaroles or with zones of hydrothermal alteration in K-rich igneous rocks. It is found with quartz, kaolinite, and other clay minerals.

*Related Minerals*

Alunite is isostructural with jarosite,  $\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$ , a secondary mineral associated with some iron ores. It forms solid solutions with natroalunite,  $\text{NaAl}_3(\text{SO}_4)_2(\text{OH})_6$ .



**FIGURE 38** Fibrous-looking antlerite coating altered granodiorite at Chuquicamata, Chile.

## X. TUNGSTATES, MOLYBDATES, AND CHROMATES

### Tungstate Group

wolframite series

huebnerite	MnWO <sub>4</sub>
ferberite	FeWO <sub>4</sub>
scheelite	CaWO <sub>4</sub>

### Molybdate Group

wulfenite	PbMoO <sub>4</sub>
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### Chromate Group

crocoite	PbCrO <sub>4</sub>
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Tungstates, molybdates, and chromates are chemically and structurally related to the anhydrous sulfates. Generally rare minerals, they may be locally concentrated in ore deposits.

## Wolframite

### (Fe,Mn)WO<sub>4</sub>

#### Origin of Name

The name's origin is unclear; perhaps it comes from the German words for "wolf" and *rahm*, meaning "soot," in reference to its color.

#### Hand Specimen Identification

High specific gravity, dark color, and one good cleavage help identify wolframite. It is sometimes confused with hornblende and occasionally with scheelite.

#### Physical Properties

hardness	4 to 4½
specific gravity	7.25 to 7.60
cleavage/fracture	one perfect (010)/uneven
luster/transparency	submetallic/opaque unless very thin
color	black, red-brown
streak	black, red-brown

#### Optical Properties

Generally opaque. Biaxial (+),  $\alpha = 2.17$  to 2.31,  $\beta = 2.22$  to 2.40,  $\gamma = 2.30$  to 2.46,  $\delta = 0.13$  to 0.15,  $2V = 73^\circ$  to 79°.

#### Crystallography

Monoclinic,  $a = 4.71$  to 4.85,  $b = 5.70$  to 5.77,  $c = 4.94$  to 4.98,  $\beta = 90^\circ$  to 91°,  $Z = 2$ ; space group  $P2/c$ ; point group 2/m.

#### Habit

Crystals are short to long prisms or tabs, often showing vertical striations. Wolframite may form bladed, subparallel crystal groups.

#### Structure and Composition

A complete solid solution exists between ferberite ( $FeWO_4$ ) and huebnerite ( $MnWO_4$ ), the two principal wolframite end members. The basic structure consists of layers of distorted  $(WO_4)^{2-}$  tetrahedra joined by octahedral Fe or Mn.

#### Occurrence and Associations

Wolframite is a rare mineral. Usually found in high-temperature quartz veins associated with granitic igneous rocks, it is, however, the most important tungsten ore mineral. It is also found in sulfide-rich veins, associated with scheelite, cassiterite, pyrite, or galena. It may contain minor amounts of Ca, Mg, or rare earth elements.

#### Related Minerals

Similar minerals include the rare tungstates sanmartinite,  $(Zn,Fe)WO_4$ , and raspite,  $Pb(WO_4)$ .

## Scheelite

### CaWO<sub>4</sub>

#### Origin of Name

Named after K. W. Scheele (1742–1786), a Swedish chemist.

#### Hand Specimen Identification

High specific gravity, crystal habit, distinct cleavage, and fluorescence under ultraviolet light are characteristic. It may be confused with quartz or feldspar when uncolored.

#### Physical Properties

hardness	4½ to 5
specific gravity	6.11
cleavage/fracture	good pyramidal {101}, poor {112}/uneven
luster/transparency	subadamantine/transparent to translucent
color	colorless, white, yellow, brown
streak	white

#### Optical Properties

Uniaxial (+),  $\omega = 1.920$ ,  $\epsilon = 1.934$ ,  $\delta = 0.014$ .

#### Crystallography

Tetragonal,  $a = 5.25$ ,  $c = 11.40$ ,  $Z = 4$ ; space group  $I4_1/a$ ; point group 4/m.

#### Habit

Scheelite is found in massive, columnar, or granular aggregates and as individual crystals, usually dipyrramids.

#### Structure and Composition

Scheelite is usually close to end member composition, but a limited solid solution exists with powellite,  $CaMoO_4$ . It may also incorporate small amounts of

Cu or Mn. In the structure, isolated  $(\text{WO}_4)^{2-}$  tetrahedra are linked by 8-coordinated Ca.

#### *Occurrence and Associations*

Scheelite is a high-temperature mineral found in metamorphic aureoles, in granites and pegmatites, and in some hydrothermal veins. It may be found with cassiterite,  $\text{SnO}_2$ ; topaz,  $\text{Al}_2\text{SiO}_4(\text{F},\text{OH})_2$ ; fluorite,  $\text{CaF}_2$ ; apatite,  $\text{Ca}_5(\text{PO}_4)_3(\text{OH},\text{F},\text{Cl})$ ; and with other tungstates or molybdates.

#### *Related Minerals*

Scheelite is isostructural with wulfenite,  $\text{PbMoO}_4$ .

## **Wulfenite**

## **PbMoO<sub>4</sub>**

#### *Origin of Name*

Named after Austrian mineralogist F. X. von Wulfen (1728–1805).

#### *Hand Specimen Identification*

Crystal habit and orange-yellow color are distinctive. Wulfenite is occasionally confused with native sulfur.

#### *Physical Properties*

hardness	3
specific gravity	6.7 to 7.0
cleavage/fracture	good but rarely seen pyramidal {011}, poor (001)/subconchoidal
luster/transparency	adamantine, silvery/transparent to translucent
color	yellow, orange, red, brown, green
streak	white

#### *Optical Properties*

Uniaxial (−),  $\omega = 2.404$ ,  $\epsilon = 2.283$ ,  $\delta = 0.121$ .

#### *Crystallography*

Tetragonal,  $a = 5.42$ ,  $c = 12.10$ ,  $Z = 4$ ; space group  $I4_1/a$ ; point group  $4/m$ .

#### *Habit*

Crystals are square tablets, often thin or pyramidal.

#### *Occurrence and Associations*

Wulfenite is a rare secondary mineral found in the oxidized portions of Pb deposits. It may be associated with galena,  $\text{PbS}$ ; cerussite,  $\text{PbCO}_3$ ; vanadinite,  $\text{Pb}_5(\text{VO}_4)_3\text{Cl}$ ; or pyromorphite,  $\text{Pb}_5\text{Cl}(\text{PO}_4)_3$ . Wulfenite is isostructural with scheelite,  $\text{CaWO}_4$ , with which it forms limited solid solutions. It also forms limited solid solutions with powellite,  $\text{CaMoO}_4$ , and raspite,  $\text{Pb}(\text{WO}_4)$ .

## **Crocoite**

## **PbCrO<sub>4</sub>**

#### *Origin of Name*

From the Greek word *krokos*, meaning “saffron,” referring to its color.

#### *Hand Specimen Identification*

Distinctive reddish orange color and luster, its specific gravity and habit, and association usually make crocoite easy to identify. It is occasionally confused with wulfenite,  $\text{PbMoO}_4$ , or with vanadinite,  $\text{Pb}_5(\text{VO}_4)_3\text{Cl}$ .

#### *Physical Properties*

hardness	$2\frac{1}{2}$ to 3
specific gravity	6.0
cleavage/fracture	perfect {110}, poor (001)/subconchoidal
luster/transparency	adamantine/translucent
color	reddish orange
streak	orange

#### *Optical Properties*

Biaxial (+),  $\alpha = 2.31$ ,  $\beta = 2.37$ ,  $\gamma = 2.66$ ,  $\delta = 0.35$ ,  $2V = 54^\circ$ .

#### *Crystallography*

Monoclinic,  $a = 7.11$ ,  $b = 7.41$ ,  $c = 6.81$ ,  $\beta = 102.55^\circ$ ,  $Z = 4$ ; space group  $P2_1/n$ ; point group  $2/m$ .

#### *Habit*

Crystals are acicular or columnar. The thin prismatic crystals often have striations parallel to prism faces. More rarely, crocoite forms granular aggregates or patches.

#### *Structure and Composition*

Crocoite is isostructural with monazite,  $(\text{Ce},\text{La},\text{Th},\text{Y})\text{PO}_4$ . It consists of distorted  $(\text{CrO}_4)^{2-}$  tetrahedra alternating with Pb in 9-fold coordination.

#### *Occurrence and Associations*

Crocoite is a rare secondary Pb mineral associated with veined lead deposits. It may be found with cerussite,  $\text{PbCO}_3$ ; pyromorphite,  $\text{Pb}(\text{PO}_4)_3\text{Cl}$ ; or wulfenite,  $\text{PbMoO}_4$ .

#### *Related Minerals*

Crocoite is isostructural with monazite,  $(\text{Ce},\text{La},\text{Th},\text{Y})\text{PO}_4$ , and with several other rare earth silicates and phosphates. It is closely related to xenotime,  $\text{Y}(\text{PO}_4)$ , and pucherite,  $\text{Bi}(\text{VO}_4)$ .

## XI. PHOSPHATES, ARSENATES, AND VANADATES

### Phosphate Group Minerals

monazite	$(Ce, La, Th, Y)PO_4$
triphylite	$Li(Fe, Mn)PO_4$
apatite	$Ca_5(PO_4)_3(OH, F, Cl)$
pyromorphite	$Pb_5(PO_4)_3Cl$
amblygonite	$LiAl(PO_4)_3F$
lazulite	$(Mg, Fe)Al_2(PO_4)_2(OH)_2$
wavellite	$Al_3(PO_4)_2(OH)_3 \cdot 5H_2O$
turquoise	$CuAl_6(PO_4)_4(OH)_8 \cdot 4H_2O$
autunite	$Ca(UO_2)_2(PO_4)_2 \cdot 10H_2O$

### Vanadate Group Minerals

vanadinite	$Pb_5(VO_4)_3Cl$
carnotite	$K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$

### Arsenate Group Minerals

erythrite	$Co_3(AsO_4)_2 \cdot 8H_2O$
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The phosphate group contains many minerals, but most are extremely rare. Apatite is the only common example. Vanadates and arsenates, which are closely related to the phosphates in chemistry and structure, are also rare.

## Monazite

### $(Ce, La, Th, Y)PO_4$

#### Origin of Name

From the Greek word *monazein*, meaning “to live alone,” referring to its rare occurrences in the outcrops where it was first found.

#### Hand Specimen Identification

Radioactivity, color, crystal habit, and associations help identify monazite. It may be confused with zircon,  $ZrSiO_4$ , but is not as hard and has different forms. It can be distinguished from titanite (sphene),  $CaTiSiO_5$ , by its crystal shape and high density.

#### Physical Properties

hardness	5 to $5\frac{1}{2}$
specific gravity	4.9 to 5.2
cleavage/fracture	perfect (001), good (100)/subconchoidal
luster/transparency	variable, subresinous/translucent
color	red, brown, yellowish
streak	white

#### Optical Properties

Monazite is colorless, gray, or yellow-brown in thin section. It has high positive relief and displays up to third or fourth order interference colors. Biaxial (+),  $\alpha = 1.785$  to  $1.800$ ,  $\beta = 1.786$  to  $1.801$ ,  $\gamma = 1.838$  to  $1.850$ ,  $\delta = 0.005$ ,  $2V = 10^\circ$  to  $20^\circ$ .

#### Crystallography

Monoclinic,  $a = 6.79$ ,  $b = 7.01$ ,  $c = 6.46$ ,  $\beta = 104.4^\circ$ ,  $Z = 4$ ; space group  $P2_1/n$ ; point group  $2/m$ .

#### Habit

Crystals are usually small, tabular, or prismatic, often forming granular masses or individual grains in sand.

#### Structure and Composition

Monazite is isostructural with crocoite. In its structure, distorted  $(PO_4)^{3-}$  polyhedra are bonded to rare earth elements in 9-fold coordination. All the rare earths may be present, but Ce, La, and Th are usually the dominant large cations. Small amounts of Si may substitute for P in the tetrahedral sites.

#### Occurrence and Associations

Monazite is a rare secondary mineral in silicic igneous rocks. It is also found in unconsolidated beach or stream sediments, where it is associated with other heavy minerals such as magnetite and ilmenite.

#### Varieties

Rare earth content varies, so the names monazite-(Ce), monazite-(La), and so on are sometimes used to designate the dominant rare earth.

#### Related Minerals

Monazite is isostructural with crocoite,  $PbCrO_4$ , and forms solid solutions with buttonite,  $ThSiO_4$ . It is chemically related to xenotime,  $Y(PO_4)$ , with which it forms a minor solid solution.

## Triphylite

### $Li(Fe, Mn)PO_4$

#### Origin of Name

From the Greek words for “three” and “family,” in reference to its three cations.

#### Hand Specimen Identification

Association,  $90^\circ$  cleavage, and resinous luster help identify triphylite.

#### Physical Properties

hardness	5 to $5\frac{1}{2}$
specific gravity	3.5 to 5.5
cleavage/fracture	perfect (001), good (010)/subconchoidal
luster/transparency	vitreous, resinous/transparent to translucent
color	variable, blue, green, brown
streak	white, gray

#### Optical Properties

Biaxial (-),  $\alpha = 1.68$ ,  $\beta = 1.68$ ,  $\gamma = 1.69$ ,  $\delta = 0.01$ ,  $2V = 0^\circ$  to  $56^\circ$ .

*Crystallography*

Orthorhombic,  $a = 6.01$ ,  $b = 4.68$ ,  $c = 10.36$ ,  $Z = 4$ ;  
space group  $P2_1/m2_1/c2_1/n$ ; point group  $2/m2/m2/m$ .

*Habit*

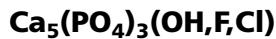
Euhedral crystals are rare; triphyllite is typically fine grained and massive.

*Structure and Composition*

The cations occupy octahedra forming zigzag chains between  $(\text{PO}_4)^{3-}$  tetrahedra. A complete solid solution exists between the Fe and Mn end members. Compositions near the Mn end member are given the name *lithiophilite*.

*Occurrence and Associations*

Triphyllite, typically a pegmatite mineral, is found with other phosphates, quartz, feldspar, spodumene, and beryl.

**Apatite***Origin of Name*

From the Greek word *apate*, meaning “deceit,” because it is often difficult to distinguish it from other minerals.

*Hand Specimen Identification*

Hexagonal prismatic crystals, color, hardness, and lack of distinct cleavage are most diagnostic of apatite. It is occasionally confused with beryl or with epidote. (Figure 39)

*Physical Properties*

hardness	5
specific gravity	3.2
cleavage/fracture	good {001}, poor {100}/conchoidal
luster/transparency	subresinous/transparent to translucent
color	green, yellow, variable
streak	white

*Optical Properties*

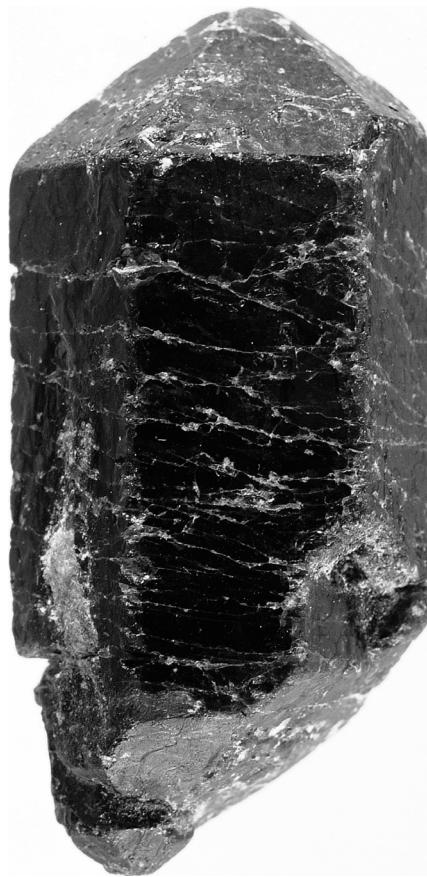
Apatite appears similar to quartz in thin section. It is colorless, does not develop good cleavage, and has very low birefringence. Quartz, however, has lower relief and is uniaxial (+). Uniaxial (-),  $\omega = 1.633$ ,  $\epsilon = 1.630$ ,  $\delta = 0.003$ .

*Crystallography*

Hexagonal,  $a = 9.38$ ,  $c = 6.86$ ,  $Z = 2$ ; space group  $P6_3/m$ ; point group  $6/m$ .

*Habit*

Apatite typically forms prismatic crystals, but may be colloform, massive, or granular.



**FIGURE 39** Large (8 cm tall) apatite crystal from Minas Gerais, Brazil

*Structure and Composition*

Complete solid solution exists between hydroxyapatite (OH end member), fluorapatite (F end member), and chlorapatite (Cl end member). In addition, transition metals or Sr may replace Ca; and  $(\text{CO}_3)^{2-}$ ,  $\text{OH}^-$ , or  $(\text{SO}_4)^{2-}$  may replace some  $(\text{PO}_4)^{3-}$ . In the apatite structure,  $\text{Ca}-\text{PO}_4$  chains run parallel to the c-axis.  $\text{Ca}^{2+}$  is located around channels occupied by (F, Cl, OH).

*Occurrence and Associations*

Apatite is a common accessory mineral but only rarely a major rock former. It is common in all igneous rocks, including pegmatites and hydrothermal veins, in metamorphic rocks, and in marine sediments.

*Varieties*

Collophane is a massive cryptocrystalline form of apatite that comprises some phosphate rocks and bones.

*Related Minerals*

A large number of phosphates, sulfates, arsenates, vanadates, and silicates are isostructural with apatite, but none are common.

**Pyromorphite***Origin of Name*

From the Greek words meaning “fire” and “form,” because it typically develops large faces when crystallizing from a magma.

*Hand Specimen Identification*

Bright green-yellow or brown color, habit, density, and luster identify pyromorphite. It is sometimes confused with apatite.

*Physical Properties*

hardness	$3\frac{1}{2}$ to 4
specific gravity	7.0
cleavage/fracture	poor {100}, poor {101}
luster/transparency	resinous/transparent to translucent
color	bright green, yellow, variable
streak	white, yellow

*Optical Properties*

Uniaxial (-),  $\omega = 2.058$ ,  $\epsilon = 2.048$ ,  $\delta = 0.010$ .

*Crystallography*

Hexagonal,  $a = 9.97$ ,  $c = 7.32$ ,  $Z = 2$ ; space group  $P6_3/m$ ; point group  $6/m$ .

*Habit*

Pyromorphite is typically prismatic, having a barrel shape; it is less commonly granular, fibrous, cavernous (hollow prisms), globular, or reniform.

*Structure and Composition*

Pyromorphite is isostructural with apatite (see **apatite**). Some Ca may substitute for Pb. P may be replaced by As.

*Occurrence and Associations*

Pyromorphite is a secondary mineral, found with other oxidized Pb or Zn minerals, in oxidized zones associated with Pb deposits. It is isostructural with apatite and with mimetite,  $\text{Pb}(\text{AsO}_4)_3\text{Cl}$ , with which it forms a complete solid solution.

**Amblygonite***Origin of Name*

From the Greek word *amblygonios*, referring to its cleavage angle.

*Hand Specimen Identification*

Single perfect cleavage and conchoidal fracture help distinguish amblygonite from feldspar.

*Physical Properties*

hardness	6
specific gravity	3.0
cleavage/fracture	perfect (100), good (110), poor (011)/subconchoidal
luster/transparency	vitreous, greasy/transparent to translucent
color	white, green
streak	white

*Optical Properties*

Biaxial (-),  $\alpha = 1.59$ ,  $\beta = 1.60$ ,  $\gamma = 1.62$ ,  $\delta = 0.03$ ,  $2V = 52^\circ$  to  $90^\circ$ .

*Crystallography*

Triclinic,  $a = 5.19$ ,  $b = 7.12$ ,  $c = 5.04$ ,  $\alpha = 112.02^\circ$ ,  $\beta = 97.82^\circ$ ,  $\gamma = 68.12^\circ$ ,  $Z = 2$ ; space group  $P\bar{1}$ ; point group  $\bar{1}$ .

*Habit*

Rare crystals may be equant or columnar. Amblygonite is more commonly found as rough masses or in irregular aggregates.

*Structure and Composition*

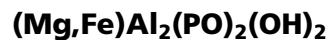
Amblygonite is composed of alternating  $(\text{PO}_4)^{3-}$  tetrahedra and  $\text{AlO}_5\text{F}$  octahedra linked by  $\text{Li}^+$  ions. F ay be replaced by OH. Minor Na may be present.

*Occurrence and Associations*

Amblygonite is a rare mineral found in pegmatites rich in Li and P. Typical associated minerals include lepidolite, spodumene, apatite, and tourmaline.

*Related Minerals*

Several other phosphate minerals, some occurring as gems, are similar to amblygonite and are found in pegmatites: herderite,  $\text{CaBe}(\text{PO}_4)(\text{F},\text{OH})$ ; beryllonite,  $\text{NaBePO}_4$ ; and brazillianite,  $\text{NaAl}_3(\text{PO}_4)_2(\text{OH})_4$ . Complete solid solution exists between amblygonite and a hydroxy end member, montebrasite,  $\text{LiAl}(\text{PO}_4)(\text{OH})$ .

**Lazulite***Origin of Name*

From an Arabic word meaning “heaven,” referring to its sky-blue color.

*Hand Specimen Identification*

Lazulite's azure-blue color is distinctive. When crystalline, the pyramidal form distinguishes lazulite from other blue minerals. When massive, identification is problematic.

*Physical Properties*

hardness	5 to 5½
specific gravity	3.0
cleavage/fracture	poor (011)/uneven
luster/transparency	vitreous/translucent
color	azure-blue
streak	white

*Optical Properties*

Biaxial (-),  $\alpha = 1.612$ ,  $\beta = 1.634$ ,  $\gamma = 1.643$ ,  $\delta = 0.031$ ,  $2V = 70^\circ$ .

*Crystallography*

Monoclinic,  $a = 7.16$ ,  $b = 7.26$ ,  $c = 7.24$ ,  $\beta = 120.67^\circ$ ,  $Z = 2$ ; space group  $P2_1/c$ ; point group  $2/m$ .

*Habit*

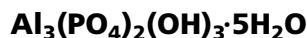
Typically massive, granular, or compact; rare crystals are prismatic or pyramidal with steep faces.

*Structure and Composition*

Octahedral Mg and Fe are linked to octahedral Al by sharing of  $O^{2-}$  and  $OH^-$ . The  $(Mg,Fe,Al)$  octahedra bond to  $(PO_4)^{3-}$  tetrahedra. Complete solid solution exists between the Mg and Fe end members. *Scorzalite* is the name given to Fe-rich members of the series.

*Occurrence and Associations*

Lazulite and related minerals are rare, found only in some pegmatites and high-grade metamorphic rocks. They may be associated with rutile, kyanite, corundum, and sillimanite.

**Wavellite***Origin of Name*

Named after W. Wavel (d. 1829), who discovered it.

*Hand Specimen Identification*

Globular aggregates containing radiating crystals, light color, and associations distinguish wavellite (Figure 40).



**FIGURE 40** Wavellite,  $\text{Al}(\text{PO}_4)_2(\text{OH})_3 \cdot 5\text{H}_2\text{O}$ , from Montgomery County, Arkansas, showing typical radiating crystals.

*Physical Properties*

hardness	3½ to 4
specific gravity	2.36
cleavage/fracture	perfect prismatic {101}, perfect (010)/subconchoidal
luster/transparency	vitreous/translucent
color	white, greenish yellow, gray, brown
streak	white

*Optical Properties*

Biaxial (+),  $\alpha = 1.525$ ,  $\beta = 1.534$ ,  $\gamma = 1.552$ ,  $\delta = 0.027$ ,  $2V = 72^\circ$ .

*Crystallography*

Orthorhombic,  $a = 9.62$ ,  $b = 17.36$ ,  $c = 6.99$ ,  $Z = 4$ ; space group  $P2_1/c2_1/m2_1/n$ ; point group  $2/m2/m2/m$ .

*Habit*

Globular aggregates and radiating crystals are most common (Figure 40).

*Structure and Composition*

Wavellite's structure is incompletely known. It may contain small amounts of Fe and Mg.

*Occurrence and Associations*

Wavellite is a secondary mineral found in rock cavities or on joint surfaces, in low-grade aluminous metamorphic rocks, and in phosphorite deposits. It is commonly associated with limonite and with other phosphate minerals.

**Turquoise***Origin of Name*

From the French word *turquoise*, meaning "Turkish," in reference to the source of the original stones imported into Europe.

*Hand Specimen Identification*

Turquoise has a distinctive blue color; it is distinguished from chrysocolla, hydrated Cu-silicate, by its superior hardness.

*Physical Properties*

hardness	6
specific gravity	2.7
cleavage/fracture	perfect but rarely seen (001), good (010)/subconchoidal, brittle
luster/transparency	resinous, waxy/translucent
color	blue, green
streak	white, green

*Optical Properties*

Biaxial (+),  $\alpha = 1.61$ ,  $\beta = 1.62$ ,  $\gamma = 1.65$ ,  $\delta = 0.04$ ,  $2V = 40^\circ$ .

*Crystallography*

Triclinic,  $a = 7.48$ ,  $b = 9.95$ ,  $c = 7.69$ ,  $\alpha = 111.65^\circ$ ,  $\beta = 115.38^\circ$ ,  $\gamma = 69.43^\circ$ ,  $Z = 1$ ; space group  $P\bar{1}$ ; point group 1.

*Habit*

Rare small crystals are known; reniform, massive, or granular varieties are more typical.

*Structure and Composition*

The structure consists of a framework of  $(PO_4)^{3-}$ -tetrahedra and Al octahedra. Holes in the structure contain Cu, which bonds to the polyhedra,  $OH^-$  and to  $H_2O$ .  $Fe^{3+}$  may substitute for Al.

*Occurrence and Associations*

Turquoise occurs as a secondary mineral associated with Al-rich volcanic rocks. It forms in small seams, veins, stringers, and crusts. Associated minerals include kaolinite,  $Al_2Si_2O_5(OH)_4$ ; limonite,  $Fe(O,OH)_n$ ; and chalcedony,  $SiO_2$ .

*Varieties*

Blue-green varieties of turquoise are called *faustite*.

*Related Minerals*

Complete solid solution exists between turquoise and chalcosiderite,  $CuFe_6(PO_4)_4(OH)_8 \cdot 4H_2O$ .

**Autunite***Origin of Name*

Named for Autun, France, where it is found.

*Hand Specimen Identification*

Radioactivity, fluorescence under ultraviolet light, and typical yellow-green tetragonal plates typify autunite.

*Physical Properties*

hardness	2 to $2\frac{1}{2}$
specific gravity	3.15
cleavage/fracture	perfect basal (001), good prismatic (100), (010) and {110}/uneven
luster/transparency	pearly, adamantine/transparent to translucent
color	yellow
streak	yellow

*Optical Properties*

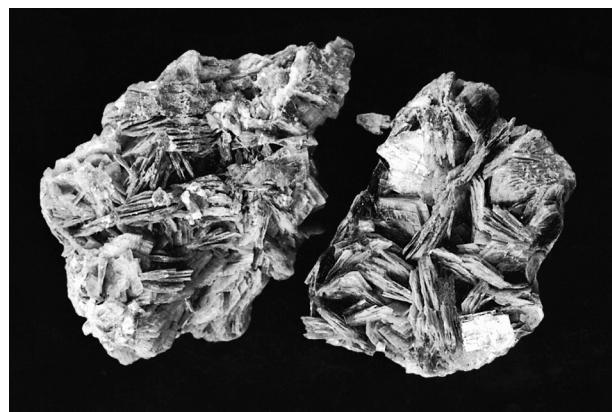
Uniaxial (-),  $\omega = 1.577$ ,  $\epsilon = 1.553$ ,  $\delta = 0.024$ .

*Crystallography*

Tetragonal,  $a = 7.00$ ,  $c = 20.67$ ,  $Z = 4$ ; space group  $I\bar{4}/m2/m2/m$ ; point group  $4/m2/m2/m$ .

*Habit*

Thin tabular or flaky crystals, often square, are typical (Figure 41).



**FIGURE 41** Flakes of autunite, a rare uranium phosphate mineral, from Spokane, Washington.

*Structure and Composition*

$(PO_4)^{3-}$ -tetrahedra link to U octahedra to form uneven layers, which are joined by weakly bonded  $H_2O$  molecules. Other alkaline earths may substitute for Ca in small amounts; the amount of water in the structure is somewhat variable.

*Occurrence and Associations*

Autunite is a secondary uranium mineral, often forming after uraninite,  $UO_2$ . Torbernite,  $Cu(UO_2)_2(PO_4)_2 \cdot nH_2O$ , and uraninite are common associated minerals.

*Related Minerals*

Torbernite is isostructural with autunite and has similar properties.

**Vanadinite***Origin of Name*

Named in reference to its vanadium content.

*Hand Specimen Identification*

Hexagonal crystal form, density, luster, and color help identify vanadinite. Color helps distinguish it from apatite, pyromorphite, or mimetite.

*Physical Properties*

hardness	3
specific gravity	6.9
cleavage/fracture	none/subconchoidal
luster/transparency	resinous/translucent
color	ruby red, orange-red, brown, yellow
streak	white, yellow

*Optical Properties*

Uniaxial (-),  $\omega = 2.416$ ,  $\epsilon = 2.350$ ,  $\delta = 0.066$ .

*Crystallography*

Hexagonal,  $a = 10.33$ ,  $c = 7.35$ ,  $Z = 2$ ; space group  $P6_3/m$ ; point group  $6/m$ .

**Habit**

Vanadinite often forms prisms, sometimes hollow, with or without pyramidal faces. It may also be rounded or globular.

**Structure and Composition**

Vanadinite is isostructural with apatite. P or As may substitute for V in small amounts. Minor amounts of Ca, Zn, and Cu may also be present.

**Occurrence and Associations**

Vanadinite is a rare mineral found in the oxidized portions of Pb deposits where it is often associated with galena, cerussite, or limonite.

**Related Minerals**

Vanadinite is isostructural with apatite,  $\text{Ca}_5(\text{PO}_4)_3(\text{OH},\text{F},\text{Cl})$ , and with a number of other arsenates, vanadates, and phosphates. It forms solid solutions with mimetite,  $\text{Pb}_5(\text{AsO}_4)_3\text{Cl}$ , and intermediate compositions are called *endlichite*.

**Carnotite** **$\text{K}_2(\text{UO}_2)_2(\text{VO}_4)_2 \cdot 3\text{H}_2\text{O}$** **Origin of Name**

Named after M. A. Carnot (1839–1920), a French mining engineer and Inspector General of Mines.

**Hand Specimen Identification**

Radioactivity and yellow color, often with a greenish stain, characterize carnotite. It is sometimes confused with other secondary uranium minerals.

**Physical Properties**

hardness	1
specific gravity	4.5
cleavage/fracture	perfect but rarely seen (001)/uneven
luster/transparency	dull, earthy/translucent
color	yellow, yellow-green
streak	yellow

**Optical Properties**

Biaxial (−),  $\alpha = 1.75$ ,  $\beta = 1.92$ ,  $\gamma = 1.95$ ,  $\delta = 0.20$ ,  $2V = 38^\circ$  to  $44^\circ$ .

**Crystallography**

Monoclinic,  $a = 10.47$ ,  $b = 8.41$ ,  $c = 6.91$ ,  $\beta = 103.67^\circ$ ,  $Z = 1$ ; space group  $P2_1/a$ ; point group  $2/m$ .

**Habit**

Fine powder or crumbly aggregates characterize carnotite. It may also be disseminated.

**Structure and Composition**

The structure contains layers of edge-sharing uranium and vanadium polyhedra. The layers are joined by weak bonds to interlayer K and  $\text{H}_2\text{O}$ .

**Occurrence and Associations**

Carnotite is a secondary mineral found in sandstones or conglomerates that have been altered by circulation of meteoric waters.

**Related Minerals**

A number of other hydrated uranium oxides are known, including tyuyamunite,  $\text{Ca}(\text{UO}_2)_2(\text{VO}_4)_2 \cdot n\text{H}_2\text{O}$ ; torbernite,  $\text{Cu}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot n\text{H}_2\text{O}$ ; and autunite,  $\text{Ca}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 10\text{H}_2\text{O}$ .

**Erythrite** **$\text{Co}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$** **Origin of Name**

From the Greek word *erythros*, meaning “red.”

**Hand Specimen Identification**

Association with other cobalt minerals, often crusty appearance, and distinctive pink-red-purple color identify erythrite.

**Physical Properties**

hardness	$1\frac{1}{2}$ to $2\frac{1}{2}$
specific gravity	3.06
cleavage/fracture	perfect basal (010)/sectile
luster/transparency	adamantine/transparent to translucent
color	crimson, pink, purple-red
streak	pale purple

**Optical Properties**

Biaxial (−),  $\alpha = 1.626$ ,  $\beta = 1.661$ ,  $\gamma = 1.699$ ,  $\delta = 0.073$ ,  $2V = 90^\circ$ .

**Crystallography**

Monoclinic,  $a = 10.26$ ,  $b = 13.37$ ,  $c = 4.74$ ,  $\beta = 105.1^\circ$ ,  $Z = 2$ ; space group  $C2/m$ ; point group  $2/m$ .

**Habit**

Erythrite may be prismatic, acicular, reniform, or globular. Erythrite typically forms as coatings and crusts.

**Structure and Composition**

The atomic structure is layered, with the vertex sharing by As tetrahedra and Co octahedra. Ni may substitute for Co.

**Occurrence and Associations**

Erythrite may form as a pink powdery coating, called *cobalt bloom*, on other cobalt minerals such as cobaltite,  $(\text{Co},\text{Fe})\text{AsS}$ , or skutterudite,  $(\text{Co},\text{Ni})\text{As}_3$ .

**Related Minerals**

Annabergite,  $\text{Ni}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$ , also called *nickel bloom*, is isostructural with erythrite, but has an apple-green color. A complete solid solution exists between erythrite and annabergite.



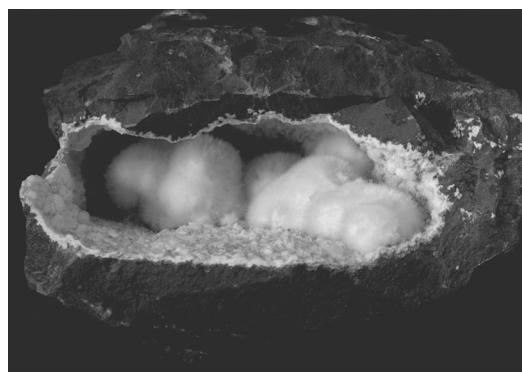
**PLATE 1.1** Tourmaline from Paraiba, Brazil, with colors showing compositional zonation.



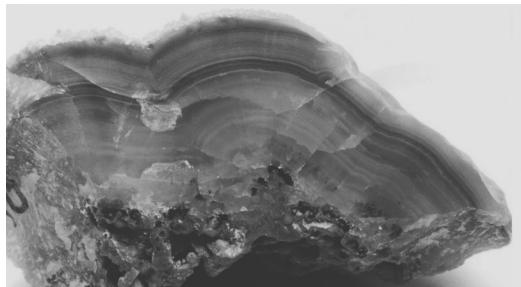
**PLATE 1.3** Pyrite crystals with pyritohedron form showing growth striations on faces.



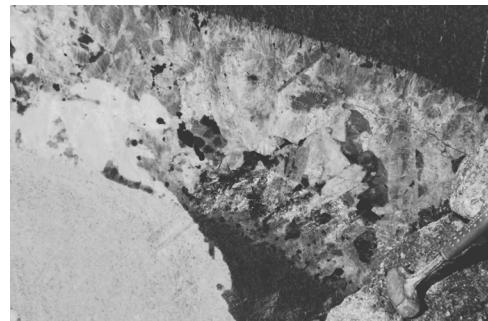
**PLATE 1.5** Orthoclase from Petschau, Bohemia, showing penetration twins.



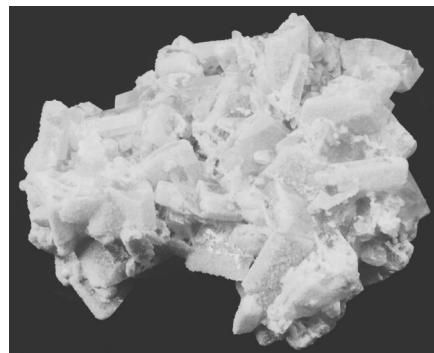
**PLATE 1.7** Acicular okenite in a geode from Bombay, India.



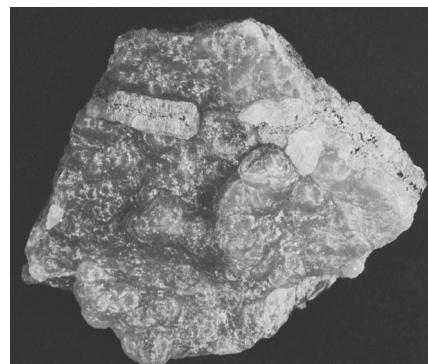
**PLATE 1.2** Smithsonite from Rush Creek, Arkansas, with colors showing compositional zonation.



**PLATE 1.4** Small pegmatite exposed in Larvikite quarry near Larvik, Norway.



**PLATE 1.6** Celestite from Lime City, Ohio.



**PLATE 1.8** Botryoidal purple smithsonite from Choix, Mexico.



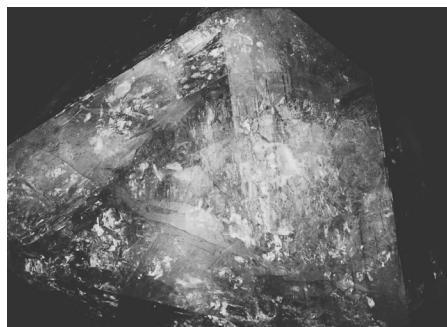
**PLATE 2.1** Rutile needles in quartz from Brazil showing conchoidal fractures.



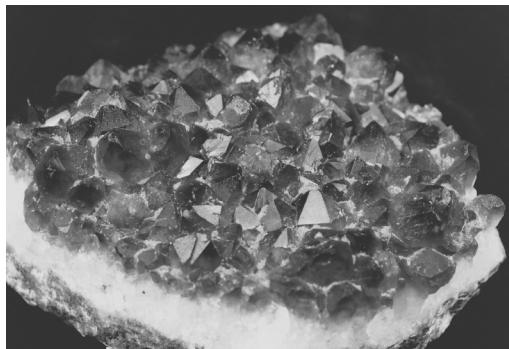
**PLATE 2.2** Rose quartz from Custer, South Dakota.



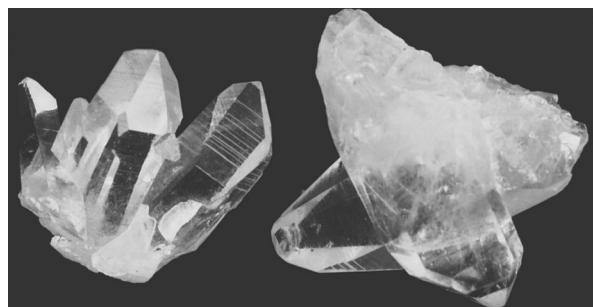
**PLATE 2.3** Amethyst, a purple variety of quartz.



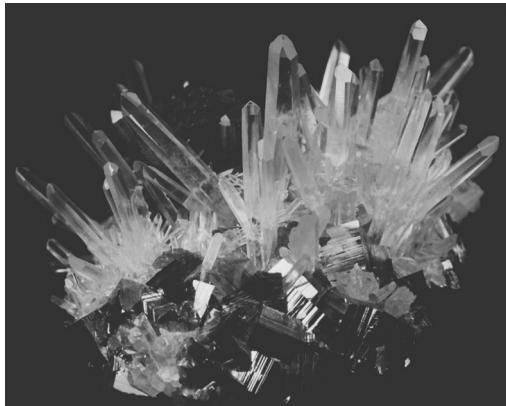
**PLATE 2.4** Quartz showing play of colors and internal reflection due to internal fractures.



**PLATE 2.5** Brown quartz from California.



**PLATE 2.6** Clear quartz crystals from Hot Springs, Arkansas, showing growth striations.



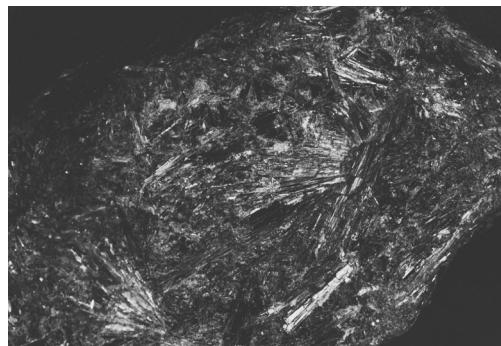
**PLATE 2.7** Prismatic quartz crystals on pyrite; sphalerite is the dark mineral behind the quartz crystals (sample from Huaron, Peru).



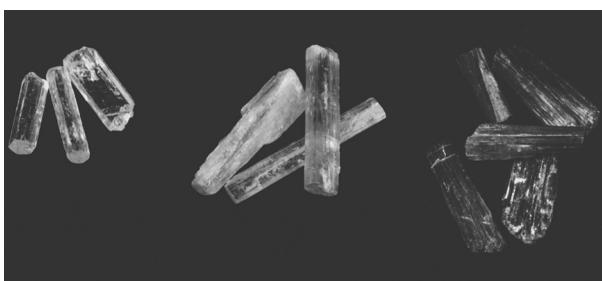
**PLATE 2.8** Herkimer diamonds (in reality, quartz crystals) from Herkimer, New York.



**PLATE 3.1** Pectolite from Patterson, New Jersey, showing radiating habit and scratch marks caused by students checking hardness.



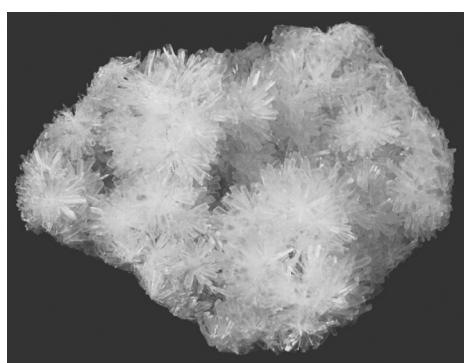
**PLATE 3.2** Actinolite from the Adirondack Mountains, New York, showing bladed habit.



**PLATE 3.3** Prismatic crystals: beryl from Nigeria (left); rubellite, a pink variety of tourmaline, from San Diego County, California (center); green tourmaline from Minas Gerais, Brazil (right).



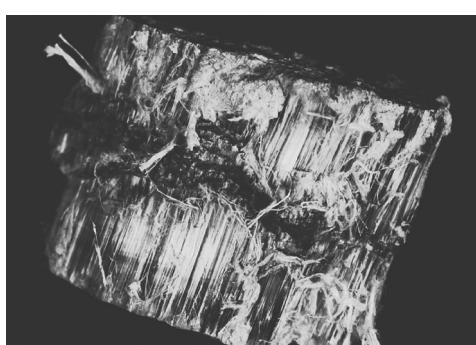
**PLATE 3.4** Fibrous anthophyllite from Gainesville, Georgia.



**PLATE 3.5** Green selenite, a variety of gypsum, from Mt. Gudson, South Australia.



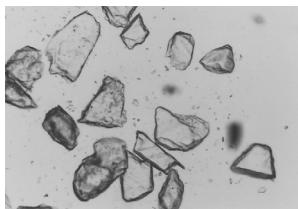
**PLATE 3.6** Bladed blue kyanite from Minas Gerais, Brazil.



**PLATE 3.7** Chrysotile, the asbestiform variety of serpentine, from Waldheim, Saxony.



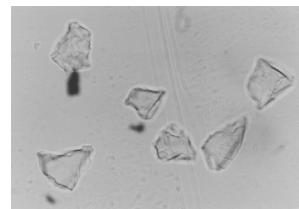
**PLATE 3.8** Calcite with drusy pyrite from the Campbell Mine, Red Lake, Ontario, Canada.



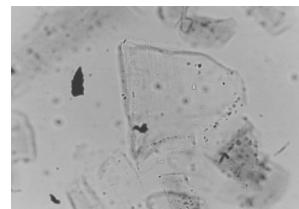
**PLATE 4.1** Fluorite showing strong relief in liquid with  $n=1.512$ .



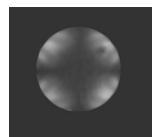
**PLATE 4.2** Fluorite showing weak relief in liquid with  $n=1.452$ .



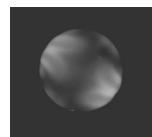
**PLATE 4.3** Fluorite in liquid with  $n=1.452$ ; the stage has been slightly lowered to show bright Becke line moving into the liquid.



**PLATE 4.4** Barite in liquid with  $n=1.636$ , nearly identical to that of barite.



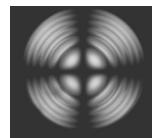
**PLATE 4.5** Olivine interference figure at extinction.



**PLATE 4.6** Olivine interference figure 15° from extinction.



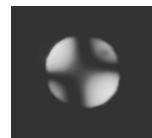
**PLATE 4.7** Olivine interference figure 45° from extinction.



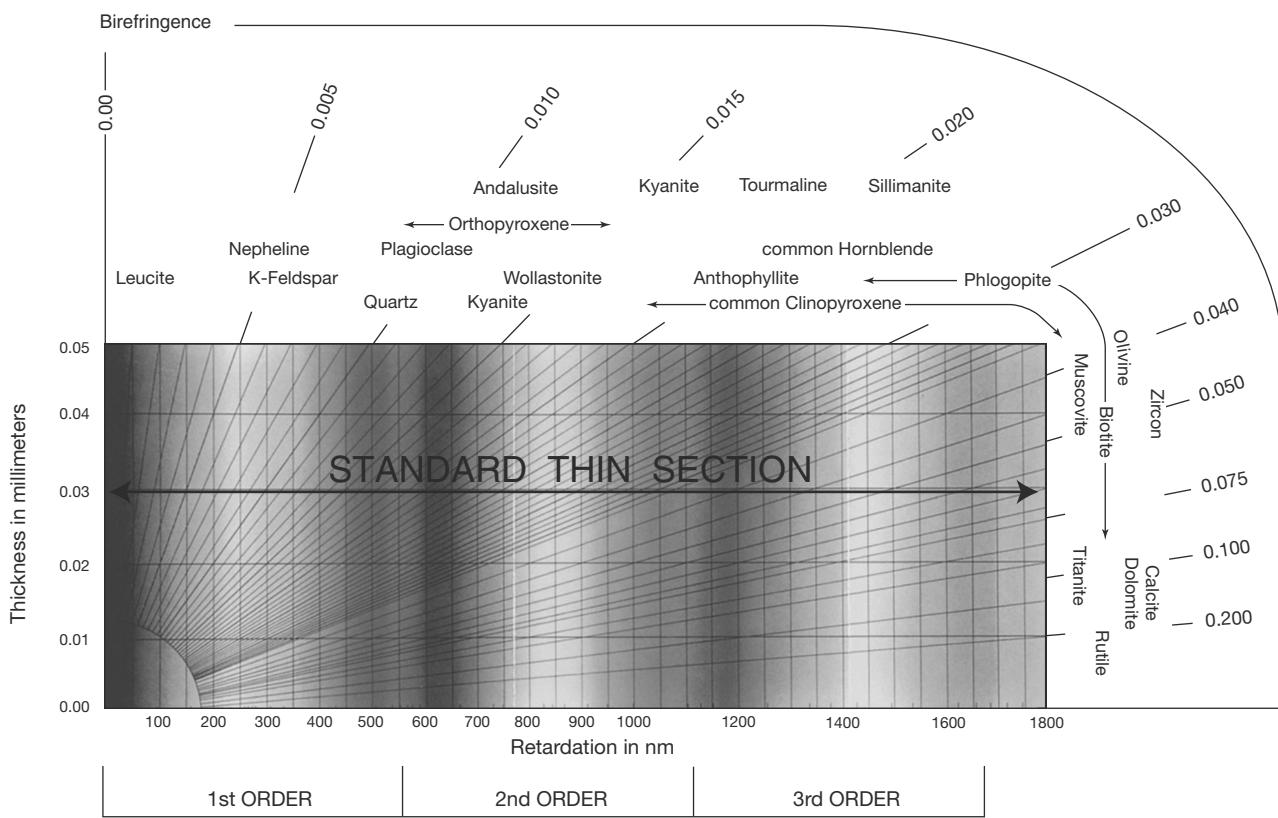
**PLATE 4.8** A nearly centered uniaxial interference figure exhibited by calcite.



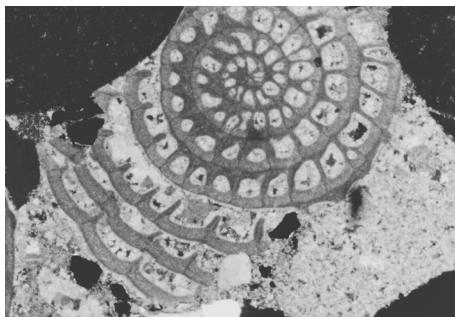
**PLATE 4.9** A nearly centered uniaxial interference figure exhibited by quartz.



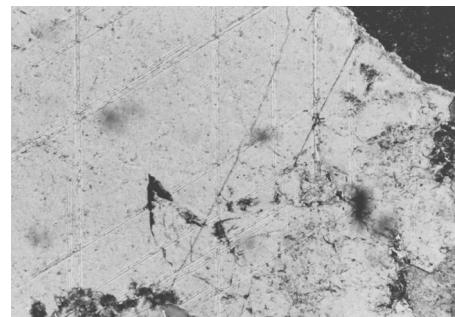
**PLATE 4.10** A nearly centered biaxial interference figure exhibited by biotite.



**PLATE 4.11** Michel Lévy Color Chart.



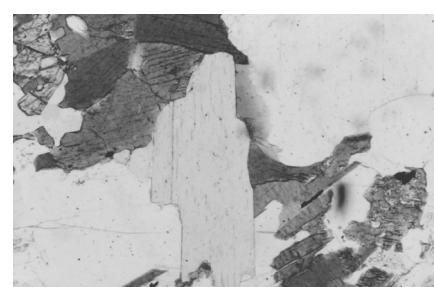
**PLATE 5.1** Thin section view of calcite replacing a foraminifera fossil.



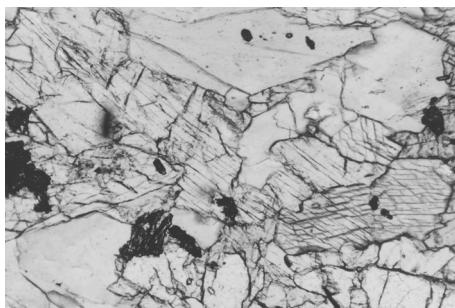
**PLATE 5.2** Calcite in thin section.



**PLATE 5.3** Thin section with brown biotite, green hornblende (with indistinct 60° cleavage), and clear quartz (PP light).



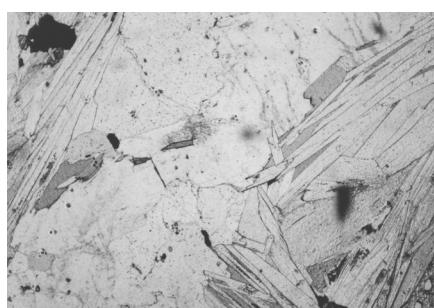
**PLATE 5.4** The same thin section as in Plate 5.3 after stage rotation; note pleochroism.



**PLATE 5.5** Sodic hornblende (blue to green with 60° cleavage), quartz (large, clear grains), chlorite (large, light green flake in top center of photo), and garnet (high-relief clear mineral in bottom center and right of photo) in thin section (PP light).



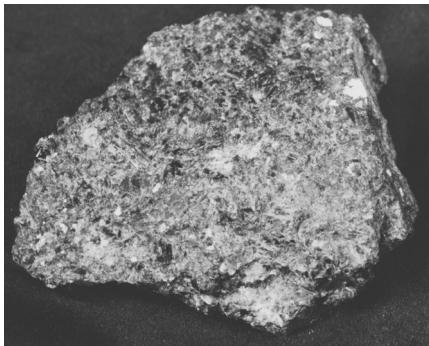
**PLATE 5.6** The same thin section as in Plate 5.5; yellow to pink interference colors in hornblende, undulatory extinction in quartz, anomalous gray interference colors in chlorite, opaque garnets (XP light).



**PLATE 5.7** Quartz, muscovite, biotite, and polysynthetically twinned plagioclase in thin section (PP light).



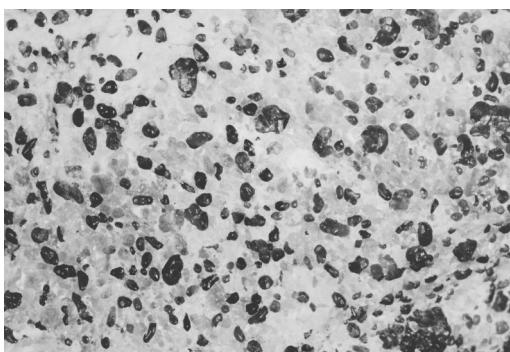
**PLATE 5.8** The same thin section as in Plate 5.7 (XP light).



**PLATE 6.1** Massive green-black augite from Monzoni, Italy.



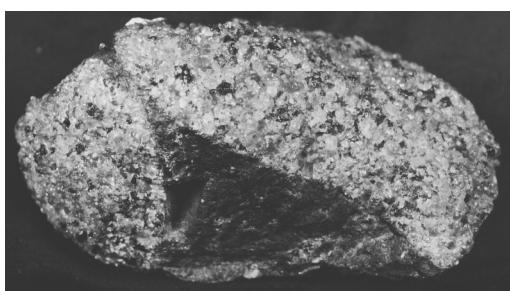
**PLATE 6.2** Chrome diopside (green) and quartz from Minas Gerais, Brazil.



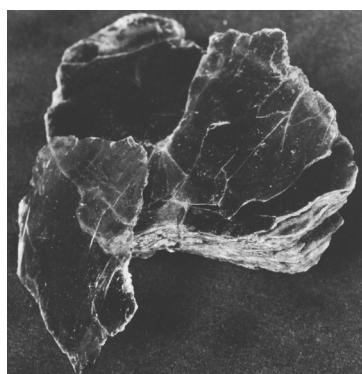
**PLATE 6.3** Marble from Lake Placid, New York, containing green diopside and white calcite.



**PLATE 6.4** Aggregate of hedenbergite crystals from Nordmarken, Sweden.



**PLATE 6.5** Green olivine crystals in a basalt from San Carlos, Arizona.



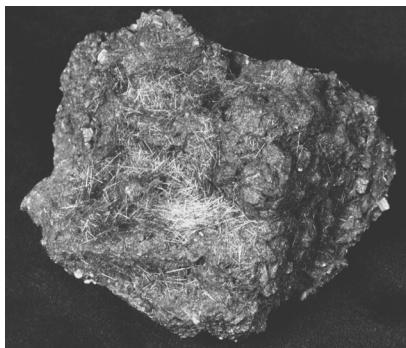
**PLATE 6.6** A book of biotite from Sioux Lookout, Ontario, Canada.



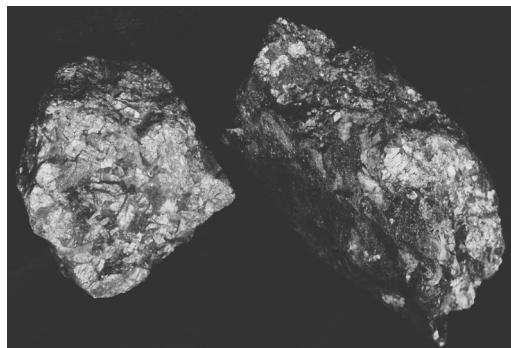
**PLATE 6.7** Perthite, a variety of K-feldspar, from Keystone, South Dakota.



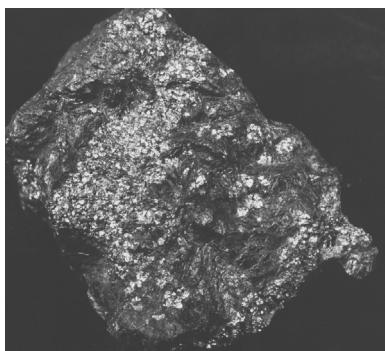
**PLATE 6.8** Albite from Amelia Courthouse, Virginia.



**PLATE 7.1** Acicular boulangerite from the Noche Buena Mine, Zacatecas, Mexico.



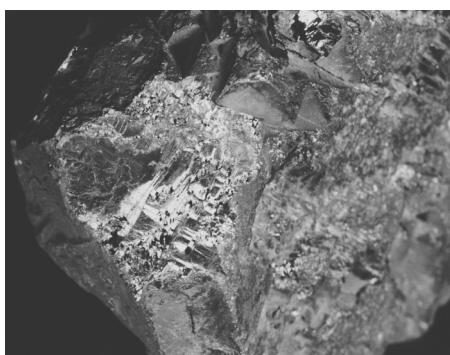
**PLATE 7.2** Arsenopyrite in a biotite schist from the Homestake Mine, Lead, South Dakota.



**PLATE 7.3** Covellite (purple tarnish) and pyrite (gold) from Sudbury, Ontario, Canada.



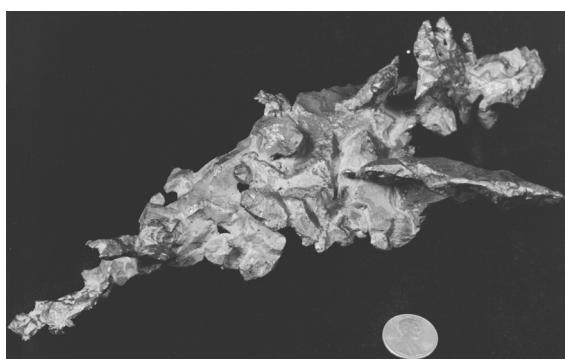
**PLATE 7.4** Sphalerite from Tennessee.



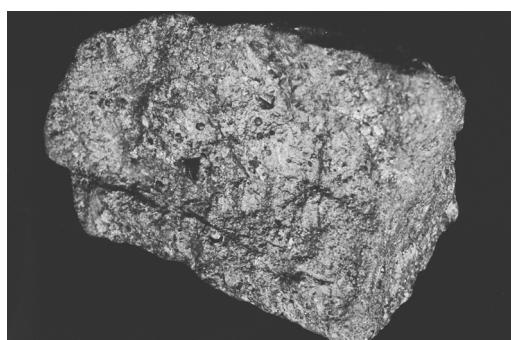
**PLATE 7.5** Galena in ore from Joplin, Missouri.



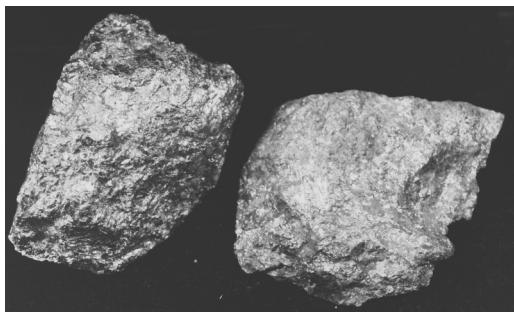
**PLATE 7.6** Orpiment (yellow) and realgar (orange-pink).



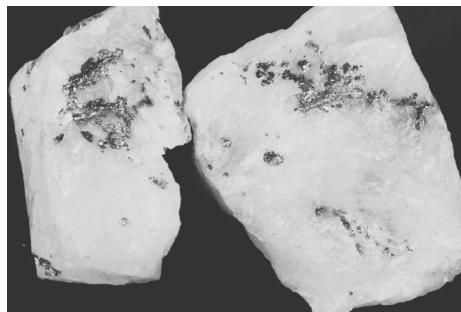
**PLATE 7.7** Native copper from the Keweenaw Peninsula, Michigan.



**PLATE 7.8** Chalcopyrite from Timmins, Ontario, Canada.



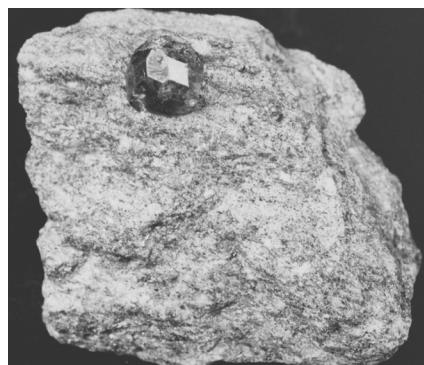
**PLATE 8.1** Pentlandite (silver) with minor pyrrhotite (yellow-gold) from Cobalt, Ontario, Canada.



**PLATE 8.2** Molybdenite in quartz.



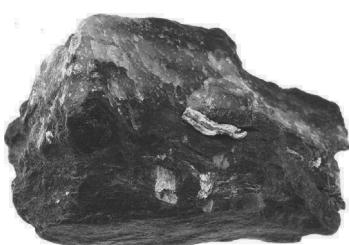
**PLATE 8.3** Amazonite, a gemmy blue variety of microcline (K-feldspar) from Norway.



**PLATE 8.4** Almandine in a schist from western Massachusetts.



**PLATE 8.5** A collection of gem minerals. Back row, left to right: blue aquamarine (beryl), topaz, pink tourmaline; middle row: yellow beryl, blue-green tourmaline, red ruby (corundum); front row: emerald (beryl), kunzite (a variety of spodumene), yellow sapphire, blue sapphire.



**PLATE 8.7** Gold ore from Montana. This specimen, 5 cm across, contains visible gold flakes, wires and stringers. It is exceptionally high-grade gold ore.



**PLATE 8.6** Drusy goethite crystals in cavities in iron formation from the Steep Rock Mine, Atikokan, Ontario, Canada.



**PLATE 8.8** Ipé Pegmatite Mine in Minas Gerais, Brazil.

# Descriptions of Minerals Color Plates



**PLATE 1.1** Tourmaline from Paraiba, Brazil, with colors showing compositional zonation.



**PLATE 1.3** Pyrite crystals with pyritohedron form showing growth striations on faces.



**PLATE 1.6** Celestite from Lime City, Ohio.



**PLATE 1.2** Smithsonite from Rush Creek, Arkansas, with colors showing compositional zonation.



**PLATE 1.5** Orthoclase from Petschau, Bohemia, showing penetration twins.



**PLATE 1.8** Botryoidal purple smithsonite from Choix, Mexico.



**PLATE 2.1** Rutile needles in quartz from Brazil showing conchoidal fractures.



**PLATE 2.2** Rose quartz from Custer, South Dakota.



**PLATE 2.3** Amethyst, a purple variety of quartz.



**PLATE 2.4** Quartz showing play of colors and internal reflection due to internal fractures.



**PLATE 2.5** Brown quartz from California.



**PLATE 2.6** Clear quartz crystals from Hot Springs, Arkansas, showing growth striations.



**PLATE 2.7** Prismatic quartz crystals on pyrite; sphalerite is the dark mineral behind the quartz crystals (sample from Huaron, Peru).



**PLATE 2.8** Herkimer diamonds (in reality, quartz crystals) from Herkimer, New York.



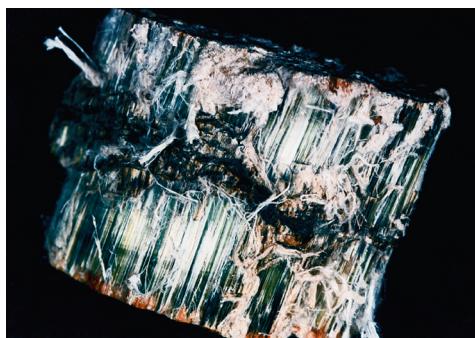
**PLATE 3.1** Pectolite from Patterson, New Jersey, showing radiating habit and scratch marks caused by students checking hardness.



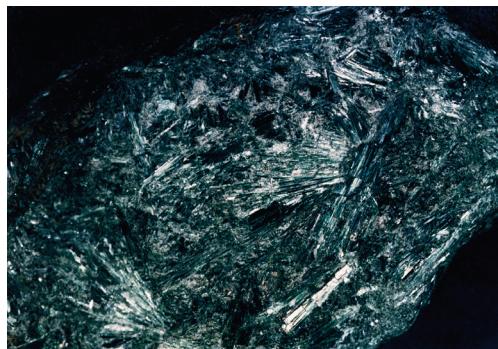
**PLATE 3.3** Prismatic crystals: beryl from Nigeria (left); rubellite, a pink variety of tourmaline, from San Diego County, California (center); green tourmaline from Minas Gerais, Brazil (right).



**PLATE 3.5** Green selenite, a variety of gypsum, from Mt. Gudson, South Australia.



**PLATE 3.7** Chrysotile, the asbestiform variety of serpentine, from Waldheim, Saxony.



**PLATE 3.2** Actinolite from the Adirondack Mountains, New York, showing bladed habit.



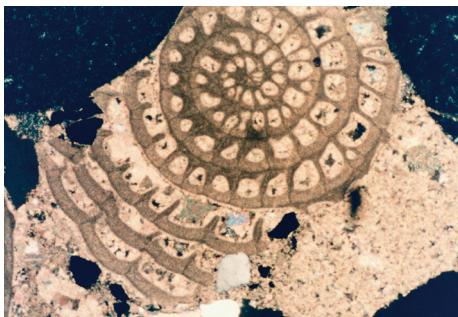
**PLATE 3.4** Fibrous anthophyllite from Gainesville, Georgia.



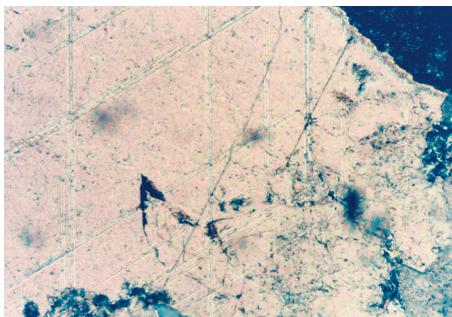
**PLATE 3.6** Bladed blue kyanite from Minas Gerais, Brazil.



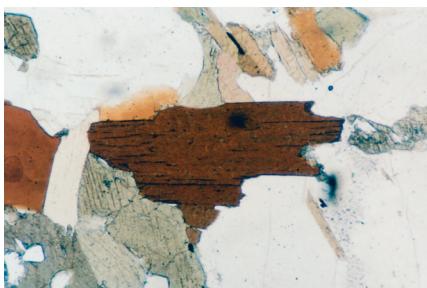
**PLATE 3.8** Calcite with drusy pyrite from the Campbell Mine, Red Lake, Ontario, Canada.



**PLATE 5.1** Thin section view of calcite replacing a foraminifera fossil.



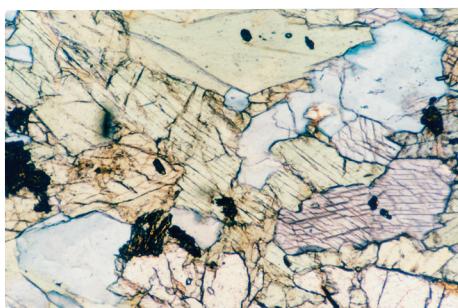
**PLATE 5.2** Calcite in thin section.



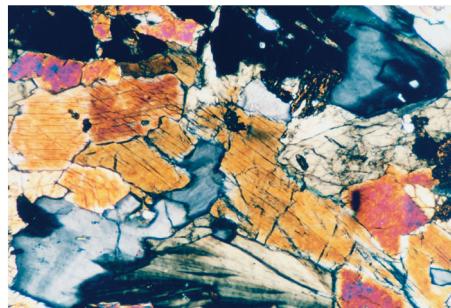
**PLATE 5.3** Thin section with brown biotite, green hornblende (with indistinct 60° cleavage), and clear quartz (PP light).



**PLATE 5.4** The same thin section as in Plate 5.3 after stage rotation; note pleochroism.



**PLATE 5.5** Sodic hornblende (blue to green with 60° cleavage), quartz (large, clear grains), chlorite (large, light green flake in top center of photo), and garnet (high-relief clear mineral in bottom center and right of photo) in thin section (PP light).



**PLATE 5.6** The same thin section as in Plate 5.5; yellow to pink interference colors in hornblende, undulatory extinction in quartz, anomalous gray interference colors in chlorite, opaque garnets (XP light).



**PLATE 5.7** Quartz, muscovite, biotite, and polysynthetically twinned plagioclase in thin section (PP light).



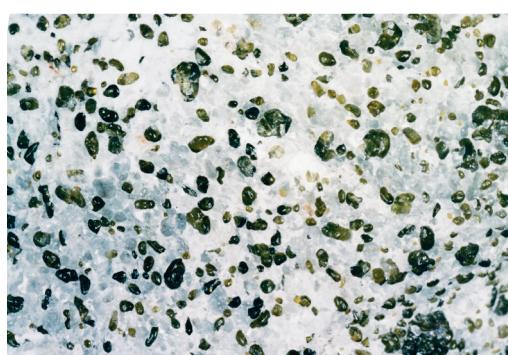
**PLATE 5.8** The same thin section as Plate 5.7 (XP light).



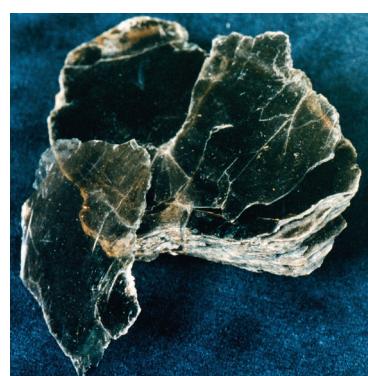
**PLATE 6.1** Massive green-black augite from Monzoni, Italy.



**PLATE 6.2** Chrome diopside (green) and quartz from Minas Gerais, Brazil.



**PLATE 6.3** Marble from Lake Placid, New York, containing green diopside and white calcite.



**PLATE 6.6** A book of biotite from Sioux Lookout, Ontario, Canada.



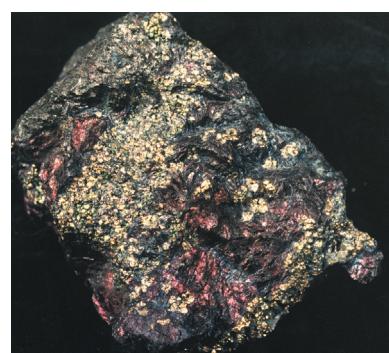
**PLATE 6.7** Perthite, a variety of K-feldspar, from Keystone, South Dakota.



**PLATE 6.8** Albite from Amelia Courthouse, Virginia.



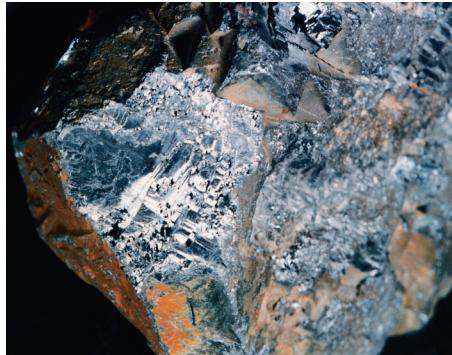
**PLATE 7.2** Arsenopyrite in a biotite schist from the Homestake Mine, Lead, South Dakota.



**PLATE 7.3** Covellite (purple tarnish) and pyrite (gold) from Sudbury, Ontario, Canada.



**PLATE 7.4** Sphalerite from Tennessee.



**PLATE 7.5** Galena in ore from Joplin, Missouri.



**PLATE 7.6** Orpiment (yellow) and realgar (orange-pink).



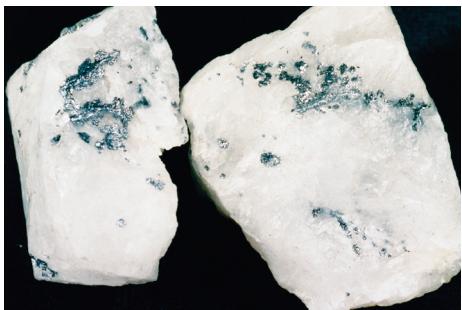
**PLATE 7.7** Native copper from the Keweenaw Peninsula, Michigan.



**PLATE 7.8** Chalcopyrite from Timmins, Ontario, Canada.



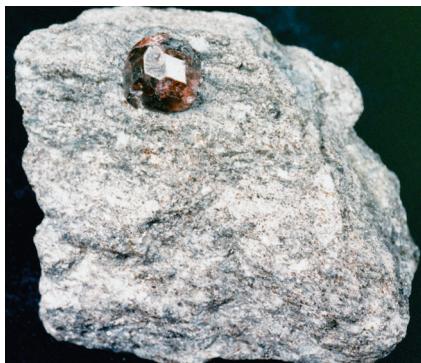
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**PLATE 8.6** Drusy goethite crystals in cavities in iron formation from the Steep Rock Mine, Atikokan, Ontario, Canada.



**PLATE 8.7** Gold ore from Montana. This specimen, 5 cm across, contains visible gold flakes, wires and stringers. It is exceptionally high-grade gold ore.

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# APPENDIX

## Classified List of Minerals

Class (Subclass)	Group	Series or Subgroup	Species	Chemical Formula
Silicate (Framework Silicates)	Silica Group		quartz cristobalite tridymite coesite stishovite	$\text{SiO}_2$ $\text{SiO}_2$ $\text{SiO}_2$ $\text{SiO}_2$ $\text{SiO}_2$
	Feldspar Group	Potassium Feldspars	orthoclase sanidine microcline	$\text{KAlSi}_3\text{O}_8$ $(\text{K}, \text{Na})\text{AlSi}_3\text{O}_8$ $\text{KAlSi}_3\text{O}_8$
		Plagioclase Feldspar Series	albite anorthite	$\text{NaAlSi}_3\text{O}_8$ $\text{CaAl}_2\text{Si}_2\text{O}_8$
	Feldspathoid Group		analcime leucite nepheline	$\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$ $\text{KAlSi}_2\text{O}_6$ $(\text{Na}, \text{K})\text{AlSiO}_4$
	Scapolite Group	Scapolite Series	marialite meionite	$\text{Na}_4(\text{AlSi}_3\text{O}_8)_3\text{Cl}$ $\text{Ca}_4(\text{Al}_2\text{Si}_2\text{O}_8)_3(\text{CO}_3, \text{SO}_4)$
	Zeolite Group		natrolite chabazite heulandite stilbite sodalite	$\text{Na}_2\text{Al}_2\text{Si}_3\text{O}_{10} \cdot 2\text{H}_2\text{O}$ $\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 6\text{H}_2\text{O}$ $\text{CaAl}_2\text{Si}_7\text{O}_{18} \cdot 6\text{H}_2\text{O}$ $\text{CaAl}_2\text{Si}_7\text{O}_{18} \cdot 7\text{H}_2\text{O}$ $\text{Na}_3\text{Al}_3\text{Si}_3\text{O}_{12} \cdot \text{NaCl}$
	Other		beryl cordierite	$\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$ $(\text{Mg}, \text{Fe})_2\text{Al}_4\text{Si}_5\text{O}_{18}$
Silicate (Sheet Silicates)	Serpentine Group	Serpentine Minerals	antigorite chrysotile lizardite	$\text{Mg}_6\text{Si}_4\text{O}_{10}(\text{OH})_8$ $\text{Mg}_6\text{Si}_4\text{O}_{10}(\text{OH})_8$ $\text{Mg}_6\text{Si}_4\text{O}_{10}(\text{OH})_8$
	Clay Mineral Group	Smectite Subgroup	montmorillonite	$(\text{Ca}, \text{Na})_{0.2-0.4}(\text{Al}, \text{Mg}, \text{Fe})_2(\text{Si}, \text{Al})_4\text{O}_{10}(\text{OH})_2 \cdot n\text{H}_2\text{O}$
		Illite Subgroup	illite	micalike clay of variable composition
		Other Clays	kaolinite pyrophyllite talc	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$ $\text{Al}_2\text{Si}_4\text{O}_{10}(\text{OH})_2$ $\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$
	Mica Group	Biotite Series	phlogopite annite	$\text{KMg}_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ $\text{KFe}_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$
		Other Micas	muscovite margarite paragonite lepidolite	$\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ $\text{CaAl}_2(\text{Al}_2\text{Si}_2\text{O}_{10})(\text{OH})_2$ $\text{NaAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ $\text{K}(\text{Li}, \text{Al})_{2-3}(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$
	Chlorite Group		chlorite	variable combinations of talc + brucite
Other Sheet Silicates		prehnite	$\text{Ca}_2\text{Al}(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$	
		sepiolite	$\text{Mg}_4\text{Si}_6\text{O}_{15}(\text{OH})_2 \cdot 6\text{H}_2\text{O}$	
		apophyllite	$\text{KCa}_4\text{Si}_8\text{O}_{20}\text{F} \cdot 8\text{H}_2\text{O}$	

Appendix

<b>Class (Subclass)</b>	<b>Group</b>	<b>Series or Subgroup</b>	<b>Species</b>	<b>Chemical Formula</b>
Silicate (Chain Silicates)	Pyroxene Group	Orthopyroxene (Hypersthene Series)	enstatite ferrosilite	$Mg_2Si_2O_6$ $Fe_2Si_2O_6$
		Clinopyroxene (Diopside-Hedenbergite Series)	diopside hedenbergite	$CaMgSi_2O_6$ $CaFeSi_2O_6$
		Other Clinopyroxenes	pigeonite augite jadeite spodumene	$(Ca,Mg,Fe)_2Si_2O_6$ $(Ca,Mg,Fe,Na)(Mg,Fe,Al)(Si,Al)_2O_6$ $NaAlSi_2O_6$ $LiAlSi_2O_6$
		Cummingtonite Series	cummingtonite grunerite	$(Mg,Fe)_7Si_8O_{22}(OH)_2$ $Fe_7Si_8O_{22}(OH)_2$
	Amphibole Group	Tremolite Series	tremolite actinolite	$Ca_2Mg_5Si_8O_{22}(OH)_2$ $Ca_2(Fe,Mg)_5Si_8O_{22}(OH)_2$
		Other	anthophyllite glaucophane hornblende kaersutite	$(Mg,Fe)_7Si_8O_{22}(OH)_2$ $Na_2Mg_3Al_2Si_8O_{22}(OH)_2$ $(K,Na)_{0-1}(Ca,Na,Fe,Mg)_2(Mg,Fe,Al)_5(Si,Al)_8O_{22}(OH)_2$ Ti-rich hornblende
		Pyroxenoid Group	wollastonite rhodonite pectolite	$CaSiO_3$ $MnSiO_3$ $NaCa_2(SiO_3)_3H$
Silicate (Ring Silicates)	Melilite Group		gehlenite åkermanite	$Ca_2Al_2SiO_7$ $Ca_2MgSi_2O_7$
		Other	tourmaline	$(Na,Ca)(Fe,Mg,Al,Li)_3Al_6(BO_3)_3Si_6O_{18}(OH)_4$
Silicate (Isolated Tetrahedral Silicates)	Garnet Group	Pyralspite Series	pyrope almandine spessartine	$Mg_3Al_2Si_3O_{12}$ $Fe_3Al_2Si_3O_{12}$ $Mn_3Al_2Si_3O_{12}$
		Ugrandite Series	uvarovite grossular andradite	$Ca_3Cr_2Si_3O_{12}$ $Ca_3Al_2Si_3O_{12}$ $Ca_3Fe_2Si_3O_{12}$
		Olivine Series	forsterite fayalite	$Mg_2SiO_4$ $Fe_2SiO_4$
		Other	monticellite	$CaMgSiO_4$
	Humite Group		norbergite chondrodite humite clinohumite	$Mg_3SiO_4(OH,F)_2$ $Mg_5(SiO_4)_2(OH,F)_2$ $Mg_7(SiO_4)_3(OH,F)_2$ $Mg_9(SiO_4)_4(OH,F)_2$
	Aluminosilicate Group		kyanite andalusite sillimanite	$Al_2SiO_5$ $Al_2SiO_5$ $Al_2SiO_5$
Other Isolated Tetrahedral Silicates		staurolite chloritoid titanite (sphene) topaz zircon		$FeAl_9Si_4O_{23}(OH)$ $(Fe,Mg)Al_2SiO_5(OH)_2$ $CaTiSiO_5$ $Al_2SiO_4(F,OH)_2$ $ZrSiO_4$
Silicate (Paired Tetrahedral Silicates)	Lawsonite Group		lawsonite	$CaAl_2Si_2O_7(OH)_2 \cdot H_2O$
	Epidote Group		epidote clinozoisite	$Ca_2(Al,Fe)_3Si_3O_{12}(OH)$ $Ca_2Al_3Si_3O_{12}(OH)$
	Other Paired Tetrahedral Silicates		vesuvianite	$Ca_{10}(Mg,Fe)_2Al_4Si_9O_{34}(OH)_4$

Class (Subclass)	Group	Series or Subgroup	Species	Chemical Formula
Native Element	Native Metal Group	gold	Au	
		silver	Ag	
		platinum	Pt	
	Native Semimetal Group	copper	Cu	
		arsenic	As	
		antimony	Sb	
	Native Nonmetal Group	bismuth	Bi	
		diamond	C	
		graphite	C	
		sulfur	S	
Sulfide	Tetrahedral Sulfide Group	chalcopyrite	CuFeS <sub>2</sub>	
		bornite	Cu <sub>5</sub> FeS <sub>4</sub>	
		enargite	Cu <sub>3</sub> AsS <sub>4</sub>	
		wurtzite	ZnS	
		sphalerite	ZnS	
	Octahedral Sulfide Group	galena	PbS	
		pyrrhotite	Fe <sub>1-x</sub> S	
		niccolite	NiAs	
	Mixed Sulfide Group	pentlandite	(Ni,Fe) <sub>9</sub> S <sub>8</sub>	
Sulfides, Arsenides, and Sulfosalts	Sulfides	molybdenite	MoS <sub>2</sub>	
		millerite	NiS	
		cinnabar	HgS	
		covellite	CuS	
		chalcocite	Cu <sub>2</sub> S	
		argentite	Ag <sub>2</sub> S	
		pyrite	FeS <sub>2</sub>	
		cobaltite	(Co,Fe)AsS	
		marcasite	FeS <sub>2</sub>	
	Arsenides and Sulfosalts	arsenopyrite	FeAsS	
		sutterudite	(Co,Ni)As <sub>3</sub>	
		stibnite	Sb <sub>2</sub> S <sub>3</sub>	
		boulangerite	Pb <sub>5</sub> Sb <sub>4</sub> S <sub>11</sub>	
		tetrahedrite	Cu <sub>12</sub> Sb <sub>4</sub> S <sub>13</sub>	
		proustite	Ag <sub>3</sub> AsS <sub>3</sub>	
		pyrargyrite	Ag <sub>3</sub> SbS <sub>3</sub>	
Halide		orpiment	As <sub>2</sub> S <sub>3</sub>	
		realgar	AsS	
		halite	NaCl	
		sylvite	KCl	
		chlorargerite	AgCl	
		atacamite	Cu <sub>2</sub> Cl(OH) <sub>3</sub>	
		carnallite	KMgCl <sub>3</sub> •6H <sub>2</sub> O	
Oxide	Tetrahedral Oxide Group	fluorite	CaF <sub>2</sub>	
		cryolite	Na <sub>3</sub> AlF <sub>6</sub>	
	Octahedral Oxide Group	zincite	ZnO	
		anatase	TiO <sub>2</sub>	
		rutile	TiO <sub>2</sub>	
	Other Octahedral Oxides	brookite	TiO <sub>2</sub>	
		periclase	MgO	
		hematite	Fe <sub>2</sub> O <sub>3</sub>	
		corundum	Al <sub>2</sub> O <sub>3</sub>	
		ilmenite	FeTiO <sub>3</sub>	

Appendix

<b>Class (Subclass)</b>	<b>Group</b>	<b>Series or Subgroup</b>	<b>Species</b>	<b>Chemical Formula</b>
			cassiterite pyrolusite columbite tantalite	$\text{SnO}_2$ $\text{MnO}_2$ $(\text{Fe}, \text{Mn})\text{Nb}_2\text{O}_6$ $(\text{Fe}, \text{Mn})\text{Ta}_2\text{O}_6$
	Spinel Group	"Inverse" Spinels	spinel magnetite	$\text{MgAl}_2\text{O}_4$ $\text{Fe}_3\text{O}_4$
		"Normal" Spinels	chromite franklinite	$\text{FeCr}_2\text{O}_4$ $\text{ZnFe}_2\text{O}_4$
	Cubic Oxides		uraninite	$\text{UO}_2$
	Other Oxides		chrysoberyl perovskite cuprite	$\text{BeAl}_2\text{O}_4$ $\text{CaTiO}_3$ $\text{Cu}_2\text{O}$
Hydroxide			gibbsite brucite manganite goethite diaspore lepidocrocite romanechite	$\text{Al}(\text{OH})_3$ $\text{Mg}(\text{OH})_2$ $\text{MnO}(\text{OH})$ $\text{FeO}(\text{OH})$ $\text{AlO}(\text{OH})$ $\text{FeO}(\text{OH})$ $\text{BaMn}_9\text{O}_{16}(\text{OH})_4$
Carbonate and Nitrate	Calcite Group		calcite magnesite siderite rhodochrosite smithsonite	$\text{CaCO}_3$ $\text{MgCO}_3$ $\text{FeCO}_3$ $\text{MnCO}_3$ $\text{ZnCO}_3$
	Dolomite Group		dolomite ankerite	$\text{CaMg}(\text{CO}_3)_2$ $\text{CaFe}(\text{CO}_3)_2$
	Aragonite Group		aronite witherite strontianite cerussite	$\text{CaCO}_3$ $\text{BaCO}_3$ $\text{SrCO}_3$ $\text{PbCO}_3$
	Other Carbonates		malachite azurite trona	$\text{Cu}_2\text{CO}_3(\text{OH})_2$ $\text{Cu}_3(\text{CO}_3)_2(\text{OH})_2$ $\text{Na}_3\text{H}(\text{CO}_3)_2 \cdot 2\text{H}_2\text{O}$
	Nitrate Group		nitratite niter	$\text{NaNO}_3$ $\text{KNO}_3$
Borate	Anyhdrous Borate Group		boracite sinhalite	$\text{Mg}_3\text{ClB}_7\text{O}_{13}$ $\text{MgAlBO}_4$
	Hydrous Borate Group		borax kernite ulexite colemanite	$\text{Na}_2\text{B}_4\text{O}_5(\text{OH})_4 \cdot 8\text{H}_2\text{O}$ $\text{Na}_2\text{B}_4\text{O}_6(\text{OH})_2 \cdot 3\text{H}_2\text{O}$ $\text{NaCaB}_5\text{O}_6(\text{OH})_6 \cdot 5\text{H}_2\text{O}$ $\text{CaB}_3\text{O}_4(\text{OH})_3 \cdot \text{H}_2\text{O}$
Sulfate	Anhydrous Sulfate Group		anhydrite barite celestite anglesite	$\text{CaSO}_4$ $\text{BaSO}_4$ $\text{SrSO}_4$ $\text{PbSO}_4$
	Hydrous Sulfate Group		gypsum chalcanthite epsomite antlerite alunite	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ $\text{Cu}_3\text{SO}_4(\text{OH})_4$ $\text{KAl}_3(\text{SO}_4)_2(\text{OH})_6$

<b>Class (Subclass)</b>	<b>Group</b>	<b>Series or Subgroup</b>	<b>Species</b>	<b>Chemical Formula</b>
Chromate, Tungstate, and Molybdate	Tungstate Group	Wolframite Series	huebnerite ferberite	$\text{MnWO}_4$ $\text{FeWO}_4$
		Other Tungstates	scheelite	$\text{CaWO}_4$
	Molybdate Group		wulfenite powellite	$\text{PbMoO}_4$ $\text{Ca}(\text{Mo}, \text{W})\text{O}_4$
	Chromate Group		crocoite	$\text{PbCrO}_4$
Phosphate, Arsenate, and Vanadate	Phosphate Group		monazite triphylite apatite pyromorphite amblygonite lazulite wavellite vivianite variscite turquoise autunite	$(\text{Ce}, \text{La}, \text{Th}, \text{Y})\text{PO}_4$ $\text{Li}(\text{Fe}, \text{Mn})\text{PO}_4$ $\text{Ca}_5(\text{PO}_4)_3(\text{OH}, \text{F}, \text{Cl})$ $\text{Pb}_5(\text{PO}_4)_3\text{Cl}$ $\text{LiAl}(\text{PO}_4)\text{F}$ $(\text{Mg}, \text{Fe})\text{Al}_2(\text{PO}_4)_2(\text{OH})_2$ $\text{Al}_3(\text{PO}_4)_2(\text{OH})_3 \cdot 5\text{H}_2\text{O}$ $\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$ $\text{AlPO}_4 \cdot 2\text{H}_2\text{O}$ $\text{CuAl}_6(\text{PO}_4)_4(\text{OH})_8 \cdot 4\text{H}_2\text{O}$ $\text{Ca}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 10\text{H}_2\text{O}$
	Vanadate Group		vanadinite carnotite	$\text{Pb}_5(\text{VO}_4)_3\text{Cl}$ $\text{K}_2(\text{UO}_2)_2(\text{VO}_4)_2 \cdot 3\text{H}_2\text{O}$
	Arsenate Group		erythrite scorodite	$\text{Co}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$ $\text{FeAsO}_4 \cdot 4\text{H}_2\text{O}$

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# APPENDIX

## Mineral Identification Tables

This appendix contains tables that can be used to help identify unknown minerals in hand specimen. For the sake of being complete, we have included a few commonly used unaccredited mineral names, and some common nonminerals that have mineral-like properties. The names of the most common minerals are in bold print. The tables do not include information on many extremely rare or uncommon minerals. To identify one of those, you will have to use other reference books or rely on optical, X-ray diffraction, or other sophisticated methods to make identification.

The identification process is keyed to two physical properties that normally can be determined with minimal equipment: luster and hardness. First you must decide whether the unknown mineral has metallic or nonmetallic luster. This question is not always answered unambiguously. For example, graphite is not considered to be a metal. However, most mineralogists consider graphite to have a metallic luster. Other minerals, such as muscovite, have pearly or vitreous lusters, which may be misinterpreted as metallic. Because some submetallic minerals are difficult to classify as metallic or nonmetallic, these minerals have been placed on both the metallic and nonmetallic lists.

After determining the luster of an unknown mineral, you reduce the list of possible minerals by comparing the hardness of the unknown mineral to three common reference materials: an American copper penny (Mohs' hardness scale of 3), a glass slide (5.5), and quartz (7). Relative hardness may be difficult to determine if the unknown mineral has a value that is close to one of the reference materials or if it cleaves or fractures easily. In addition, some minerals have a range of possible hardness values. For these reasons, some minerals appear in more than one of the tables.

Tables 1 to 7 consist of six or seven columns. The data given for a mineral include hardness, name, chemical formula, color, the mineral's environment (where it is found), and miscellaneous remarks that describe its properties. Metallic minerals also have a column for their streak color. The streak color of

nonmetallic minerals is often white or nonexistent, especially for the harder minerals, and so is omitted. The hardness of the minerals is based on the traditional 1–10 Mohs' scale. Several minerals have a range of possible hardness values. The names of the minerals may include British spellings or other common variations, which are listed in parentheses.

The environment column lists the possible rock and sediment types where a particular mineral *may* be found. Typically, however, only a small minority of a particular rock or sediment type will contain the mineral in question. Even if they do contain the mineral, it may be present as a **minor mineral**, or an **accessory mineral**. For example, gold is listed as occurring in placer deposits (river and stream sediments), but the vast majority of river and stream sediments do not contain gold. Even when it is present, gold is rarely visible until the ore has been concentrated. Some minerals are **essential minerals**, and therefore **major minerals**; these are, in particular, rock or sediment types, by definition. For example, pyroxenites mostly consist of pyroxenes, and granites always contain major amounts of quartz and K-feldspar.

The remarks section contains information on the properties of the mineral and other comments that may be useful for identification. Properties listed in this column include: luster, magnetism, radioactivity, density, cleavage, crystal form, flame color, fluorescence, and solubility in water and acids.

The remarks sections of the tables also contain words of caution about radioactive or potentially poisonous minerals. In most cases, radioactive minerals are not harmful, but storing large volumes of uraninite or other radioactive minerals in small, unventilated areas may generate significant amounts of radiation and radon gas, which may be undesirable.

Although taste is often useful in identifying many salts and other minerals, *avoid tasting minerals or breathing the fumes of minerals that have been heated or dissolved in acids*. Besides possibly being toxic or radioactive, minerals may also have germs or parasites that could be harmful if ingested.

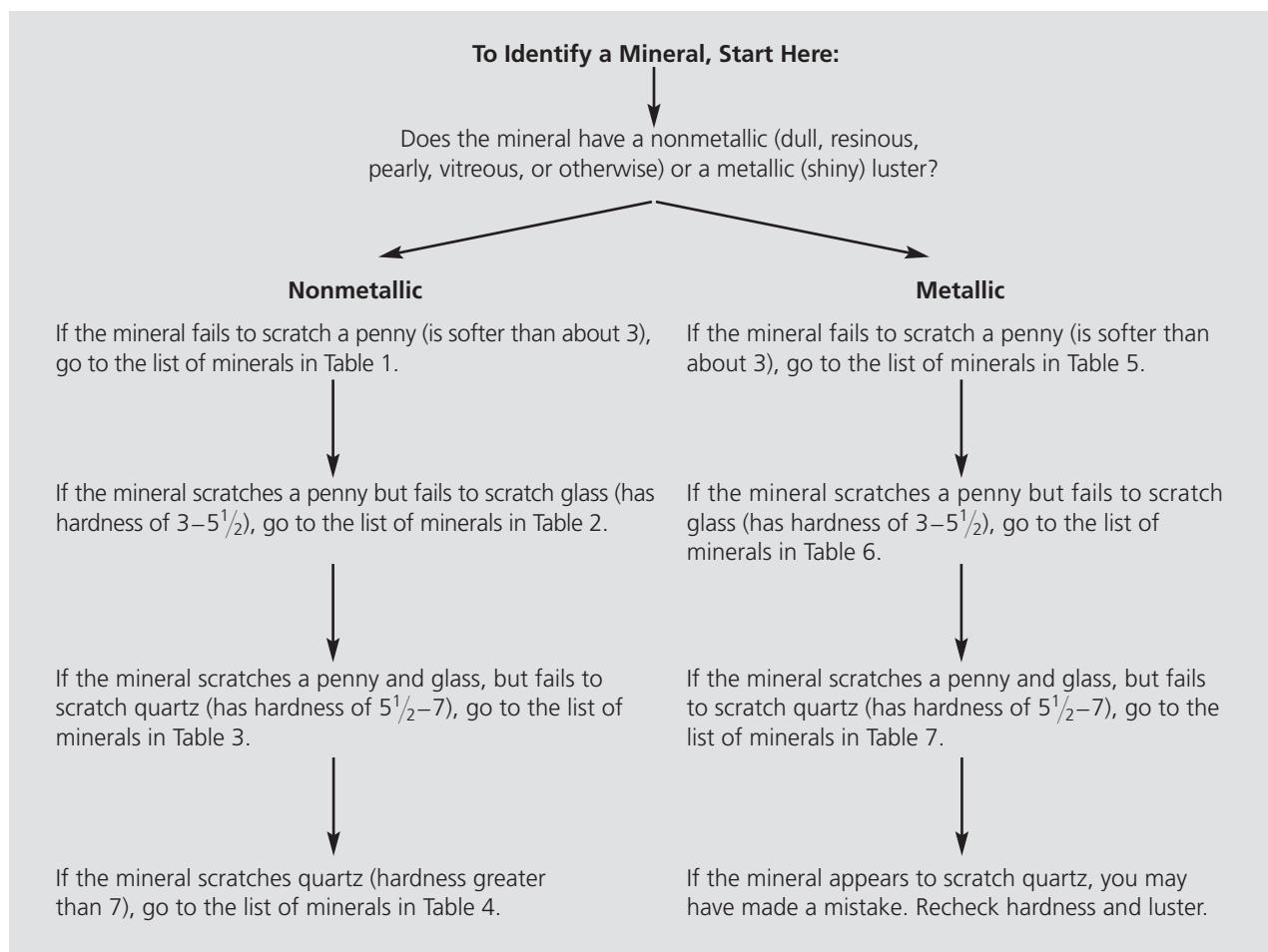
## Resources

(See also the general references listed at the end of Chapter 1.)

Blatt, H., G. Middleton, and R. Murray. *Origin of Sedimentary Rocks*, 2nd ed., Englewood Cliffs, N.J.: Prentice-Hall, 1986.

Heinrich, E. W. *Microscopic Identification of Minerals*. New York: McGraw-Hill, 1965.

Prinz, M., G. Harlow, and J. Peters. *Guide to Rocks and Minerals*, New York: Simon and Schuster, 1978.

**TABLE 1** Minerals with a Nonmetallic Luster and Hardness of Less Than 3

Name	Formula	Hardness	Color	Environment
Annabergite	$\text{Ni}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$	2½–3	Green	Alteration of nickel deposits
<i>Remarks: Possibly poisonous; do not taste, heat, or place in acids; vitreous to opaque luster; often radiating crystals</i>				
Aurichalcite	$(\text{Zn}, \text{Cu})_5(\text{CO}_3)_2(\text{OH})_3$	2	Green or blue	Oxidation of copper and zinc deposits
<i>Remarks: Pearly luster; effervesces in dilute hydrochloric acid; very light blue-green streak</i>				
Autunite	$\text{Ca}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 12\text{H}_2\text{O}$	2–2½	Yellowish green	Oxidation and weathering of uranium deposits
<i>Remarks: Radioactive; vitreous luster; yellow streak; strongly fluoresces yellowish green in ultraviolet light; soluble in most acids</i>				
Biotite	$\text{K}(\text{Mg}, \text{Fe})_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$	2½–3	Black-brown	Schists; intrusive granitic rocks; some felsic volcanics; sometimes in intermediate and mafic intrusives
<i>Remarks: Mica; platy mineral that peels off in "sheets"; pearly or vitreous luster</i>				
Borax	$\text{Na}_2\text{B}_4\text{O}_5(\text{OH})_4 \cdot 8\text{H}_2\text{O}$	2–2½	White to colorless	Arid lake deposits
<i>Remarks: Vitreous luster; soluble in water; white streak</i>				

**TABLE 1 Minerals with a Nonmetallic Luster and Hardness of Less Than 3 (continued)**

<b>Brucite</b>	Mg(OH) <sub>2</sub>	2½	White, gray, or light green	Serpentine; talc schists; chlorite schists; some marbles
<i>Remarks:</i> Pearly, waxy, or vitreous luster; dissolves in many cold dilute acids without effervescence				
Carnallite	KMgCl <sub>3</sub> •6H <sub>2</sub> O	1	Colorless or red	Evaporites
<i>Remarks:</i> Deliquescent; conchoidal fracture; vitreous or greasy luster; phosphorescent; very water soluble; lightweight.				
<b>Carnotite</b>	K <sub>2</sub> (UO <sub>2</sub> ) <sub>2</sub> (VO <sub>4</sub> ) <sub>2</sub> •3H <sub>2</sub> O	1	Bright yellow	Groundwater alteration of uranium and vanadium deposits; sometimes found in sandstones and petrified "wood"
<i>Remarks:</i> Radioactive; dull or earthy luster				
Cerargyrite	AgCl	2–3	Gray to colorless	Silver deposits
<i>Remarks:</i> Transparent to translucent; hornlike shape; fresh surface rapidly darkens to violet-brown when exposed to light				
Chalcanthite	CuSO <sub>4</sub> •5H <sub>2</sub> O	2.5	Sky blue	Oxidized zones of copper deposits
<i>Remarks:</i> Water soluble; conchoidal fracture; vitreous luster; transparent to translucent				
<b>Chlorite</b>	variable combinations of talc+brucite	2–2½	Greenish	Low-grade metamorphics, including metabasalts and many schists; shales
<i>Remarks:</i> Mica; vitreous or pearly luster; platy cleavage like other micas				
<b>Chrysocolla</b>	approx. Cu <sub>4</sub> H <sub>4</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>8</sub>	2–4	Bluish green	Oxidation of copper deposits
<i>Remarks:</i> Vitreous to greasy luster; decomposes in hydrochloric acid; produces green flame				
<b>Cinnabar</b>	HgS	2½	Red	Mercury deposits associated with volcanics and hot springs
<i>Remarks:</i> Do not heat, will release poisonous mercury vapors; also do not taste or dissolve in acids in unventilated areas; scarlet streak; high specific gravity (8.1)				
Crocoite	PbCrO <sub>4</sub>	2½–3	Orange red	Oxidized deposits containing lead and chromium
<i>Remarks:</i> Possibly poisonous; do not taste, heat, or dissolve in acids; adamantine luster; orange yellow streak				
<b>Cryolite</b>	Na <sub>3</sub> AlF <sub>6</sub>	2½	White to colorless	Granitic pegmatites
<i>Remarks:</i> Vitreous to pearly luster; because of refractive index, almost disappears in water; white streak				
Epsomite	MgSO <sub>4</sub> •7H <sub>2</sub> O	2–2½	White to colorless	Hydrothermal deposits
<i>Remarks:</i> "Epsom salts"; effloresces; forms crusts on walls; vitreous to silky appearance; dissolves in water; lightweight				
Erythrite	Co <sub>3</sub> (AsO <sub>4</sub> ) <sub>2</sub> •8H <sub>2</sub> O	1½–2½	Pink	Oxidation of cobalt arsenide deposits
<i>Remarks:</i> Possibly poisonous; do not taste or heat; adamantine to vitreous luster; acicular crystals; red streak; dissolves and produces red solution in hydrochloric acid; do not breathe any vapors!				
<b>Gibbsite</b>	Al(OH) <sub>3</sub>	2½–3½	Colorless to gray	Bauxite; laterite (a tropical soil)
<i>Remarks:</i> Sometimes red; radial or fine-grained texture; earthy luster				
Glaconite	(K,Na,Ca) <sub>0.5–1</sub> (Fe,Al,-Mg) <sub>2</sub> (Si,Al) <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub> •nH <sub>2</sub> O	2	Green	Marine sands and sandstones
<i>Remarks:</i> Often spherical; earthy or greasy luster				
<b>Gypsum</b>	CaSO <sub>4</sub> •2H <sub>2</sub> O	2	White, gray, or colorless	Evaporites; hydrothermal deposits
<i>Remarks:</i> Vitreous or silky luster; transparent to translucent; as hardness suggests, can be scratched with a fingernail; clear variety is called selenite, which should not be confused with the selenium ion with the same name				
<b>Halite</b>	NaCl	2½	Typically white	Evaporites
<i>Remarks:</i> "Table salt"; cubic crystals; translucent to transparent; dissolves in water; avoid tasting any mineral, including this one				

**TABLE 1 Minerals with a Nonmetallic Luster and Hardness of Less Than 3 (continued)**

<b>Hydrozincite</b>	$Zn_5(CO_3)_2(OH)_6$	$2-2\frac{1}{2}$	Gray or white	Oxidation of zinc deposits
<i>Remarks:</i> Earthy or vitreous masses or crusts; sometimes fibrous or stalactites; white streak; soluble in hydrochloric acid				
<b>Kaolinite</b>	$Al_2Si_2O_5(OH)_4$	2	Usually white	Common clay in humid climates
<i>Remarks:</i> Clay; earthy luster; plastic when wet; insoluble in water; often difficult to distinguish from other clays without sophisticated analytical techniques				
<b>Lepidolite</b>	$K(Li,Al)_{2-3}(AlSi_3O_{10})(OH)_2$	$2\frac{1}{2}-4$	Pink to grayish white	Lithium pegmatites
<i>Remarks:</i> Lithium mica; platy cleavage typical of micas; produces a crimson flame because of lithium; insoluble in acids				
<b>Montmoril-</b> <b>Ionite</b>	$(Na,Ca)(Al,Mg)_2(Si_4O_{10})-(OH)_2 \cdot nH_2O$	$1-1\frac{1}{2}$	White or gray	Weathered volcanic ash; tropical soils
<i>Remarks:</i> Clay; tends to expand or "swell" in water; earthy luster; crumbles easily; greasy feel				
<b>Muscovite</b>	$KAl_2(AlSi_3O_{10})(OH)_2$	$2-2\frac{1}{2}$	White or yellow	Schists; phyllites; granites; granitic pegmatites
<i>Remarks:</i> Mica; platy mineral that peels off in "sheets"; pearly or vitreous luster; transparent to translucent; difficult to distinguish from paragonite, the sodium analog of muscovite				
<b>Niter</b> (saltpeter)	$KNO_3$	2	White	Some soils and rock crusts
<i>Remarks:</i> Saltpeter; crusts of fine acicular crystals; vitreous luster; usually translucent; very soluble in water; produces violet flame because of potassium; nondeliquescent, unlike soda niter				
<b>Orpiment</b>	$As_2S_3$	$1\frac{1}{2}-2$	Lemon yellow	Hydrothermal deposits
<i>Remarks:</i> Poisonous; do not taste, heat, or place in acids; resinous luster; pale yellow streak; translucent; perfect cleavage in one direction, unlike sulfur				
<b>Phlogopite</b>	$KMg_3(AlSi_3O_{10})(OH)_2$	$2\frac{1}{2}-3$	Often yellowish brown	Metamorphosed dolostones; marbles; some metamorphosed ultramafic rocks; kimberlites
<i>Remarks:</i> Mica; platy mineral that peels off in "sheets"; pearly or vitreous luster; generally lighter color than biotite, but darker than muscovite; unlike muscovite, will decompose in sulfuric acid				
<b>Proustite</b>	$Ag_3AsS_3$	$2-2\frac{1}{2}$	Scarlet red	Low-temperature silver deposits
<i>Remarks:</i> Very similar to pyrargyrite; red streak; adamantine luster				
<b>Pyrargyrite</b>	$Ag_3SbS_3$	$2-2\frac{1}{2}$	Red	Low-temperature silver deposits
<i>Remarks:</i> Very similar to proustite; red streak, darker than proustite; adamantine luster				
<b>Pyrophyllite</b>	$Al_2Si_4O_{10}(OH)_2$	1-2	White, gray, or brown	Hydrothermally altered rhyolites; some kyanite schists; some sulfide deposits
<i>Remarks:</i> Pearly to greasy luster; translucent; perfect cleavage in one direction; may be difficult to distinguish from talc				
<b>Realgar</b>	$AsS$	$1\frac{1}{2}-2$	Red	Lead, silver, or gold deposits; hot springs; some volcanic deposits
<i>Remarks:</i> Possibly poisonous; do not taste, heat, or dissolve in acids; resinous luster; orange-red streak; good cleavage in one direction; closely associated with orpiment; long exposure to light breaks realgar down into an orange powder				
<b>Sepiolite</b>	$Mg_4Si_6O_{15}(OH)_2 \cdot 6H_2O$	$2-2\frac{1}{2}$	White or pale yellow	Alteration of serpentinite; some lake sediments
<i>Remarks:</i> Earthy luster; even fine grains are opaque; porous samples may float in water; becomes plastic when mixed with water; insoluble in water and most acids; lightweight				

**TABLE 1** Minerals with a Nonmetallic Luster and Hardness of Less Than 3 (*continued*)

<b>Nitratite</b> (Soda Niter)	NaNO <sub>3</sub>	1–2	Usually white or colorless	Arid deposits
<i>Remarks:</i> Vitreous luster; very water soluble; transparent to translucent; deliquescent; produces yellow flame; usually in crusts; crystals are rare				
<b>Sulfur</b>	S	1½–2½	Yellow	Volcanic deposits; some evaporites
<i>Remarks:</i> Produces blue flame (only heat sulfur in a well-ventilated hood); resinous luster; no cleavage; unpleasant smell even at room temperature				
<b>Sylvite</b>	KCl	2	Usually white to colorless	Evaporites
<i>Remarks:</i> Soluble in water; cubic cleavage; produces violet flame, whereas sodium in halite produces a yellow flame; taste is more bitter than halite, however tasting minerals is not recommended; less common than halite; lightweight				
<b>Talc</b>	Mg <sub>3</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub>	1	Greenish white or gray	Schists; low-temperature metamorphism of mafic rocks and dolostones
<i>Remarks:</i> Greasy luster and feel, which is why talc is often called "soap stone"; insoluble in most acids				
Torbernite	Cu(UO <sub>2</sub> ) <sub>2</sub> (PO <sub>4</sub> ) <sub>2</sub> •8 to 12H <sub>2</sub> O	2–2½	Emerald green	Alteration of uranium deposits
<i>Remarks:</i> Radioactive; pearly luster; perfect cleavage; dissolves in some strong acids; nonfluorescent in ultraviolet light				
<b>Ulexite</b>	NaCaB <sub>5</sub> O <sub>6</sub> (OH) <sub>6</sub> •5H <sub>2</sub> O	1–2½	White	Evaporites in arid lakes
<i>Remarks:</i> Silky luster; may have "cottonball" appearance; produces yellow flame; soluble in hot water; lightweight				
<b>Vermiculite</b>	(Mg,Ca) <sub>0.3</sub> (Mg,Fe,Al) <sub>3</sub> -(Al,Si) <sub>4</sub> O <sub>10</sub> (OH) <sub>4</sub> •8H <sub>2</sub> O	1½	Green or yellowish brown	Alteration of biotite and phlogopite
<i>Remarks:</i> Often used as cat litter; platy appearance; vitreous to pearly luster; pale yellow streak; slightly soluble in some strong acids; expands when heated to more than 300 °C to yellowish brown layers that may be used as packing material				
Vivianite	Fe <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> •8H <sub>2</sub> O	1½–2	Blue to green	Oxidation of sulfide deposits; alteration of iron and manganese phosphates in pegmatites; sometimes associated with fossilized bones and shells
<i>Remarks:</i> Radiating crystals; transparent to translucent; vitreous to pearly luster, sometimes earthy; white streak; soluble in strong acids				

**TABLE 2** Minerals with a Nonmetallic Luster and Hardness of 3–5½

Name	Formula	Hardness	Color	Environment
<b>Actinolite</b>	$\text{Ca}_2(\text{Mg},\text{Fe})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	5–6	Green	Metamorphosed mafic rocks
<i>Remarks:</i> Amphibole; green; vitreous luster; needlelike crystals with 56° angle; crystals tend to radiate; transparent to translucent; perfect cleavage in one direction; a solid solution exists between tremolite and ferroactinolite, with actinolite as an intermediate				
<b>Alunite</b>	$\text{KAl}_3(\text{SO}_4)_2(\text{OH})_6$	4	White, gray, or red	Alteration of felsic volcanics, syenites, and granitic intrusives by natural sulfuric acid solutions
<i>Remarks:</i> White, gray, or red; vitreous, pearly, or earthy luster; often massive; dissolves in sulfuric acid; produces an acidic solution in water; produces violet potassium flame; poor cleavage in one direction; conchoidal fracture; white streak				
<b>Analcime</b>	$\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$	5–5½	Usually white or colorless	Hydrothermal deposits in basalts and syenites
<i>Remarks:</i> Usually white or colorless; vitreous luster; transparent to translucent; produces yellow flame from sodium; no cleavage; dissolves in most acids				
<b>Anglesite</b>	$\text{PbSO}_4$	3	White, gray, or other colors	Oxidized lead deposits
<i>Remarks:</i> White, gray, or other colors; dense (specific gravity of about 6.3); transparent to translucent; vitreous or adamantine luster; unlike cerussite, will not effervesce in nitric acid; good cleavage in one direction; conchoidal fracture; when rubbed, gives off slight electrical charge				
<b>Anhydrite</b>	$\text{CaSO}_4$	3–3½	Usually colorless	Evaporites; fills cavities of some basalts
<i>Remarks:</i> Usually colorless; vitreous luster; good to perfect cleavages in three directions; unlike calcite, largely insoluble in hydrochloric acid and does not effervesce				
<b>Ankerite</b>	$\text{CaFe}(\text{CO}_3)_2$	3½	Yellowish white or yellowish brown	Carbonate layers within banded iron formations; dolostones
<i>Remarks:</i> Yellowish white or yellowish brown; crystals are rare; properties are similar to dolomite; powdered form will effervesce in hydrochloric acid				
<b>Antigorite</b>	$\text{Mg}_6\text{Si}_4\text{O}_{10}(\text{OH})_8$	~4	Green	Serpentinites; altered ultramafic rocks
<i>Remarks:</i> Platy serpentine; green; greasy luster; translucent				
<b>Antlerite</b>	$\text{Cu}_3\text{SO}_4(\text{OH})_4$	3½–4	Green to dark green	Copper deposits
<i>Remarks:</i> Green to dark green; vitreous luster; perfect cleavage in one direction; light green streak; striated prismatic crystals sometimes occur; transparent to translucent; unlike malachite, does not effervesce in hydrochloric acid				
<b>Apatite</b>	$\text{Ca}_5(\text{PO}_4)_3(\text{OH},\text{F},\text{Cl})$	5	Usually green, blue, or brown	Teeth and bones; pegmatites; common in trace amounts in carbonate rocks and many metamorphic rocks
<i>Remarks:</i> Usually green, blue, or brown; prismatic hexagonal crystals are common; vitreous luster; soluble in most acids; poor cleavage in one direction; common varieties include fluorapatite, chlorapatite, and hydroxyapatite				
<b>Apophyllite</b>	$\text{KCa}_4(\text{Si}_4\text{O}_{10})_2\text{F} \cdot 8\text{H}_2\text{O}$	4½–5	Usually white, gray, or colorless	Hydrothermal deposits in basalts
<i>Remarks:</i> Usually white, gray, or colorless; vitreous luster; tetragonal prismatic crystals; produces violet potassium flame; low solubility in most acids				
<b>Aragonite</b>	$\text{CaCO}_3$	3½–4	Usually white or colorless	Mollusk shells; hydrothermal deposits; blueschists; cavities of some basalts
<i>Remarks:</i> Usually white or colorless; vitreous luster; like calcite, effervesces in hydrochloric acid; harder than calcite, although calcite is far more abundant at surface conditions; pearls consist of aragonite				

**TABLE 2 Minerals with a Nonmetallic Luster and Hardness of 3–5½ (continued)**

Arsenic	As	3½	White when fresh	Silver, cobalt, and silver deposits
<i>Remarks: Poisonous; do not taste, heat, or dissolve in acids; white when fresh; gray tarnish; brittle; perfect cleavage; opaque; dull luster</i>				
Astrophyllite	$(\text{K},\text{Na})_3(\text{Fe},\text{Mn})_7(\text{Ti},\text{Zr})_2\text{-Si}_8(\text{O},\text{OH})_{31}$	3	Yellow or yellowish brown	Nepheline syenites and other alkaline rocks
<i>Remarks: Yellow or yellowish brown; perfect platy cleavage; vitreous luster, almost metallic; yellow streak; partially soluble in some acids</i>				
Atacamite	$\text{Cu}_2\text{Cl}(\text{OH})_3$	3–3½	Green	Oxidized copper deposits, rarer than most other copper minerals
<i>Remarks: Green; adamantine to vitreous luster; transparent to translucent; prismatic striated crystals; fibrous; unlike malachite, does not effervesce in hydrochloric acid</i>				
<b>Augite</b>	$(\text{Ca},\text{Mg},\text{Fe},\text{Na})(\text{Mg},\text{Fe},\text{Al})-(\text{Si},\text{Al})_2\text{O}_6$	5–6	Dark green to black	Basalts; andesites; gabbros; peridotites; high-temperature metamorphic rocks (for example, granulites)
<i>Remarks: Very common pyroxene; dark green to black; cleavage at 87° and 93°, but imperfect; short prismatic crystals; vitreous to resinous luster; insoluble in most acids; augite is an intermediate member of a solid solution between diopside and hedenbergite</i>				
Azurite	$\text{Cu}_3(\text{CO}_3)_2(\text{OH})_2$	3½–4	Bright blue	Copper deposits
<i>Remarks: Bright blue; usually vitreous luster; striated crystals common; crystals may radiate; perfect cleavage in one direction; light blue streak; effervesces in hydrochloric acid; not as common as malachite</i>				
<b>Barite</b>	$\text{BaSO}_4$	3–3½	Usually white or colorless	Limestones; siltstones; clays; hydrothermal deposits
<i>Remarks: Usually white or colorless; dense compared to most other nonmetallic minerals (specific gravity of 4.5); vitreous luster; perfect cleavage in one direction; insoluble in water and many acids; may be fluorescent in ultraviolet light</i>				
Brochantite	$\text{Cu}_4\text{SO}_4(\text{OH})_6$	3½–4	Green	Oxidation of copper deposits
<i>Remarks: Green; acicular or prismatic crystals; may radiate; crystals may have striations; vitreous luster; pale green streak; soluble in acids; produces green flame</i>				
<b>Calcite</b>	$\text{CaCO}_3$	3	Usually white or colorless	Limestones; many marine fossils; chalk; marbles; hot springs; carbonatites; veins in some metamorphic and igneous rocks
<i>Remarks: Very common mineral; usually white or colorless; easily effervesces with dilute hydrochloric acid; rhombohedral crystals; transparent to translucent; vitreous to dull luster; exhibits double refraction: Words on paper may appear double when viewed through large transparent crystals</i>				
<b>Celestite</b>	$\text{SrSO}_4$	3–3½	Usually colorless or white	Limestones; evaporites; lead and hydrothermal deposits
<i>Remarks: Usually colorless or white; vitreous luster; transparent to translucent; prismatic crystals; perfect cleavage parallel to base; may be fluorescent in ultraviolet light; partially soluble in water and acids; produces bright red flame because of strontium; lower density than barite</i>				
<b>Cerussite</b>	$\text{PbCO}_3$	3–3½	Usually white, gray, or colorless	Lead deposits
<i>Remarks: Usually white, gray, or colorless; very dense (specific gravity of about 6.5); good cleavage in one direction; adamantine luster; insoluble in hydrochloric acid; effervesces and dissolves in warm dilute nitric acid (Note: do not pour any acidic solutions containing lead down the drain; they should be disposed of properly and legally); may produce bluish green fluorescence in ultraviolet light</i>				
<b>Chabazite</b>	$\text{Ca}_2\text{Al}_2\text{Si}_4\text{O}_{12} \cdot 6\text{H}_2\text{O}$	4–5	Variable	Hydrothermal deposits in cavities of basalts and other igneous rocks
<i>Remarks: White, brown, or variety of other colors; vitreous luster; transparent to translucent; rhombohedral (pseudocubic) crystals are common; poor cleavage in one direction; soluble in hydrochloric acid, but does not effervesce</i>				

**TABLE 2 Minerals with a Nonmetallic Luster and Hardness of 3–5½ (continued)**

<b>Chrysocolla</b>	approx. Cu <sub>4</sub> H <sub>4</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>8</sub>	2–4	Green or bluish green	Oxidized copper deposits
Remarks: Green or bluish green; black runs together when impure; typically amorphous; vitreous, greasy, or earthy luster; conchoidal fracture; decomposes in hydrochloric acid to produce silica gel; produces green flame; similar appearance to turquoise, but not as hard				
<b>Chrysotile</b>	Mg <sub>6</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>8</sub>	4	Usually green to white	Serpentinites; altered ultramafic rocks
Remarks: Asbestos; <i>do not breathe fibers, possible carcinogen</i> ; usually green to white; fibrous serpentine; dissolves in strong acids				
Colemanite	CaB <sub>3</sub> O <sub>4</sub> (OH) <sub>3</sub> • H <sub>2</sub> O	4–4½	Usually white or colorless	Arid lake deposits
Remarks: Usually white or colorless; short prismatic crystals; vitreous luster; transparent to translucent; perfect cleavage in one direction; insoluble in water; acid solutions produce green flame because of boron				
Crocidolite	NaFe <sub>5</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	4	Dark blue to nearly black	Granites; syenites; pegmatites
Remarks: Blue asbestos (fibrous riebeckite); dark blue to nearly black; white to light blue streak; vitreous to silky luster; produces yellow flame because of sodium; insoluble in most acids; croosite is an intermediate in the partial solid solution series between glaucophane and riebeckite				
Cuprite	Cu <sub>2</sub> O	3½–4	Ruby red	Oxidized copper deposits
Remarks: Ruby red; adamantine to almost metallic luster; translucent to nearly opaque; reddish brown streak; cubic, octahedral, or dodecahedral crystals; may be fibrous; produces green flame; dissolves in concentrated hydrochloric acid				
Datolite	CaB(SiO <sub>4</sub> )(OH)	5–5½	White or light green	Cavities in basalts; serpentinites; hydrothermal deposits
Remarks: White or light green; vitreous luster; transparent to translucent; multifaceted monoclinic crystals; conchoidal fracture; dissolves in most acids				
<b>Diopside</b>	CaMgSi <sub>2</sub> O <sub>6</sub>	5–6	Typically light green	Marbles; metamorphosed siliceous limestones and dolostones
Remarks: Pyroxene; white, light green, or other colors depending on impurities such as chromium, manganese, or vanadium; cleavage at 87° and 93°, but imperfect; prismatic crystals; vitreous to resinous luster; insoluble in most acids; forms solid solution with hedenbergite				
Diopside	Cu <sub>6</sub> (Si <sub>6</sub> O <sub>18</sub> ) • 6H <sub>2</sub> O	5	Bright green	Oxidized copper deposits
Remarks: Bright green; rhombohedral crystals are often noticeable; green streak; vitreous luster; transparent to translucent; decomposes in most strong acids to yield silica gel				
<b>Dolomite</b>	CaMg(CO <sub>3</sub> ) <sub>2</sub>	3½–4	Commonly white-pink	Dolostones; limestones; marbles; talc schists; serpentinites; hydrothermal deposits
Remarks: Very common mineral; white, pink, colorless, or a variety of other colors depending on presence of impurities; vitreous luster; transparent to translucent; white streak; tends not to effervesce in hydrochloric acid unless the mineral is powdered; perfect cleavage in one direction; rhombohedral crystals; forms complete solid solution series with ankerite				
<b>Fluorite</b>	CaF <sub>2</sub>	4	Variable	Dolostones; limestones; hydrothermal deposits; some felsic volcanics; some granitic and intermediate intrusives
Remarks: Purple, colorless, or a variety of other colors; perfect cleavage; vitreous luster; transparent to translucent; cubic or octahedral cleavage; insoluble in water and hydrochloric acid; strongly fluorescent in ultraviolet light				

**TABLE 2** Minerals with a Nonmetallic Luster and Hardness of 3– $5\frac{1}{2}$  (*continued*)

<b>Goethite</b>	FeO(OH)	5– $5\frac{1}{2}$	Yellow to brown	Weathering product of serpentine, hematite, and other iron-bearing minerals
<i>Remarks:</i> Yellow to brown; adamantine, greasy, or earthy luster; often fibrous, acicular, or tabular; yellowish brown streak; nonmagnetic, unless heated; perfect cleavage in one direction; partially soluble in hydrochloric acid				
<b>Greenockite</b>	CdS	3– $3\frac{1}{2}$	Yellow	Hydrothermal deposits with sphalerite
<i>Remarks:</i> Possibly poisonous; do not heat, taste, or dissolve in acids; yellow; usually coatings rather than distinct crystals; perfect cleavage; adamantine to resinous luster; orange or red streak; when zinc is present, greenockite fluoresces yellowish orange				
<b>Harmotome</b>	Ba(Al <sub>2</sub> Si <sub>6</sub> O <sub>16</sub> ) • 6H <sub>2</sub> O	4 $\frac{1}{2}$	White to gray	Hydrothermal deposits; basalts; phonolites; trachytes
<i>Remarks:</i> Zeolite; white, gray, or a variety of other colors; distinct cleavage; vitreous luster; transparent to translucent; decomposes in hydrochloric acid				
<b>Hedenbergite</b>	CaFeSi <sub>2</sub> O <sub>6</sub>	5–6	Black	Iron-rich metamorphic rocks, including skarns; iron-rich igneous intrusions
<i>Remarks:</i> Pyroxene; black; short prismatic crystals; often radiating; nearly opaque; greenish brown streak; cleavage at 87° and 93°, but imperfect; insoluble in most acids				
<b>Hemimorphite</b>	Zn <sub>4</sub> (Si <sub>2</sub> O <sub>7</sub> ) <sub>2</sub> • H <sub>2</sub> O	4 $\frac{1}{2}$ –5	Usually white	Oxidized zinc deposits
<i>Remarks:</i> Usually white; hemimorphic orthorhombic crystals; often fibrous; transparent to translucent. Vitreous luster; strongly piezoelectric and pyroelectric; dissolves in most acids to produce a silica gel; specific gravity of about 3.4, which is higher than prehnite				
<b>Heulandite</b>	CaAl <sub>2</sub> Si <sub>7</sub> O <sub>18</sub> • 6H <sub>2</sub> O	3 $\frac{1}{2}$ –4	White, orange, colorless, red, or yellow	Cavities of basalts
<i>Remarks:</i> Usually white, orange, colorless, red, or yellow; vitreous luster; perfect cleavage in one direction; decomposes in hydrochloric acid to produce a silica gel; white streak				
<b>Hornblende</b>	(K,Na) <sub>0–1</sub> (Ca,Na,Fe,Mg) <sub>2–5</sub> (Mg,Fe,Al) <sub>5</sub> (Si,Al) <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	5–6	Dark green to black	Amphibolites; schists; granodiorites; tonalites; monzonites; hornblendites; quartz porphyries; dacites; latites; andesites
<i>Remarks:</i> Very common amphibole; dark green to black; fibrous to prismatic crystals with 56° and 124° cleavage angles; vitreous luster; insoluble in most acids				
<b>Hypersthene</b>	(Mg,Fe)SiO <sub>3</sub>	5–6	Dark green to brown	Peridotites; gabbros; pyroxenites; basalts; granulites; gneisses
<i>Remarks:</i> Orthopyroxene in enstatite-orthoferrosilite solid solution series (that is, hypersthene is 50%–80% enstatite end member); dark green to brown; vitreous luster, may be pearly to submetallic; translucent to opaque; insoluble in most acids; may be difficult to distinguish from augite without optical methods				
<b>Kyanite</b>	Al <sub>2</sub> SiO <sub>5</sub>	5–7	Usually blue	High-pressure Al-rich metamorphics, including schists, some eclogites, and kimberlites
<i>Remarks:</i> Polymorph of sillimanite and andalusite; usually blue; hardness of about 5 parallel to length of crystals and about 7 perpendicular; bladed crystals with perfect cleavage in one direction; vitreous luster; insoluble in most acids				
<b>Laumontite</b>	Ca(Al <sub>2</sub> Si <sub>4</sub> O <sub>12</sub> ) • 4H <sub>2</sub> O	4	White, pink, or light yellow	Cavities and veins in variety of intrusive igneous and volcanic rocks; hydrothermal deposits
<i>Remarks:</i> Usually white, pink, or light yellow; prismatic or fibrous crystals; perfect cleavage; vitreous luster; transparent to translucent; decomposes in hydrochloric acid to form silica gel; becomes powdery when exposed to dry air and light				

**TABLE 2 Minerals with a Nonmetallic Luster and Hardness of 3–5½ (continued)**

Lazulite	$(\text{Mg},\text{Fe})\text{Al}_2(\text{PO}_4)_2(\text{OH})_2$	5–5½	Blue	Pegmatites; high-grade metamorphics, including certain quartzites and schists
<i>Remarks:</i> Blue; vitreous luster; translucent; insoluble in most acids; falls apart when heated; usually massive, rarely pseudodipyramidal crystals				
Lazurite	$(\text{Na},\text{Ca})_8(\text{AlSiO}_4)_6(\text{SO}_4,\text{S},\text{Cl})_2$	5–5½	Blue, greenish blue, or violet blue	Contact metamorphosed limestones; usually associated with pyrite
<i>Remarks:</i> Lapis lazuli gems; blue, greenish blue, or violet blue; usually massive; vitreous luster; translucent; produces yellow flame from sodium and dissolves in hydrochloric acid, but <i>beware of release of poisonous hydrogen sulfide ("rotten egg") gases!</i>				
Lepidochrosite	$\text{FeO}(\text{OH})$	5	Red to brown	Laterites (soils found in warm and humid climates); associated with its polymorph goethite
<i>Remarks:</i> Red to brown; platy to fibrous crystals; orange streak; translucent; adamantine luster; soluble in nitric acid, less soluble in hydrochloric acid; perfect platy cleavage; nonmagnetic unless heated				
Lepidolite	$\text{K}(\text{Li},\text{Al})_{2-3}(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$	2½–4	Pink or light gray	Lithium-rich pegmatites
<i>Remarks:</i> Lithium mica; pink or light gray; vitreous to pearly luster; platy micaceous cleavage in one direction; translucent; produces red flame from the presence of lithium; insoluble in most acids				
Limonite	$\text{FeO}(\text{OH}) \cdot n\text{H}_2\text{O}$	5–5½	Yellow to brown	Laterites (soils found in warm and humid climates); weathering product of many iron minerals
<i>Remarks:</i> Mineraloid, since it is mostly amorphous (noncrystalline); yellow to brown; light brown streak; often earthy coatings on iron minerals; sometimes vitreous; dissolves slowly in most strong acids; variable composition and properties; may contain some crystalline iron phases, such as goethite				
Lithiophilite–Triphylite	$\text{Li}(\text{Mn},\text{Fe})\text{PO}_4$ to $\text{Li}(\text{Fe},\text{Mn})\text{PO}_4$	4½–5	Blue-pink	Pegmatites
<i>Remarks:</i> Solid solution series exists between lithiophilite and triphylite; lithiophilite is usually brown or pink, while triphylite tends to be bluish gray; vitreous to resinous luster; may be stained with black manganese oxide stain; produces red flame from lithium; usually massive with nearly perfect cleavage in one direction and imperfect cleavage in another				
Magnesite	$\text{MgCO}_3$	3½–5	Usually white, gray, or yellow	Hydrothermal deposits in peridotites and other ultramafic igneous rocks; pegmatites; serpentinites; talc schists; limestones; dolostones
<i>Remarks:</i> Solid solution exists between magnesite and siderite; usually white, gray, or yellow; vitreous luster; transparent to translucent; higher density than dolomite or calcite (specific gravity of about 3.1); white streak; sometimes fluorescent; drops of cold dilute hydrochloric acid will not effervesce on the mineral				
Malachite	$\text{Cu}_2\text{CO}_3(\text{OH})_2$	3½–4	Green	Oxidized copper deposits; can be seen on weathered pennies and copper statues as a green stain
<i>Remarks:</i> Green; often earthy; sometimes occurs as crystals with adamantine or vitreous luster; may occur as agate-like concretions; light green streak; effervesces in hydrochloric acid; copper in the mineral produces a green flame				

**TABLE 2 Minerals with a Nonmetallic Luster and Hardness of 3–5½ (continued)**

Margarite	$\text{CaAl}_2(\text{Al}_2\text{Si}_2\text{O}_{10})(\text{OH})_2$	3½–5	White, pink, or gray	Chlorite, staurolite, and other schists; weathering product of corundum and other aluminum minerals
<i>Remarks:</i> White, pink, or gray; translucent; brittle; micaceous (platy) cleavage; insoluble in cold hydrochloric acid, but partially soluble in hot hydrochloric acid				
Mimetite	$\text{Pb}_5(\text{AsO}_4)_3\text{Cl}$	3½	Yellowish brown, colorless, or orange	Oxidation of lead deposits
<i>Remarks:</i> Possibly poisonous; do not heat, taste, or dissolve in acids; usually yellowish brown, colorless, or orange; prismatic hexagonal crystals; resinous or adamantine luster; translucent; white streak				
Monazite	$(\text{Ce},\text{La},\text{Y},\text{Th})\text{PO}_4$	5–5½	Yellowish to reddish brown	Usually, but not always, as microscopic crystals in granites, syenites, gneisses, pegmatites, and placer deposits
<i>Remarks:</i> Thorium varieties are radioactive; yellowish to reddish brown; conchoidal fracture; translucent; insoluble in hydrochloric acid; fairly high density (specific gravity of about 5.0); resinous luster				
Natrolite	$\text{Na}_2\text{Al}_2\text{Si}_3\text{O}_{10} \cdot 2\text{H}_2\text{O}$	5–5½	Usually white or colorless	Cavities in basalts; hydrothermal deposits in nepheline syenites, phonolites, and serpentinites
<i>Remarks:</i> Usually white or colorless; transparent to translucent; vitreous luster; perfect cleavage in one direction; decomposes in hydrochloric acid to produce silica gel; presence of sodium produces a yellow flame; prismatic to fibrous crystals; sometimes fluoresces in ultraviolet light				
Neptunite	$\text{KNa}_2\text{Li}(\text{Fe},\text{Mn})_2\text{TiO}_2 \cdot (\text{Si}_4\text{O}_{11})_2$	5–6	Usually black	Nepheline pegmatites and syenites; serpentinites
<i>Remarks:</i> Usually black; prismatic monoclinic crystals; vitreous luster; perfect cleavage; translucent to opaque; red streak; insoluble in hydrochloric acid				
Omphacite	$(\text{Ca},\text{Na})(\text{Mg},\text{Fe},\text{Al})\text{Si}_2\text{O}_6$	5–6	Green	Eclogites
<i>Remarks:</i> Sodium-rich pyroxene; green; prismatic crystals; cleavage at 87° and 93°, but imperfect; vitreous luster; translucent; white to light green streak; insoluble in most acids				
Opal	$\text{SiO}_2 \cdot n\text{H}_2\text{O}$	5–6	Variable	Hydrothermal deposits; volcanic tuffs; petrified wood; marine sediments
<i>Remarks:</i> Mineraloid; white, colorless, yellow, black, red, or a variety of other colors depending on the presence of impurities; vitreous to resinous luster; transparent to translucent; may fluoresce in ultraviolet light; conchoidal fracture; insoluble in most acids				
Pectolite	$\text{NaCa}_2(\text{SiO}_3)_3\text{H}$	5	Usually white, colorless, or gray	Cavities in basalts; hydrothermal deposits; serpentinites; contact metamorphosed limestones
<i>Remarks:</i> Pyroxenoid; usually white, colorless, or gray; vitreous luster; white streak; decomposes in hydrochloric acid and forms silica gel; produces yellow flame; transparent; perfect cleavage in two directions, which may produce needlelike crystals				
Phillipsite	$\text{KCa}(\text{Al}_3\text{Si}_5\text{O}_{16}) \cdot 6\text{H}_2\text{O}$	4½–5	Usually white or colorless	Cavities in basalts; hydrothermal alterations of volcanic ashes and feldspar-bearing rocks
<i>Remarks:</i> Usually white or colorless; small prismatic crystals; distinct cleavage; vitreous luster; translucent and transparent; dissolves in acids				
Romanechite (Psilomelane)	$\text{BaMn}_9\text{O}_{16}(\text{OH})_4$	5–6	Black	Associated with pyrolusite ( $\text{MnO}_2$ ) in marine sedimentary rocks (for example, limestones)
<i>Remarks:</i> Black; submetallic luster; greasy feel; brownish black streak; opaque; dissolves in hydrochloric acid; branchlike forms on rock surfaces				

**TABLE 2 Minerals with a Nonmetallic Luster and Hardness of 3–5½ (continued)**

<b>Pyromorphite</b>	$\text{Pb}_5(\text{PO}_4)_3\text{Cl}$	3½–4	Usually green, brown, or colorless	Oxidized lead deposits
<i>Remarks:</i> Usually green, brown, or colorless; translucent; dense (specific gravity of about 7); prismatic hexagonal crystals; sometimes crystals are hollow; resinous to adamantine luster; white streak; soluble in most acids				
<b>Rhodochrosite</b>	$\text{MnCO}_3$	3½–4	Usually pink	Hydrothermal deposits of silver, lead, or copper; manganese deposits
<i>Remarks:</i> Usually pink; vitreous luster; white or light pink streak; transparent or translucent; rhombohedral cleavage; insoluble in cold hydrochloric acid, but effervesces and is soluble in hot concentrated hydrochloric acid; softer than rhodonite				
<b>Riebeckite</b>	$\text{Na}_2\text{Fe}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	5	Dark blue to nearly black	Granites; syenites; pegmatites
<i>Remarks:</i> Amphibole; if coarse shows typical 60°–120° amphibole cleavage angles; dark blue to nearly black; white to light blue streak; vitreous luster; translucent; produces yellow flame because of sodium; insoluble in most acids; crossite is an intermediate in the partial solid solution series between glaucophane and riebeckite; optical or other sophisticated analytical methods may be needed to distinguish this amphibole from other bluish amphiboles				
<b>Scapolite</b>	$(\text{Na},\text{Ca},\text{K})_4\text{Al}_3(\text{Al},\text{Si})_3\text{Si}_6\text{O}_{24}(\text{Cl},\text{SO}_4,\text{CO}_3)_2$	5–6	White, blue, gray, or pink	Schists; amphibolites; gneisses; granulites; skarns; pegmatites
<i>Remarks:</i> Group of metamorphic minerals, including marialite-meionite solid solution series with mizzonite as an intermediate member; usually white, blue, gray, or pink; poor cleavage in two directions; vitreous luster; transparent or translucent; usually fluoresces in ultraviolet light; decomposes in hydrochloric acid, leaving a silica gel				
<b>Scheelite</b>	$\text{CaWO}_4$	4½–5	Usually yellow, brown, or green	Hydrothermal deposits in granitic rocks; granitic pegmatites; contact metamorphic rocks
<i>Remarks:</i> Partial solid solution exists with powellite ( $\text{CaMoO}_4$ ); usually yellow, brown, or green; very dense (specific gravity of about 6); vitreous to adamantine luster; usually translucent; usually fluoresces in ultraviolet light; good cleavage in one direction; white streak				
<b>Scolecite</b>	$\text{CaAl}_2\text{Si}_3\text{O}_{10} \cdot 3\text{H}_2\text{O}$	5–5½	Usually white or colorless	Cavities in basalt; schists; contact metamorphosed limestones
<i>Remarks:</i> Usually white or colorless; radiating and striated prismatic crystals; perfect cleavage; decomposes in hydrochloric acid and leaves a silica gel; vitreous luster; usually transparent				
<b>Serpentine</b>	$\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$	3–5	Usually green	Serpentinites; weathered mafic and ultramafic rocks
<i>Remarks:</i> Two major serpentine minerals: antigorite (platy variety) and chrysotile (asbestiform variety); usually green; translucent to opaque; massive to fibrous; antigorite is greasy, while chrysotile tends to have silky luster				
<b>Siderite</b>	$\text{FeCO}_3$	3½–4	Light to dark brown	Shales; coal; hydrothermal deposits
<i>Remarks:</i> Light to dark brown; vitreous luster; transparent to translucent; rhombohedral crystals; fairly dense (specific gravity of about 4); white streak; often in concretions; insoluble in cold hydrochloric acid; soluble and effervescent in hot hydrochloric acid				
<b>Smithsonite</b>	$\text{ZnCO}_3$	4–4½	Variable	Zinc deposits, especially, in carbonate rocks
<i>Remarks:</i> Usually brown or blue, but may be colorless, white, green, violet, or pink				
<b>Sphalerite</b>	$\text{ZnS}$	3½–4	Variable	Zinc deposits; contact metamorphic deposits
<i>Remarks:</i> Usually brown to black, sometimes yellow, red, colorless, pink, or green; resinous to submetallic luster; white, yellow, red, or brown streak; coarser crystals show perfect cleavage in one direction; releases poisonous hydrogen sulfide gas when heated or dissolved in strong acids; use ventilation!				

**TABLE 2 Minerals with a Nonmetallic Luster and Hardness of 3–5½ (continued)**

Titanite (Sphene)	$\text{CaTiSiO}_5$	5–5½	Variable	Usually as microscopic crystals in felsic to intermediate igneous and metamorphic rocks; hydrothermal deposits; contact metamorphosed carbonate rocks
<i>Remarks:</i> Green, black, yellow, or a variety of other colors; resinous to adamantine luster; often wedge-shaped crystals; transparent to translucent; white streak; soluble in sulfuric acid and partially soluble in hydrochloric acid				
Stilbite	$\text{CaAl}_2\text{Si}_7\text{O}_{18} \cdot 7\text{H}_2\text{O}$	3½–4	Usually white	Cavities in basalt
<i>Remarks:</i> Usually white; vitreous luster; transparent to translucent; tabular or radiating fibrous crystals, often in a sheaf-like mass (like a bundle of wheat); perfect cleavage in one direction; decomposes in hydrochloric acid, but the silica in the mineral does not dissolve				
Strontianite	$\text{SrCO}_3$	3½–4	Usually colorless, white, or gray	Low-temperature hydrothermal deposits, especially in carbonate rocks
<i>Remarks:</i> Usually colorless, white, or gray; adamantine luster; transparent to translucent; very dense (specific gravity near 6.6); effervesces and dissolves in warm nitric acid; soluble in hydrochloric acid; crystals may be fibrous or in prismatic aggregates; white streak; may fluoresce in ultraviolet light; strontium in the mineral produces a bright red flame				
Thomsonite	$\text{NaCa}_2(\text{Al}_5\text{Si}_5\text{O}_{20}) \cdot 6\text{H}_2\text{O}$	3–4½	Usually white	Cavities in basalts; schists; contact metamorphosed limestones
<i>Remarks:</i> Usually white or sometimes brown; often prismatic crystals in radiating spheres; vitreous to pearly luster; decomposes in hydrochloric acid to produce a silica gel				
Tremolite	$\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	5–6	Usually white	Dolomitic marbles; schists (often associated with talc); serpentinites
<i>Remarks:</i> Amphibole, often displaying typical 60°–120° cleavage angle; usually white; forms complete solid solution series with ferroactinolite, with actinolite as an intermediate; vitreous luster; usually prismatic or radiating needlelike crystals; transparent to nearly opaque; insoluble in most acids				
Trona	$\text{Na}_3\text{H}(\text{CO}_3)_2 \cdot 2\text{H}_2\text{O}$	3	Usually colorless, white, or yellowish white	Evaporites in arid lake deposits
<i>Remarks:</i> Usually colorless, white, or yellowish white; may occur as microcrystalline earthy crusts or as radiating prismatic or acicular crystals; perfect cleavage; white streak; soluble in water and most acids				
Vanadinite	$\text{Pb}_5(\text{VO}_4)_3\text{Cl}$	3	Usually red, orange-red, yellow, or brown	Oxidized lead deposits
<i>Remarks:</i> Usually red, orange-red, yellow, or brown; resinous to adamantine luster; very dense (specific gravity of about 6.9); transparent to translucent; often hexagonal prismatic crystals; may have fibrous or radiating crystals; no cleavage; light yellow streak; soluble in most acids				
Variscite	$\text{Al}(\text{PO}_4) \cdot 2\text{H}_2\text{O}$	3½–4½	Bluish green	Hydrothermal alteration of feldspar-rich igneous rocks
<i>Remarks:</i> Bluish green; usually occurs as turquoise-like crusts or veins, but softer than turquoise; conchoidal fracture; vitreous to greasy luster; translucent				
Wavellite	$\text{Al}_3(\text{PO}_4)_2(\text{OH})_3 \cdot 5\text{H}_2\text{O}$	3½–4	Usually white, yellow, gray, green, or brown	Hydrothermal deposits in pegmatites and pelitic metamorphic rocks
<i>Remarks:</i> Usually white, yellow, gray, green, or brown; often as fibrous radiating crystals; translucent				

**TABLE 2 Minerals with a Nonmetallic Luster and Hardness of 3–5½ (continued)**

Witherite	$\text{BaCO}_3$	3½	Usually white, colorless, or gray	Lead deposits
<i>Remarks:</i> Usually white, colorless, or gray; vitreous luster; translucent; often occurs as pseudohexagonal striated dipyrramids; effervesces and dissolves in hydrochloric acid; when a few drops of sulfuric acid are added to witherite dissolved in dilute hydrochloric acid, a white barium sulfate precipitate will form; produces yellowish green flame				
Wolframite	$(\text{Fe}, \text{Mn})\text{WO}_4$	4–4½	Brown to black	Pegmatites; granites; placer deposits
<i>Remarks:</i> Solid solution series exists between ferberite ( $\text{FeWO}_4$ ) and heubnerite ( $\text{MnWO}_4$ ) with wolframite as an intermediate; brown (heubnerite) to black (ferberite); submetallic to resinous luster; translucent to opaque; very dense (specific gravity of 7–7.5); brown to black streak; perfect cleavage in one direction; insoluble in most acids				
Wollastonite	$\text{CaSiO}_3$	5–5½	Usually white	Contact metamorphic limestones
<i>Remarks:</i> Pyroxenoid; usually white; vitreous luster; prismatic or fibrous crystals, sometimes radiating; perfect to good cleavage in three directions; two perfect cleavages are separated by approximately 84°; decomposes in hydrochloric acid to produce insoluble silica				
Wulfenite	$\text{PbMoO}_4$	3	Usually orange red	Oxidized lead deposits
<i>Remarks:</i> Usually orange red; vitreous, resinous, or adamantine luster; white streak; very dense (specific gravity of about 6.8); transparent to translucent; tabular tetragonal crystals; dissolves slowly in most strong acids				
Zincite	$\text{ZnO}$	4	Usually red or yellowish orange	Some zinc deposits, very rare
<i>Remarks:</i> Usually red or yellowish orange; adamantine luster; usually massive, crystals are very uncommon; yellowish orange streak; translucent; soluble in hydrochloric acid				

**TABLE 3** Minerals with a Nonmetallic Luster and Hardness of  $5\frac{1}{2}$ – $6\frac{1}{2}$ 

Name	Formula	Hardness	Color	Environment
<b>Actinolite</b>	$\text{Ca}_2(\text{Mg},\text{Fe})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	5–6	Green	Metamorphosed mafic rocks
<i>Remarks:</i> Amphibole; a solid solution exists between tremolite and ferroactinolite with actinolite as an intermediate; green; vitreous luster; needlelike crystals with $56^\circ$ and $124^\circ$ cleavage angle; crystals tend to radiate; transparent to translucent; perfect cleavage in one direction				
Aegirine (Acmite)	$\text{NaFeSi}_2\text{O}_6$	$6-6\frac{1}{2}$	Green or brown	Nepheline syenites; phonolites
<i>Remarks:</i> Pyroxene; green or brown; vitreous luster; translucent; prismatic crystals with angles of $87^\circ$ and $93^\circ$ ; optical tests may be required to distinguish from other pyroxenes				
<b>Albite</b>	$\text{NaAlSi}_3\text{O}_8$	6	Usually white or gray	Granites; syenites; rhyolites; trachytes; granitic pegmatites; schists; gneisses
<i>Remarks:</i> Plagioclase feldspar; usually white or gray; bladed crystals; vitreous luster; good basal cleavage; white streak; striations (twinning) are often visible; insoluble in hydrochloric acid; optical or other sophisticated analytical methods are probably needed to distinguish from other feldspars				
<b>Allanite</b>	$(\text{Ca},\text{Ce})_2\text{FeAl}_2\text{Si}_3\text{O}_{12})(\text{OH})$	$5\frac{1}{2}$ –6	Brown or black	Often as microscopic crystals in granites, peg-matites, syenites, and diorites
<i>Remarks:</i> Brown or black; weakly radioactive; resinous to submetallic luster; may be coated with yellowish brown oxide layer; usually massive; translucent to opaque; decomposes in hydrochloric acid to produce a silica gel				
Amblygonite	$\text{LiAlFPO}_4$	6	Variable	Granitic pegmatites
<i>Remarks:</i> White, light green, or variety of other colors; vitreous luster; translucent; usually massive; produces red flame from presence of lithium; white streak; insoluble in most acids; perfect cleavage in one direction; good to distinct cleavages in two other directions				
Anatase	$\text{TiO}_2$	$5\frac{1}{2}$ –6	Usually black, yellow, or blue	Hydrothermal deposits in granites and granitic pegmatites; placer deposits
<i>Remarks:</i> Usually black, yellow, or blue; perfect cleavage; usually dipyramidal crystals; adamantine to submetallic luster; transparent to translucent; pale yellow streak; insoluble in most acids				
<b>Andesine</b>	$\text{Ab}_{70}\text{An}_{30}$ to $\text{Ab}_{50}\text{An}_{50}$	6	Usually white or gray	Diorites; andesites
<i>Remarks:</i> Plagioclase feldspar; usually white or gray; bladed crystals; vitreous luster; perfect basal cleavage; white streak; striations (twinning) are often visible along with a "play of colors" on the faces of the mineral; insoluble in hydrochloric acid; optical methods are usually required to distinguish from other plagioclase minerals				
<b>Anorthite</b>	$\text{CaAl}_2\text{Si}_2\text{O}_8$	6	Usually white	Gabbros; peridotites; contact metamorphic limestones
<i>Remarks:</i> Plagioclase feldspar; white or a variety of other colors; tabular crystals; vitreous luster; white streak; unlike albite, decomposes in hydrochloric acid to form a silica gel; optical methods are usually required to distinguish from other plagioclase minerals				
<b>Anthophyllite</b>	$(\text{Mg},\text{Fe})_7\text{Si}_8\text{O}_{22}(\text{OH})_2$	$5\frac{1}{2}$ –6	Gray, green, or brown	Cordierite, talc, or other schists; amphibolites; serpentinites; metamorphosed ultramafic rocks
<i>Remarks:</i> Amphibole, polymorph of cummingtonite; gray, green, or brown; vitreous luster; often fibrous; translucent; insoluble in most acids; optical methods are usually needed to distinguish from other amphiboles				
Arfvedsonite	$\text{Na}_3\text{Fe}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	6	Green to black	Nepheline syenites and pegmatites
<i>Remarks:</i> Amphibole; green to black; prismatic, tabular crystals; opaque; vitreous luster; dark blue streak; insoluble in acids; usually requires optical or other sophisticated analytical methods to distinguish from other amphiboles				

**TABLE 3** Minerals with a Nonmetallic Luster and Hardness of  $5\frac{1}{2}$ – $6\frac{1}{2}$  (*continued*)

Name	Formula	Hardness	Color	Environment
<b>Augite</b>	(Ca,Mg,Fe,Na)(Mg,Fe,Al)- (Si,Al) <sub>2</sub> O <sub>6</sub>	5–6	Dark green to black	Basalts; andesites; gabbros; peridotites; high-temperature metamorphic rocks (for example, granulites)
				<i>Remarks:</i> Pyroxene; dark green to black; cleavage at 87° and 93°, but imperfect; short prismatic crystals; vitreous to resinous luster; insoluble in most acids; augite is an intermediate member of a solid solution between diopside and hedenbergite
Axinite	(Ca,Fe,Mn) <sub>3</sub> Al <sub>2</sub> (BO <sub>3</sub> ) <sub>3</sub> (Si <sub>4</sub> O <sub>12</sub> )(OH)	$6\frac{1}{2}$ –7	Variable	Cavities in granites
				<i>Remarks:</i> Brown, gray, violet, or other colors are possible; vitreous luster; transparent to translucent; triclinic crystals with very acute angles; distinct cleavage in one direction
Benitoite	BaTiSi <sub>3</sub> O <sub>9</sub>	$6\frac{1}{2}$	Blue	Blueschist and serpentinite complexes
				<i>Remarks:</i> Blue; vitreous to adamantine luster; transparent to translucent; prismatic dipyrasidal crystals; pleochroic; fluoresces in ultraviolet light; crystals are frequently zoned
Bronzite	(Mg,Fe) <sub>2</sub> Si <sub>2</sub> O <sub>6</sub>	$5\frac{1}{2}$	Brownish green to black	Some gabbros and basalts; some ultramafic plutons
				<i>Remarks:</i> Orthopyroxene; bronzite is an intermediate member in the enstatite-ferrosilite solid solution series, bronzite is 80%–88.5% enstatite end member; brownish green to black; submetallic bronzelike luster; good cleavage; short prismatic crystals; insoluble in acids; may need optical or other sophisticated methods to distinguish from other pyroxenes
Brookite	TiO <sub>2</sub>	$5\frac{1}{2}$ –6	Brown to black	Granites; gneisses; contact metamorphic rocks
				<i>Remarks:</i> Polymorph of rutile; brown to black; tabular crystals, often striated; adamantine to submetallic luster; poor cleavage; transparent to translucent; light yellow or light brown streak; insoluble in most acids
Bytownite	Ab <sub>30</sub> An <sub>70</sub> to Ab <sub>10</sub> An <sub>90</sub>	6	Typically white to gray	Some gabbros, diabases, basalts, anorthosites, and diorites
				<i>Remarks:</i> Plagioclase feldspar; white or a variety of other colors; tabular crystals; vitreous luster; white streak; optical or other sophisticated analytical methods are usually required to distinguish from other plagioclase minerals
Cancrinite	Na <sub>6</sub> Ca(CO <sub>3</sub> )(AlSiO <sub>4</sub> ) <sub>6</sub> • 2H <sub>2</sub> O	5–6	Violet, red, or other	Syenites
				<i>Remarks:</i> Violet, red, or other colors; usually massive or fine grained; perfect cleavage; vitreous to greasy luster; transparent to translucent; white streak; effervesces in concentrated hydrochloric acid and produces a silica gel
Cassiterite	SnO <sub>2</sub>	6–7	Brown to black	Hydrothermal deposits in granites and granitic pegmatites; placer deposits
				<i>Remarks:</i> Usually brown to black; submetallic to adamantine luster; translucent; very dense (specific gravity near 7); white streak; may have elbow-shaped twins; imperfect cleavage in one direction; conchoidal fracture; insoluble in most acids
<b>Chloritoid</b>	(Fe,Mg)Al <sub>2</sub> SiO <sub>5</sub> (OH) <sub>2</sub>	$6\frac{1}{2}$	Usually green to black	Iron-rich phyllites and pelitic schists; some quartzites; some contact metamorphic marbles; some hydrothermal deposits
				<i>Remarks:</i> Chloritoid is not a mica—do not confuse with chlorite, which is softer; usually green to black; often massive; sometimes pseudohexagonal crystals; good cleavage in one direction, but not as good as micas; brittle; translucent; vitreous to pearly luster; light green to colorless streak; soluble in concentrated sulfuric acid, but insoluble in hydrochloric acid

**TABLE 3 Minerals with a Nonmetallic Luster and Hardness of 5½–6½ (continued)**

Name	Formula	Hardness	Color	Environment
Chondrodite	Mg <sub>5</sub> (SiO <sub>4</sub> ) <sub>2</sub> (F,OH) <sub>2</sub>	6–6½	Pale yellow, reddish brown, or red	Dolomitic marbles
<i>Remarks:</i> Pale yellow, reddish brown, or red; vitreous to resinous luster; translucent; usually massive; soluble in hot hydrochloric acid; optical and other sophisticated analytical methods may be needed to distinguish from other humites				
Clinzoisite	Ca <sub>2</sub> Al <sub>3</sub> (Si <sub>3</sub> O <sub>12</sub> )(OH)	6–6½	Light green to gray	Amphibolites; grossular schists; slates; quartzites; contact metamorphic rocks; hydrothermal alteration of anorthitic (calcic) plagioclases in intrusives
<i>Remarks:</i> Light green to gray; vitreous luster; striated crystals; perfect cleavage in one direction and imperfect in another; transparent to translucent; insoluble in most acids; optical and sophisticated analytical methods may be needed to positively identify				
Columbite-Tantalite solid solution series	(Fe,Mn)Nb <sub>2</sub> O <sub>6</sub> to (Fe,Mn)Ta <sub>2</sub> O <sub>6</sub> , often with tin (Sn) and tungsten (W) impurities	6	Black	Granitic intrusives, including pegmatites
<i>Remarks:</i> Black; dark red or black streak; submetallic luster; may be iridescent; good cleavage in one direction; fairly dense, specific gravity up to 7.9; prismatic or tabular crystals; insoluble in acids				
Cristobalite	SiO <sub>2</sub>	6½	Colorless, white, or gray	Felsic volcanics 1,470° SiO <sub>2</sub> 1,728°
<i>Remarks:</i> Colorless, white, or gray; vitreous luster; usually translucent; usually microcrystalline massive deposits; no cleavage; conchoidal fracture; insoluble in hydrochloric and nitric acids				
Cummingtonite	(Mg,Fe) <sub>7</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	5½–6	White to brown	Amphibolites; schists; some gneisses
<i>Remarks:</i> Amphibole; usually white to brown (darker specimens have more iron); usually fibrous, sometimes used as asbestos; perfect prismatic cleavage in one direction; translucent; vitreous to silky luster; insoluble in most acids; forms a solid solution with grunerite, the iron end member; optical and sophisticated analytical techniques are often needed to distinguish from other amphiboles				
Diaspore	AlO(OH)	6½–7	Usually white, gray, or green	Bauxites; aluminum-rich schists and other metamorphic rocks
<i>Remarks:</i> Usually white, gray, or green; vitreous to pearly luster; transparent to translucent; perfect cleavage in one direction; massive or bladed crystals; insoluble in most acids, but may partially dissolve in very alkaline solutions				
Diopside	CaMgSi <sub>2</sub> O <sub>6</sub>	5–6	White-green	Marbles; metamorphosed siliceous limestones and dolostones
<i>Remarks:</i> Pyroxene; white, light green, or other colors depending on impurities, such as chromium, manganese, or vanadium; cleavage at 87° and 93°, but imperfect; prismatic crystals; vitreous to resinous luster; insoluble in most acids; forms solid solution with hedenbergite				
Enstatite	MgSiO <sub>3</sub>	5½	Usually green	Peridotites; pyroxenites; gabbros; basalts; granulites; meteorites
<i>Remarks:</i> Orthopyroxene; usually green; short prismatic crystals; vitreous luster; translucent; good cleavage in one direction; forms a solid solution series with the uncommon iron end member, ferrosilite (FeSiO <sub>3</sub> ), and with bronzite and hypersthene as intermediate members; optical and other sophisticated analytical methods are required to distinguish from other pyroxenes				

**TABLE 3 Minerals with a Nonmetallic Luster and Hardness of 5½–6½ (continued)**

Name	Formula	Hardness	Color	Environment
<b>Epidote</b>	$\text{Ca}_2(\text{Al},\text{Fe})\text{Al}_2\text{Si}_3\text{O}_{12}(\text{OH})$	6–7	Usually yellowish green	Hydrothermal veins in granitic plutons; amphibolites; basalts
<i>Remarks:</i> Usually yellowish green; vitreous to dull luster; often as coatings on other minerals; sometimes as prismatic crystals; insoluble in most acids				
Fayalite	$(\text{Fe},\text{Mg})_2\text{SiO}_4$ with $(\text{Fe} \gg \text{Mg})$	$6\frac{1}{2}$	Dark green to brown	Highly metamorphosed banded iron formations; pegmatites; some granitic plutons and felsic volcanics
<i>Remarks:</i> Iron-rich olivine, forms a solid solution series with forsterite, magnesium-rich olivine; rarer than forsterite; dark green to brown; vitreous luster; short crystals; conchoidal fracture; slowly decomposes in hydrochloric acid to produce reddish brown silica gel; pure fayalite is practically non-existent; optical or analytical methods are required to determine the amount of iron and magnesium in this olivine				
Fergusonite	$(\text{Y},\text{Er},\text{Ce},\text{Fe})\text{NbO}_4$	$5\frac{1}{2}$ –6	Usually gray, yellow, or brown	Granitic pegmatites
<i>Remarks:</i> Usually gray, yellow, or brown; usually massive with dark brown surface coating; light brown to black streak; indistinct cleavage; conchoidal fracture; dull luster, although finer grains may be vitreous; partially soluble in hydrochloric acid				
<b>Forsterite</b>	$(\text{Mg},\text{Fe})_2\text{SiO}_4$ with $\text{Mg} \gg \text{Fe}$	$6\frac{1}{2}$	Green	Gabbros; peridotites; basalts; other mafic and ultramafic igneous rocks; dolomitic marbles
<i>Remarks:</i> Magnesium olivine; green; vitreous luster; transparent to translucent; conchoidal fracture; slowly decomposes in hydrochloric acid to produce a silica gel; optical or other sophisticated analytical methods are needed to determine the magnesium or iron contents of an olivine specimen				
Gadolinite	$\text{YFeBe}_2\text{Si}_2\text{O}_{10}$	$6\frac{1}{2}$ –7	Usually green or brown	Syenitic or granitic pegmatites
<i>Remarks:</i> Radioactive; usually green or brown; vitreous luster; no cleavage; conchoidal or bladed fracture; usually massive; usually transparent; decomposes in most strong acids to produce silica gel				
<b>Garnet</b>	$(\text{Mg},\text{Fe}^{2+},\text{Mn}^{2+},\text{Ca})_3-(\text{Al},\text{Cr},\text{Fe}^{3+})_2\text{Si}_3\text{O}_{12}$	$6\frac{1}{2}$ – $7\frac{1}{2}$	Variable	Schists; gneisses; amphibolites; peridotites; kimberlites; eclogites; contact metamorphosed limestones; rarer in granitic and alkaline igneous intrusives
<i>Remarks:</i> Red, brown, green, or other colors, depending on composition; no cleavage; adamantine luster; transparent to translucent; dodecahedrons are common; insoluble in most acids; common types: almandine, andradite, grossular, pyrope, spessartine, and mixtures of these end members; hydrogrossularite( $\text{Ca}_3\text{Al}_2\text{Si}_2\text{O}_8(\text{SiO}_4)_{1-n}(\text{OH})_{4n}$ ), hydrated garnet, may contain up to 8.5% water				
Glaucophane	$\text{Na}_2\text{Mg}_3\text{Al}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$	$6-6\frac{1}{2}$	Usually blue to violet-blue	Blueschists; eclogites
<i>Remarks:</i> Amphibole, rarely coarse enough to show 60°–120° cleavage angle; usually blue to violet-blue; vitreous luster; translucent; often fibrous; perfect cleavage; insoluble in most acids; optical or other analytical methods are needed to distinguish glaucophane from riebeckite and other amphiboles				
Grossular	$\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	$6\frac{1}{2}$	Usually white, green, yellow, or brown	Marbles; contact metamorphosed limestones
<i>Remarks:</i> Garnet; usually white, green, yellow, or brown; vitreous luster; usually transparent; often dodecahedra; no cleavage; fluorescent in ultraviolet light; insoluble in most acids				
<b>Grunerite</b>	$\text{Fe}_7\text{Si}_8\text{O}_{22}(\text{OH})_2$	6	Brown	Iron-rich schists
<i>Remarks:</i> Amphibole, often showing 60°–120° cleavage angle; forms solid solution series with cummingtonite; brown; translucent; silky luster; often radiating and fibrous; optical or other analytical methods are needed to distinguish grunerite from other amphiboles				

**TABLE 3 Minerals with a Nonmetallic Luster and Hardness of 5½–6½ (continued)**

Name	Formula	Hardness	Color	Environment
Hauynite	(Na,Ca) <sub>4–8</sub> (AlSiO <sub>4</sub> ) <sub>6</sub> (SO <sub>4</sub> ) <sub>1–2</sub>	5½–6	Usually blue, white, or green	Nepheline syenites; phonolites
<i>Remarks:</i> Usually blue, white, or green; usually occurs as small round grains rather than euhedral dodecahedral crystals; vitreous luster; transparent to translucent; decomposes in strong acids to form a silica gel; optical or other sophisticated analytical techniques may be needed to positively identify				
<b>Hedenbergite</b>	CaFeSi <sub>2</sub> O <sub>6</sub>	5–6	Black	Iron-rich metamorphic rocks, including skarns; iron-rich igneous intrusives
<i>Remarks:</i> Pyroxene; black; short prismatic crystals; often radiating; nearly opaque; greenish brown streak; cleavage at 87° and 93°, but imperfect; insoluble in most acids; optical or other sophisticated analytical methods may be needed to distinguish from other pyroxenes				
<b>Hematite</b>	Fe <sub>2</sub> O <sub>3</sub>	5½–6½	Red, brown, or black	Sandstones; banded iron formations; granitic intrusives; felsic volcanics; various metamorphic rocks; common in at least trace amounts in many other lithologies
<i>Remarks:</i> Red, brown, or black; red streak; metallic to earthy luster; slowly dissolves in hydrochloric acid; may be iridescent				
<b>Hornblende</b>	(K,Na) <sub>0–1</sub> (Ca,Na,Fe,Mg) <sub>2–3</sub> (Mg,Fe,Al) <sub>3–8</sub> O <sub>22</sub> (OH) <sub>2</sub>	5–6	Dark green to black	Amphibolites; schists; granodiorites; tonalites; monzonites; hornblendites; quartz porphyryes; dacites; latites; andesites
<i>Remarks:</i> Very common amphibole; dark green to black; fibrous to prismatic crystals with 56° and 124° angles; translucent; vitreous luster; insoluble in most acids				
<b>Hypersthene</b>	(Mg,Fe)SiO <sub>3</sub>	5–6	Usually dark green to brown	Peridotites; gabbros; pyroxenites; basalts; granulites; gneisses
<i>Remarks:</i> Orthopyroxene, intermediate in the enstatite-orthoferrosilite solid solution series; hypersthene is 50%–80% enstatite end member; usually dark green to brown; vitreous luster, may be pearly to submetallic; translucent to opaque; insoluble in most acids; may be difficult to distinguish from augite without optical methods				
Vesuvianite (Idocrase)	Ca <sub>10</sub> (Mg,Fe) <sub>2</sub> Al <sub>4</sub> Si <sub>9</sub> O <sub>34</sub> (OH) <sub>4</sub>	6½	Usually brown, yellow, or green	Contact metamorphosed limestones
<i>Remarks:</i> Usually brown, yellow, or green; vitreous to resinous luster; usually translucent; often occurs as striated tetragonal prisms; poor cleavage in one direction; conchoidal fracture; insoluble in most acids				
Jadeite	NaAlSi <sub>2</sub> O <sub>6</sub>	6½–7	Usually light or emerald green	Blueschists; serpentinites; other high-pressure metamorphic rocks
<i>Remarks:</i> Sodium-rich pyroxene; usually light or emerald green; vitreous luster; like other pyroxenes, cleavage angles of 87° and 93°; usually fibrous; insoluble in most acids; optical or other sophisticated analytical methods may be needed to distinguish from other pyroxenes				
Johannsenite	CaMnSi <sub>2</sub> O <sub>6</sub>	6	Usually dark green or gray	Marbles; skarns; hydrothermal deposits in rhyolites
<i>Remarks:</i> Pyroxene; usually dark green or gray; vitreous or greasy luster; good cleavage with angles of 87° and 93°; translucent to opaque; may have black manganese oxide coating; insoluble in hydrochloric acid unless the acid is heated; optical or other sophisticated analytical methods may be needed to distinguish from other pyroxenes				
<b>Labradorite</b>	Ab <sub>50</sub> An <sub>50</sub> to Ab <sub>30</sub> An <sub>70</sub>	6	Typically blue-gray	Gabbros; basalts; anorthosites
<i>Remarks:</i> Plagioclase feldspar; white or a variety of other colors; often twinned; usually massive; vitreous luster; white streak; often shows iridescence (play of colors); optical methods are usually required to distinguish from other plagioclase minerals				

**TABLE 3 Minerals with a Nonmetallic Luster and Hardness of 5½–6½ (continued)**

Name	Formula	Hardness	Color	Environment
Lazulite-Scorzalite	(Mg,Fe)Al <sub>2</sub> (PO <sub>4</sub> ) <sub>2</sub> (OH) <sub>2</sub> (Lazulite has Mg > Fe, while scorzalite has Fe > Mg)	5–5½	Usually blue	Pegmatites; pelitic schists
	Remarks: Usually blue; vitreous luster; usually translucent; usually massive; indistinct prismatic cleavage; fragments when heated; insoluble in most acids; optical and other sophisticated analytical methods may be needed to distinguish from other blue minerals. Associated with pyrite			
Lechatelierite	SiO <sub>2</sub>	6–7	Variable	Lightning strikes on sand deposits; recent meteorite impacts; sand deposits in contact with recently erupted volcanics
	Remarks: Natural silica glass; mineraloid; amorphous; colors vary depending on impurities; glassy luster; natural glasses tend to weather away rapidly over time			
Leucite	KAlSi <sub>2</sub> O <sub>6</sub>	5½–6	Usually white or gray	Recent silica-poor volcanics (for example, basalts and phonolites), often as phenocrysts
	Remarks: Usually white or gray; translucent to opaque; vitreous luster; tetragonal form often consists of trapezohedrons; no cleavage; conchoidal fracture; soluble in most strong acids; tetragonal form is stable below 605 °C, while isometric form occurs above this temperature			
Marialite- Meionite	Na <sub>4</sub> (AlSi <sub>3</sub> O <sub>8</sub> ) <sub>3</sub> (Cl <sub>2</sub> ,CO <sub>3</sub> ,SO <sub>4</sub> ) to Ca <sub>4</sub> (Al <sub>2</sub> Si <sub>2</sub> O <sub>8</sub> ) <sub>3</sub> (Cl <sub>2</sub> ,CO <sub>3</sub> , SO <sub>4</sub> )	5½–6	Usually white or gray	Schists; gneisses; amphibolites; contact metamorphosed limestones; pegmatites
	Remarks: Scapolite minerals; marialite is the sodium end member of a solid solution series with meionite, the calcium end member; usually white or gray, but may be a variety of colors; vitreous luster; transparent to translucent; often prismatic crystals with vertical striations; distinct cleavage in two directions; often fluoresces in ultraviolet light; decomposes in hydrochloric acid to produce a silica gel			
Microcline	KAlSi <sub>3</sub> O <sub>8</sub>	6	Typically white	Granitic intrusives; syenites; arkosic sandstones and conglomerates; gneisses
	Remarks: Potassium feldspar; very common mineral; usually white, sometimes bluish green ("amazonstone"); perfect cleavage in one direction and good in another; vitreous luster; may be twinned, especially carlsbad (penetration twins); usually translucent; prismatic crystals; insoluble in hydrochloric and nitric acids; optical and other sophisticated analytical techniques may be needed to distinguish from other feldspars			
Microlite	Ca <sub>2</sub> Ta <sub>2</sub> O <sub>6</sub> (O,OH,F)	5½	Usually brown	Granitic pegmatites
	Remarks: Usually brown, but may be yellow or colorless; usually massive; vitreous to resinous luster; usually translucent to opaque; yellow to brown streak; partially soluble in hydrochloric acid			
Nepheline	(Na,K)AlSiO <sub>4</sub>	5½–6	White, yellow-gray	Syenites; syenitic pegmatites; trachytes
	Remarks: Feldspathoid; white, gray, or a variety of other colors; often massive with greasy luster, but may exist as transparent vitreous crystals; distinct cleavage in one direction; unlike feldspars, decomposes in hydrochloric acid to produce silica gels			
Neptunite	KNa <sub>2</sub> Li(Fe,Mn) <sub>2</sub> TiO <sub>2</sub> (Si <sub>4</sub> O <sub>11</sub> ) <sub>2</sub>	5–6	Usually black	Nepheline pegmatites and syenites; serpentinites
	Remarks: Usually black; prismatic monoclinic crystals; vitreous luster; perfect cleavage; translucent to opaque; red streak; insoluble in hydrochloric acid			
Oligoclase	Ab <sub>90</sub> An <sub>10</sub> to Ab <sub>70</sub> An <sub>30</sub>	6	Usually white or gray	Granodiorites; monzonites; dacites; latites
	Remarks: Plagioclase feldspar; usually white or gray; bladed crystals; vitreous luster; mostly insoluble in hydrochloric acid; optical or other sophisticated analytical methods are probably needed to distinguish from other feldspars			

**TABLE 3** Minerals with a Nonmetallic Luster and Hardness of  $5\frac{1}{2}$ – $6\frac{1}{2}$  (*continued*)

Name	Formula	Hardness	Color	Environment
Olivine	$(Mg,Fe)_2SiO_4$	$6\frac{1}{2}$ –7	Various shades of green	Gabbros; peridotites; basalts; other mafic and ultramafic igneous rocks; dolomitic marbles; highly metamorphosed banded iron formations
<i>Remarks:</i> Forsterite-fayalite solid solution series dominates the composition of olivines; most are Mg-rich in various shades of green; vitreous luster; transparent to translucent; conchoidal fracture; slowly decomposes in hydrochloric acid to produce a silica gel; optical or other sophisticated analytical methods are needed to determine the magnesium or iron contents of an olivine specimen				
Omphacite	$(Ca,Na)(Mg,Fe,Al)Si_2O_6$	5–6	Green	Eclogites
<i>Remarks:</i> Sodium-rich pyroxene; green; prismatic crystals; cleavage at $87^\circ$ and $93^\circ$ , but imperfect; vitreous luster; translucent; white to light green streak; insoluble in most acids				
Opal	$SiO_2 \cdot nH_2O$	5–6	Variable	Hydrothermal deposits; volcanic tuffs; "petrified wood"; marine sediments
<i>Remarks:</i> Mineraloid; amorphous; white, colorless, yellow, black, red, or a variety of other colors, depending on the presence of impurities; vitreous to resinous luster; transparent to translucent; may fluoresce in ultraviolet light; conchoidal fracture; insoluble in most acids				
Orthoclase	$KAlSi_3O_8$	6	Usually white, or gray, pink	Granites; granodiorites; syenites; granitic pegmatites; gneisses; arkosic sandstones and conglomerates
<i>Remarks:</i> Potassium feldspar; usually white, gray, or pink; vitreous luster; often carlsbad (penetration) twins; prismatic or tabular crystals, but may be massive; imperfect to perfect cleavage in three directions, two cleavages at almost $90^\circ$ ; insoluble in most acids; optical or other sophisticated analytical methods may be needed to distinguish from other feldspars				
Periclase	MgO	$5\frac{1}{2}$	White	Dolomitic marbles
<i>Remarks:</i> Rare; usually microscopic; octahedral sheets or cubic crystals				
Perovskite	$CaTiO_3$	$5\frac{1}{2}$	Reddish brown, yellow, or black	Nepheline syenites; carbonatites
<i>Remarks:</i> Reddish brown, yellow, or black; usually pseudocubic crystals or massive; adamantine to submetallic luster; no cleavage; conchoidal fracture; light yellow streak				
Petalite	$Li(AlSi_4O_{10})$	6– $6\frac{1}{2}$	Usually white, gray, or colorless	Lithium-bearing pegmatites
<i>Remarks:</i> Usually white, gray, or colorless; vitreous luster; brittle; perfect cleavage in one direction and good cleavage in another; often columnar crystals; transparent to translucent; produces red flame from the presence of lithium; insoluble in most acids				
Piemontite	$Ca_2MnAl_2(Si_3O_{12})(OH)$	$6\frac{1}{2}$	Reddish or purplish brown	Manganese deposits
<i>Remarks:</i> Manganese epidote; reddish or purplish brown; bright red streak; often massive, sometimes in long slender prisms; vitreous luster; translucent; insoluble in acids; optical or other analytical methods may be needed to distinguish from other epidotes				
Pigeonite	$(Ca,Mg,Fe)_2Si_2O_6$	6	Greenish brown, brown, or black	Basalts; diabases
<i>Remarks:</i> Pyroxene; greenish brown, brown, or black; good cleavage in one direction; optical or other analytical methods are required to distinguish pigeonite from other pyroxenes, especially augite				

**TABLE 3** Minerals with a Nonmetallic Luster and Hardness of  $5\frac{1}{2}$ – $6\frac{1}{2}$  (*continued*)

Name	Formula	Hardness	Color	Environment
<b>Plagioclase</b>	$\text{Ab}_{100}\text{An}_0$ to $\text{Ab}_0\text{An}_{100}$	6	Usually white or gray	Intrusive igneous rocks of various types (for example, granites, syenites, and gabbros); felsic to mafic volcanics; pegmatites; schists; gneisses; contact metamorphic limestones
				<i>Remarks:</i> Very common feldspar; usually white or gray; bladed crystals; vitreous luster; usually translucent; white streak; twinning is common; some intermediate varieties may show a “play of colors”; albite is insoluble in hydrochloric acid, while anorthite decomposes to form a silica gel; optical and other sophisticated analytical methods are needed to quantify the calcium and sodium compositions of most plagioclases
<b>Prehnite</b>	$\text{Ca}_2\text{Al}(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$	$6-6\frac{1}{2}$	Usually white or light green	Cavities in basalts
				<i>Remarks:</i> Usually white or light green; vitreous luster; usually translucent; often massive, radiating crystals; optical or other sophisticated analytical techniques may be needed to positively identify
Psilomelane	$(\text{Ba},\text{Mn})_3(\text{O},\text{OH})_6\text{Mn}_8\text{O}_{16}$ (Romanechite)	5–6	Black	Associated with pyrolusite ( $\text{MnO}_2$ ) in marine sedimentary rocks (for example, limestones)
				<i>Remarks:</i> Black; submetallic luster; greasy feel; brownish black streak; opaque; dissolves in hydrochloric acid; branchlike forms on rock surfaces
<b>Rhodonite</b>	$\text{MnSiO}_3$	$5\frac{1}{2}$ –6	Usually pink	Manganese deposits; skarns
				<i>Remarks:</i> Pyroxenoid; usually pink; vitreous luster; transparent to translucent; may have brown or black surface coatings; crystals may be fibrous or tabular; nearly $90^\circ$ cleavages; insoluble in hydrochloric acid, unlike rhodochrosite; also harder than rhodochrosite
<b>Rutile</b>	$\text{TiO}_2$	$6-6\frac{1}{2}$	Usually red, brown, or black	Usually as microscopic crystals in granites, granitic pegmatites, gneisses, schists, marbles, and quartz grains
				<i>Remarks:</i> Usually red, reddish brown, or black; adamantine to metallic luster; light brown streak; transparent to translucent; often striated prismatic crystals; sometimes elbow-like twinning; frequently found as hairlike crystals inside of quartz crystals; fair cleavage in one direction; insoluble in most acids
Sanidine	$(\text{K},\text{Na})\text{AlSi}_3\text{O}_8$	6	Usually colorless or white	Phenocrysts in rhyolites and trachytes
				<i>Remarks:</i> Potassium feldspar; high-temperature solid solution series exists between sanidine and high albite with anorthoclase as an intermediate; usually colorless or white; vitreous luster; often transparent; white streak; nearly $90^\circ$ cleavage; insoluble in most acids; optical and analytical methods are needed to distinguish sanidine from other feldspars
<b>Scapolite</b>	$(\text{Na},\text{Ca})_4(\text{Al}_2\text{Si}_2\text{O}_8)_3 \cdot (\text{CO}_3,\text{SO}_4,\text{Cl})$	5–6	Usually white, blue, gray, or pink	Schists; amphibolites; gneisses; granulites; skarns; pegmatites
				<i>Remarks:</i> Group of metamorphic minerals, including marialite-meionite solid solution series with mizzonite as an intermediate member; usually white, blue, gray, or pink; poor cleavage in two directions; vitreous luster; transparent or translucent; usually fluoresces in ultraviolet light; decomposes in hydrochloric acid leaving a silica gel
<b>Sillimanite</b>	$\text{Al}_2\text{SiO}_5$	6–7	Usually white, gray, or brown	High-temperature pelitic schists and gneisses
				<i>Remarks:</i> Polymorph of kyanite and andalusite; usually brown, gray, or white; vitreous luster; perfect cleavage in one direction; usually translucent; elongated crystals or fibrous; insoluble in most strong acids
Sodalite	$\text{Na}_3\text{Al}_3\text{Si}_3\text{O}_{12} \cdot \text{NaCl}$	$5\frac{1}{2}$ –6	Typically blue	Nepheline syenites; phonolites; trachytes
				<i>Remarks:</i> Usually blue, sometimes white, gray, or light green; vitreous luster; usually translucent; poor cleavage in one direction; usually massive; produces yellow flame from the presence of sodium; decomposes in hydrochloric acid to produce a silica gel; optical or sophisticated analytical methods may be necessary to distinguish from other blue minerals

**TABLE 3 Minerals with a Nonmetallic Luster and Hardness of 5½–6½ (continued)**

Name	Formula	Hardness	Color	Environment
Spodumene	$\text{LiAlSi}_2\text{O}_6$	6½–7	Typically white	Lithium-rich pegmatites
<i>Remarks:</i> Lithium pyroxene; usually white, but may be gray, yellow, green, or pink, depending on the presence of impurities; vitreous luster; transparent to translucent; prismatic vertically striated crystals; cleavage at 87° and 93°, like most pyroxenes; lithium in the mineral produces a red flame; insoluble in most acids				
Thorianite	$\text{ThO}_2$	6½	Black to dark gray	Granitic pegmatites; placer deposits
<i>Remarks:</i> Radioactive; black to dark gray; dark green streak; often cubic or octahedral crystals; submetallic luster; opaque; very dense (specific gravity near 9.8); poor cleavage; conchoidal fracture; insoluble in hydrochloric acid, but partially soluble in nitric acid				
Tremolite	$\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	5–6	Usually white	Dolomitic marbles; schists (often associated with talc); serpentinites
<i>Remarks:</i> Amphibole; usually white; forms complete solid solution series with ferroactinolite, with actinolite as an intermediate; vitreous luster; usually prismatic or radiating needlelike crystals; transparent to nearly opaque; insoluble in most acids				
Turquoise	$\text{CuAl}_6(\text{PO}_4)_4(\text{OH})_8 \cdot 4\text{H}_2\text{O}$	6	Light blue to greenish blue	Altered aluminum-rich volcanics in arid environments
<i>Remarks:</i> Light blue to greenish blue; usually massive; perfect cleavage in one direction; conchoidal fracture; greasy luster; opaque; harder than chrysocolla; white to light green streak; insoluble in most acids, but soluble in hot hydrochloric acid				
Uraninite	$\text{UO}_2$	5½	Black	Granitic intrusives, including pegmatites; hydrothermal deposits associated with copper minerals, silver, or sulfides; sandstones
<i>Remarks:</i> Radioactive; black; brownish black streak; pitchblende is a massive variety, where some of the uranium is hexavalent rather than tetravalent; submetallic to dull luster; usually massive (pitchblende variety), but uraninite consists of octahedral, cubic, or dodecahedral crystals; very dense (specific gravity of 7.5 to 9.7 for uraninite and 6.5 to 9 for pitchblende variety); uraninite, including pitchblende, may contain substantial amounts of rare earth elements, which affects physical properties; generally insoluble in hydrochloric acid, but soluble in nitric and sulfuric acids				
Willemite	$\text{Zn}_2\text{SiO}_4$	5½	Black-brown	Zinc deposits in marbles
<i>Remarks:</i> Black, brown, sometimes colorless, or a variety of other colors; vitreous to resinous luster; transparent to translucent; usually massive; may fluoresce in ultraviolet light; good cleavage in one direction; powder decomposes in hydrochloric acid to produce a silica gel; sophisticated analytical methods may be needed to positively identify				
Zoisite	$\text{Ca}_2\text{Al}_3\text{Si}_3\text{O}_{12}(\text{OH})$	6	Pink-white	Gneisses; granulites; eclogites; hydrothermal sulfide deposits
<i>Remarks:</i> Orthorhombic polymorph of clinozoisite; white, pink, or a variety of other colors depending on the presence of impurities; vitreous luster; usually transparent or translucent; often striated prismatic crystals or massive; insoluble in most acids; optical or sophisticated analytical methods may be needed to positively identify				

**TABLE 4** Minerals with a Nonmetallic Luster and Hardness of 7 or Greater

Name	Formula	Hardness	Color	Environment
<b>Almandine</b>	$\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	7	Red	Schists
Remarks: Red garnet; no cleavage; adamantine luster; often dodecahedral form; insoluble in most acids				
<b>Andalusite</b>	$\text{Al}_2\text{SiO}_5$	$7\frac{1}{2}$	Red, brown, or green	Low pressure pelitic (aluminum-rich) metamorphic rocks, especially schists
Remarks: Polymorph of kyanite and sillimanite; red, brown, or green; vitreous luster; usually translucent to opaque; crosses may occur within prismatic crystals; insoluble in most acids				
<b>Andradite</b>	$\text{Ca}_3\text{Fe}_2\text{Si}_3\text{O}_{12}$	7	Brown, red, black, green, or yellow	Contact metamorphic limestones; skarns
Remarks: Garnet; brown, red, black (melanite), green, or yellow; no cleavage; adamantine luster; often dodecahedral form; insoluble in most acids				
Beryl	$\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$	$7\frac{1}{2}$ –8	Typically green to white	Granitic intrusives; pegmatites; biotite schists
Remarks: Green (emeralds), greenish blue (aquamarine variety), yellow, white, pink, or colorless; transparent to translucent; vitreous luster; hexagonal crystals; insoluble in most acids				
<b>Chert</b>	$\text{SiO}_2$	7	Variable	Carbonate rocks, including chalk; banded iron formations; marine sediments of various types
Remarks: Light colored; darker varieties called <i>flint</i> ; jasper is the red variety; fine grained (microcrystalline); produces sparks when struck; other properties similar to quartz				
<b>Chrysoberyl</b>	$\text{BeAl}_2\text{O}_4$	$8\frac{1}{2}$	Variable	Granitic rocks; pegmatites; schists; placer deposits
Remarks: Green, brown, yellow, gray, or colorless; vitreous luster; insoluble in most acids; often in pseudohexagonal form; fair cleavage in one direction; transparent to translucent				
<b>Cordierite</b>	$(\text{Mg},\text{Fe})_2\text{Al}_4\text{Si}_5\text{O}_{18} \cdot n\text{H}_2\text{O}$	$7-7\frac{1}{2}$	Bluish gray, black, or blue	Schists; gneisses; contact metamorphic rocks
Remarks: Bluish gray, black, or blue; pleochroic; prismatic crystals; vitreous luster; poor cleavage in one direction; conchoidal fracture; often translucent; insoluble in most acids				
Corundum	$\text{Al}_2\text{O}_3$	9	Variable	Schists; gneisses; syenites; peridotites; pegmatites; placer deposits
Remarks: White, red (rubies), blue (sapphires), gray, green, and other colors; adamantine to vitreous luster; transparent to translucent; extremely hard; insoluble in most acids; some fluoresce yellow; others display asterism, or an image of a star parallel to the c-axis of the crystal				
Diamond	C	10	Usually colorless or yellow	Kimberlites; placer deposits
Remarks: Hardest natural substance; usually colorless or yellow; adamantine luster; perfect cleavage in one direction; will burn at high temperatures; sometimes fluorescent in ultraviolet light				
Dumortierite	$\text{Al}_7\text{BSi}_3\text{O}_{18}$	7	Blue, violet, or reddish brown	Aluminum-rich metamorphic rocks, including contact metamorphic rocks; pegmatites
Remarks: Blue, violet, or reddish brown; vitreous luster; translucent; poor cleavage; insoluble in most acids; columnar or fibrous and radiating crystals				
Euclase	$\text{BeAlSiO}_4(\text{OH})$	$7\frac{1}{2}$	Variable	Granitic pegmatites; placer deposits
Remarks: Colorless, white, blue, green, or other colors; prismatic crystals; often striated; perfect cleavage; conchoidal fracture; transparent to translucent; vitreous luster; insoluble in most acids				

**TABLE 4 Minerals with a Nonmetallic Luster and Hardness of 7 or Greater (continued)**

Name	Formula	Hardness	Color	Environment
<b>Flint</b>	$\text{SiO}_2$	7	Dark	Carbonate rocks, including chalk; banded iron formations; marine sediments of various types
<i>Remarks:</i> Dark colored; red variety is jasper, while lighter varieties are called <i>chert</i> ; fine grained (microcrystalline); produces sparks when struck; other properties similar to quartz				
<b>Gahnite</b>	$\text{ZnAl}_2\text{O}_4$	$7\frac{1}{2}$ –8	Dark green	Granitic pegmatites; zinc deposits; contact metamorphosed limestones
<i>Remarks:</i> Zinc spinel; dark green; vitreous luster; commonly forms octahedral crystals				
<b>Garnet</b>	$(\text{Mg},\text{Fe}^{2+},\text{Mn}^{2+},\text{Ca})_3(\text{Al},\text{Cr},\text{Fe}^{3+})_2\text{Si}_3\text{O}_{12}$	$6\frac{1}{2}$ – $7\frac{1}{2}$	Variable	Schists; gneisses; amphibolites; peridotites; kimberlites; contact metamorphosed limestones; rarer in granitic and alkaline igneous intrusives
<i>Remarks:</i> Red, brown, green, or other colors, depending on composition; no cleavage; adamantine luster; often dodecahedral form; insoluble in most acids; common types: almandine, andradite, grossular, pyrope, spessartine, and mixtures of these end members				
<b>Hercynite</b>	$\text{FeAl}_2\text{O}_4$	$7\frac{1}{2}$ –8	Dark green	Gneisses
<i>Remarks:</i> An iron spinel; dark green; octahedral crystals; nonmagnetic; no streak				
<b>Kyanite</b>	$\text{Al}_2\text{SiO}_5$	5–7	Usually blue	High-pressure aluminum-rich schists; kimberlites; some eclogites
<i>Remarks:</i> Polymorph of andalusite and sillimanite; usually blue; hardness of about 5 parallel to length of crystals and about 7 perpendicular; bladed crystals with perfect cleavage in one direction; vitreous luster; insoluble in most acids				
<b>Lawsonite</b>	$\text{CaAl}_2\text{Si}_2\text{O}_7(\text{OH})_2 \cdot \text{H}_2\text{O}$	8	Blue to gray or colorless	Blueschists
<i>Remarks:</i> Blue, bluish gray or colorless; vitreous luster; translucent; good cleavage in two directions				
<b>Melanite</b>	$\text{Ca}_3\text{Fe}_2\text{Si}_3\text{O}_{12}$	7	Black	Alkaline igneous intrusives
<i>Remarks:</i> Black andradite garnet; no cleavage; adamantine luster; often dodecahedral form; insoluble in most acids				
<b>Phenacite</b> (Phenakite)	$\text{Be}_2\text{SiO}_4$	$7\frac{1}{2}$ –8	Colorless or white	Pegmatites; mica schists
<i>Remarks:</i> Colorless or white; vitreous luster; transparent to translucent; rhombohedral crystals, often twinned; poor cleavage in one direction; insoluble in most acids				
<b>Pyrope</b>	$\text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	7	Purple, red, or black	Ultramafic rocks, including peridotites, serpentinites, and kimberlites; eclogites
<i>Remarks:</i> Magnesium garnet; purple, red, or black; often transparent; no cleavage; adamantine luster; often dodecahedral form; insoluble in most acids				
<b>Quartz</b>	$\text{SiO}_2$	7	Variable	Very common; igneous rocks, especially felsic volcanics and granitic intrusives and pegmatites; schists, gneisses, and most other metamorphic rocks; sandstones and most sedimentary rocks, even many carbonate rocks
<i>Remarks:</i> Often white, sometimes colorless, purple, red, blue, yellow, or other colors; vitreous luster; conchoidal fracture; may contain fibrous needles of rutile; only soluble in hydrofluoric acid. <i>Warning!</i> Hydrofluoric acid is very dangerous, use with great care!				
<b>Spessartine</b>	$\text{Mn}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	7	Brown to red	Skarns; some manganese deposits
<i>Remarks:</i> Manganese garnet; brown to red; no cleavage; adamantine luster; often dodecahedral form; insoluble in most acids				

**TABLE 4** Minerals with a Nonmetallic Luster and Hardness of 7 or Greater (*continued*)

Name	Formula	Hardness	Color	Environment
<b>Spinel</b>	MgAl <sub>2</sub> O <sub>4</sub>	8	Variable	High-temperature silica-poor metamorphic rocks, including gneisses and some marbles; high-pressure ultramafics
<i>Remarks:</i> Red or various colors, depending on the amount of iron and other impurities; pure magnesium spinels are red and are easily confused with rubies; often contains some iron (hercynite); octahedral crystals; no cleavage; vitreous luster; transparent, translucent, or opaque; nonmagnetic; insoluble in most acids				
<b>Staurolite</b>	Fe <sub>2</sub> Al <sub>9</sub> Si <sub>4</sub> O <sub>23</sub> (OH) <sub>2</sub>	7–7½	Brown, reddish brown, or black	Medium-temperature aluminum-rich schists; placer deposits
<i>Remarks:</i> Brown, reddish brown, or black; pseudo-orthorhombic crystals; twinning is common and twins often form crosses or X shapes; usually resinous or dull luster; translucent to opaque; insoluble in most acids				
Topaz	Al <sub>2</sub> SiO <sub>4</sub> (F,OH) <sub>2</sub>	8	Typically colorless	Pegmatites; granitic intrusives; felsic volcanics
<i>Remarks:</i> Very hard; colorless or various colors depending on impurities; vitreous luster; transparent to translucent; perfect basal cleavage; insoluble in most acids				
<b>Tourmaline</b>	Na(Fe,Mg,Al,Li) <sub>3</sub> Al <sub>6</sub> (BO <sub>3</sub> ) <sub>3</sub> Si <sub>6</sub> O <sub>18</sub> (OH) <sub>4</sub>	7–7½	Variable	Granitic pegmatites and other granitic intrusives; schists; some metamorphosed carbonate rocks
<i>Remarks:</i> Black, blue, brown, green, yellow, pink, and other colors; vitreous to resinous luster; usually prismatic crystals with characteristic triangular shape with rounded corners; conchoidal fracture; insoluble in most acids; sometimes pleochroic. Various types: shorl (iron-rich), dravite (magnesium), elbaite (lithium), and others				
Uvarovite	Ca <sub>3</sub> Cr <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>	7½	Green	Some chromium-rich serpentinites
<i>Remarks:</i> Chromium garnet; green; no cleavage; adamantine luster; often transparent; often dodecahedral form; insoluble in most acids				
<b>Zircon</b>	ZrSiO <sub>4</sub>	7½	Usually brown	Granitic intrusives, often microscopic
<i>Remarks:</i> Usually brown; adamantine luster; usually translucent; tetragonal crystals; often microscopic crystals are found in biotite; conchoidal fracture; insoluble in most acids				

**TABLE 5 Minerals with a Metallic Luster and Hardness of Less Than 3**

Name	Formula	Hardness	Color	Environment	Streak
Argentite (Acanthite)	Ag <sub>2</sub> S	2–2½	Black	Silver and galena deposits	Shiny black
<i>Remarks:</i> Black; opaque; shiny on fresh surface, but a black oxide layer will quickly develop; soft enough to be cut with a knife; dense (specific gravity of 7.3); soluble in acids; poorer cleavage than galena; becomes isometric argentite above 179°C					
Bismuth	Bi	2–2½	Whitish silver with reddish tinge	Silver, nickel, cobalt, lead, uranium, and tin deposits	Light silver
<i>Remarks:</i> Whitish silver with reddish tinge; dense (specific gravity of 9.8); brittle; perfect cleavage in one direction; laminated; dissolves in nitric acid and forms a white precipitate after the acid solution is diluted					
Bournonite	PbCuSbS <sub>3</sub>	2½–3	Steel gray to black	Moderate-temperature hydrothermal deposits; sometimes as microscopic inclusions in galena	Gray black to black
<i>Remarks:</i> Steel gray to black; opaque; short prismatic to tabular crystals; imperfect cleavage in one direction; dissolves in nitric acid to produce a light green solution because of the copper in the mineral					
Calaverite	AuTe <sub>2</sub>	2½	Brass yellow to whitish silver	Hydrothermal deposits	Yellowish to Greenish gray
<i>Remarks:</i> Brass yellow to whitish silver; opaque; brittle; produces red solution when dissolved in sulfuric acid					
Chalcocite	Cu <sub>2</sub> S	2½–3	Gray with black tarnish	Hydrothermal sulfide deposits	Grayish black
<i>Remarks:</i> Gray with black tarnish; poor cleavage in one direction; conchoidal fracture; opaque; dissolves in nitric acid; green flame with sulfur dioxide fumes					
Copper	Cu	2½–3	Copper red	Basalts; hydrothermal deposits	Copper red
<i>Remarks:</i> Copper red; dense (specific gravity of 8.9); ductile; malleable; tetrahedral or octahedral crystals; dissolves in nitric acid					
Covellite	CuS	1½–2	Indigo blue	Copper deposits	Gray to black
<i>Remarks:</i> Indigo blue; often iridescent; opaque; micaceous or platy cleavage; when dissolved in hydrochloric acid produces a green flame					
Galena	PbS	2½	Silver	Hydrothermal deposits of lead and silver; some pegmatites; some contact metamorphic rocks	Gray
<i>Remarks:</i> Silver; usually cubic form; dense (specific gravity of about 7.5); black tarnish					
Gold	Au	2½–3	Yellow	Hydrothermal quartz veins; placer deposits; volcanics	Yellow
<i>Remarks:</i> Yellow; very dense (specific gravity of 15–19); hackly fracture; very ductile and malleable; opaque					
Graphite	C	1–2	Black	Schists; marbles; gneisses; highly metamorphosed coals	Black
<i>Remarks:</i> "Pencil lead"; black; greasy; marks paper; although nonmetal, usually has metallic luster; insoluble in most acids					
Jamesonite	Pb <sub>4</sub> FeSb <sub>6</sub> S <sub>14</sub>	2–3	Gray to gray-black	Lead deposits	Gray to grayish black
<i>Remarks:</i> Gray to grayish black; opaque; brittle; good cleavage in one direction; fibrous; difficult to distinguish from some other lead minerals without sophisticated analytical equipment					
Molybdenite	MoS <sub>2</sub>	1–1½	Gray with bluish tint	Some granites; pegmatites; some contact metamorphic rocks	Grayish black
<i>Remarks:</i> Gray with bluish tint; greasy; opaque; higher specific gravity than graphite; laminar; gives greenish streak on glazed porcelain or greenish gray mark on paper					
Pyrolusite	MnO <sub>2</sub>	1–2	Black	Surface of some limestones; bog and lake sediments; quartz veins	Bluish black
<i>Remarks:</i> Black; prismatic crystals; often as branchlike features (dendrites) on limestones look like plant fossils but are not; soluble in hydrochloric acid; greasy; marks paper					
Silver	Ag	2½–3	Silver	Hydrothermal deposits	Whitish silver
<i>Remarks:</i> Silver; brown to black tarnish; dense (specific gravity of 10–12); hackly fracture; ductile; malleable. Soluble in nitric acid					

**TABLE 5 Minerals with a Metallic Luster and Hardness of Less Than 3 (continued)**

Name	Formula	Hardness	Color	Environment	Streak
Stibnite	Sb <sub>2</sub> S <sub>3</sub>	2	Gray to black	Hydrothermal deposits	Gray to black
			Remarks: Gray to black; perfect cleavage in one direction; opaque; bladed crystals; iridescent film on surface; powder produces orange solution when dissolved in concentrated hydrochloric acid. <i>Remember to work with acids under a ventilation hood!</i>		
Sylvanite	(Au,Ag)Te <sub>2</sub>	1½–2	Whitish silver	Hydrothermal deposits	Gray
			Remarks: Whitish silver; dense (specific gravity near 8); produces red solution in concentrated sulfuric acid; better cleavage (perfect in one direction) than calaverite; soluble in nitric acid, but leaves residue of gold. <i>Remember to work with acids under a ventilation hood!</i>		

**TABLE 6 Minerals with a Metallic Luster and Hardness of 3–5½**

Name	Formula	Hardness	Color	Environment	Streak
Arsenic	As	3½	White to silver	Silver, cobalt, or nickel deposits	Gray
<i>Remarks:</i> Poisonous; do not taste, heat, or dissolve in acids; whitish silver on fresh surface, tarnish to dark gray; brittle; perfect cleavage					
Bornite	Cu <sub>5</sub> FeS <sub>4</sub>	3	Blue to purple	Copper deposits; contact metamorphic rocks; basalts	Grayish black
<i>Remarks:</i> Bronze with bluish purple tarnish ("peacock ore"); often associated with chalcocite and covellite; poor cleavage; soluble in most strong acids					
Chalcopyrite	CuFeS <sub>2</sub>	3½–4	Brass yellow	Copper deposits; schists; contact metamorphic rocks; pegmatites; metamorphosed basalts and other mafic volcanics	Greenish black
<i>Remarks:</i> Brass yellow with iridescent tarnish; softer than pyrite; brittle; tetrahedral crystals are common; no cleavage; conchoidal fracture					
Copper	Cu	2½–3	Copper red	Basalts; hydrothermal deposits	Copper red
<i>Remarks:</i> Copper red; dense (specific gravity of 8.9); ductile; malleable; tetrahedrahedral or octahedral; dissolves in nitric acid					
Enargite	Cu <sub>3</sub> AsS <sub>4</sub>	3	Grayish black to black	Hydrothermal deposits	Grayish black to black
<i>Remarks:</i> Possibly poisonous; do not heat, taste, or dissolve in acids; grayish black to black; perfect cleavage in one direction and distinct cleavages in two other directions; opaque					
Iron	Fe	4½	Gray to black	Meteorites	Gray to black
<i>Remarks:</i> Gray to black; magnetic; hackly fracture; poor cleavage in one direction; malleable; soluble in hydrochloric acid; dense (specific gravity of about 7.6)					
Manganite	MnO(OH)	4	Gray to black	Low-temperature hydrothermal deposits	Dark brown
<i>Remarks:</i> Gray to black with possible reddish brown tint; perfect cleavage in one direction and good cleavages in two other directions; opaque; striated prismatic crystals may occur; soluble in hydrochloric acid					
Metacinnabar	Hg <sub>1–n</sub> S	3	Grayish black	Mercury deposits	Black
<i>Remarks:</i> Grayish black; dense; considered stable above 344°C, but may form at ambient temperatures					
Millerite	NiS	3–3½	Pale yellow	Nickel deposits; marbles; cherty limestone	Greenish black to black
<i>Remarks:</i> Pale yellow, possibly with greenish tinge; often fine hairlike acicular crystals; good cleavages in two directions					
Niccolite	NiAs	5–5½	Copper red	Gabbros; cobalt, nickel, and silver deposits	Brownish black
<i>Remarks:</i> Possibly poisonous; do not heat, taste, or dissolve in acids; copper red with gray to black tarnish; dense (specific gravity of 7.8); opaque; no cleavage; conchoidal fracture					
Pentlandite	(Fe,Ni) <sub>9</sub> S <sub>8</sub>	3½–4	Yellowish bronze	Gabbros; nickel deposits	Brown
<i>Remarks:</i> Light yellowish bronze; octahedral parting; similar in appearance to pyrrhotite, except nonmagnetic					
Platinum	Pt	4–4½	Gray	Dunites and other ultramafic rocks; placer deposits	Gray
<i>Remarks:</i> Gray; very dense (specific gravity up to 19 with natural impurities, 21 if purified); malleable; magnetic, if sufficient iron impurities are present					
Psilomelane	(Ba,Mn) <sub>3</sub> (O,OH) <sub>6</sub> Mn <sub>8</sub> O <sub>16</sub>	5–6	Black	Associated with pyrolusite (MnO <sub>2</sub> ) in marine sedimentary rocks (for example, limestones)	Brownish black to black
<i>Remarks:</i> Black; submetallic luster; greasy feel; opaque; dissolves in hydrochloric acid; branchlike forms on rock surfaces					

**TABLE 6** Minerals with a Metallic Luster and Hardness of 3–5½ (*continued*)

Name	Formula	Hardness	Color	Environment	Streak
<b>Pyrrhotite</b>	$\text{Fe}_{1-x}\text{S}$	4	Brownish bronze	Mafic intrusives; sulfide deposits; pegmatites; contact metamorphic rocks	Black
<i>Remarks:</i> Brownish bronze; possibly magnetic, but generally weak; opaque					
Tennantite-Tetrahedrite	$\text{Cu}_{12}(\text{As},\text{Sb})_4\text{S}_{13}$	3–4½	Gray to black	Hydrothermal deposits; tetrahedrite is more common than tennantite	Black, gray, or brown
<i>Remarks:</i> Possibly poisonous; do not heat, taste, or dissolve in acids; gray to black; metallic to submetallic luster; tetrahedrite crystals; brittle; no cleavage					

**TABLE 7** Minerals with a Metallic Luster and Hardness of  $5\frac{1}{2}$ – $6\frac{1}{2}$ 

Name	Formula	Hardness	Color	Environment	Streak
<b>Arsenopyrite</b>	FeAsS	$5\frac{1}{2}$ –6	Silver-white	High-temperature hydrothermal deposits; pegmatites; contact metamorphic rocks; some crystalline limestones	Black
<i>Remarks: Possibly poisonous; may release poisonous vapors if dissolved in acid; also, do not taste or heat; silver-white; elongated prismatic crystals; produces sparks and a garlic odor when struck</i>					
<b>Chromite</b>	FeCr <sub>2</sub> O <sub>4</sub>	$5\frac{1}{2}$	Black or dark brown	Peridotites; serpentinites; other ultramafic rocks	Dark brown
<i>Remarks: Black or dark brown; opaque; submetallic or metallic luster; weakly magnetic; insoluble in most strong acids; may have yellow or green surface oxide layers</i>					
Cobaltite	(Co,Fe)AsS	$5\frac{1}{2}$	Silver-white	High-temperature metamorphic and hydrothermal rocks containing cobalt deposits	Grayish black
<i>Remarks: Possibly poisonous; may release poisonous vapors if dissolved in acid or heated; also, do not taste; silver-white, perhaps reddish or purple tinge; may occur as pyritohedrons or pseudo-isometric cubes; perfect pseudocubic cleavage</i>					
Columbite-Tantalite solid solution series	(Fe,Mn)Nb <sub>2</sub> O <sub>6</sub> to (Fe,Mn)Ta <sub>2</sub> O <sub>6</sub> , often with tin (Sn) and tungsten (W) impurities	6	Black	Granitic intrusives; granitic pegmatites	Dark red or black
<i>Remarks: Black; submetallic luster; may be iridescent; good cleavage in one direction; fairly dense, specific gravity up to 7.9; prismatic or tabular crystals; insoluble in acids</i>					
Franklinite	ZnFe <sub>2</sub> O <sub>4</sub>	6	Black	Rare; zinc deposits	Reddish brown to dark brown
<i>Remarks: Black; no cleavage; conchoidal fracture; weakly magnetic; soluble in hydrochloric acid</i>					
<b>Hematite</b>	Fe <sub>2</sub> O <sub>3</sub>	$5\frac{1}{2}$ – $6\frac{1}{2}$	Red, brown, or black	Some sandstones; banded iron formations; granitic intrusives; felsic volcanics; various metamorphic rocks; common in at least trace amounts in many other lithologies	Red
<i>Remarks: Red, brown, or black; metallic to earthy luster; slowly dissolves in hydrochloric acid; may be iridescent</i>					
<b>Ilmenite</b>	FeTiO <sub>3</sub>	$5\frac{1}{2}$ –6	Black	Gabbros; diorites; anorthosites; some pegmatites; some-magnetite-rich ("black") beach sands	Black to brownish red, but not as red as hematite
<i>Remarks: Black; may be weakly magnetic; no cleavage; powder soluble in concentrated hydrochloric acid</i>					
<b>Magnetite</b>	Fe <sub>3</sub> O <sub>4</sub>	6	Black	Various igneous and metamorphic rocks; banded iron formations; beach "black" sands	Black
<i>Remarks: Black; strongly magnetic, unlike ilmenite; opaque; slowly soluble in hydrochloric acid</i>					
<b>Marcasite</b>	FeS <sub>2</sub>	$6$ – $6\frac{1}{2}$	Pale yellow	Lead and zinc deposits; some hydrothermal deposits; limestones; concretions in clays and shales	Grayish black
<i>Remarks: Pale yellow, almost white when fresh; less stable and common than pyrite; prismatic crystals or roselike nodules; when moist, breaks down to whitish iron sulfates and sulfuric acid</i>					

**TABLE 7** Minerals with a Metallic Luster and Hardness of  $5\frac{1}{2}$ – $6\frac{1}{2}$  (*continued*)

Name	Formula	Hardness	Color	Environment	Streak
Psilomelane	$(\text{Ba}, \text{Mn})_3(\text{O}, \text{OH})_6\text{Mn}_8\text{O}_{16}$	5–6	Black	Associated with pyrolusite ( $\text{MnO}_2$ ) in marine sedimentary rocks (for example, limestones)	Brownish black
<i>Remarks:</i> Black; submetallic luster; greasy feel; opaque; dissolves in hydrochloric acid; branchlike forms on rock surfaces					
Pyrite	$\text{FeS}_2$	$6-6\frac{1}{2}$	Yellow	Common in many lithologies, including intrusive igneous rocks, limestones, shales, metamorphic rocks, and hydrothermal deposits; may also replace fossils	Black
<i>Remarks:</i> "Fool's gold"; yellow; striated cubes, pyritohedrons, or octahedral crystals; may have iridescent yellowish brown film on surface					
Rutile	$\text{TiO}_2$	$6-6\frac{1}{2}$	Red, reddish brown, or black	Usually as microscopic crystals in granites, granitic pegmatites, gneisses, schists, marbles, and quartz grains	Light brown
<i>Remarks:</i> Usually red, reddish brown, or black; adamantine to metallic luster; transparent to translucent; often striated prismatic crystals; sometimes elbowlike twinning; fair cleavage in one direction; insoluble in most acids					
Skutterudite	$(\text{Co}, \text{Ni})\text{As}_3$	$5\frac{1}{2}$ –6	White to silver gray	Cobalt and nickel deposits	Black
<i>Remarks:</i> Possibly poisonous fumes; do not dissolve in acids or heat; also, do not taste; white to silver gray; opaque; brittle; usually cubic or octahedral					
Thorianite	$\text{ThO}_2$	$6\frac{1}{2}$	Black to dark gray	Granitic pegmatites; placer deposits	Dark green
<i>Remarks:</i> Radioactive; black to dark gray; often cubic or octahedral crystals; submetallic luster; opaque; very dense (specific gravity near 9.8); poor cleavage; conchoidal fracture; insoluble in hydrochloric acid, but partially soluble in nitric acid					

# APPENDIX

## Minerals Separated by Optic System and Sign, and Ordered by Index of Refraction

### Isotropic Minerals

Mineral	Formula	Crystal System	Refractive Index ( $\bar{n}$ )
fluorite	$\text{CaF}_2$	cubic	1.43
analcime	$\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$	cubic	1.48
sodalite	$\text{Na}_3\text{Al}_3\text{Si}_3\text{O}_{12} \cdot \text{NaCl}$	cubic	1.48
sylvite	$\text{KCl}$	cubic	1.49
halite	$\text{NaCl}$	cubic	1.54
garnet	$(\text{Ca},\text{Fe},\text{Mg})_3(\text{Al},\text{Fe})_2\text{Si}_3\text{O}_{12}$	cubic	1.71–1.87
periclase	$\text{MgO}$	cubic	1.736
spinel	$\text{MgAl}_2\text{O}_4$	cubic	1.74
chlorargerite	$\text{AgCl}$	cubic	2.07
diamond	$\text{C}$	cubic	2.419
sphalerite	$\text{ZnS}$	cubic	2.42
cuprite	$\text{Cu}_2\text{O}$	cubic	2.85

### Uniaxial (–) Minerals

Mineral	Formula	Crystal System	Mean Refractive Index ( $\bar{n}$ )	Birefringence ( $\delta$ )
nitratite	$\text{NaNO}_3$	hexagonal	1.33–1.58	0.251
chabazite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 6\text{H}_2\text{O}$	hexagonal	1.48	0.003
cristobalite	$\text{SiO}_2$	tetragonal	1.48	0.007
calcite	$\text{CaCO}_3$	hexagonal	1.48–1.65	0.172
dolomite	$\text{CaMg}(\text{CO}_3)_2$	hexagonal	1.5–1.67	0.179
magnesite	$\text{MgCO}_3$	hexagonal	1.5–1.7	0.191
nepheline	$(\text{Na},\text{K})\text{AlSiO}_4$	hexagonal	1.54	0.004
scapolite	$(\text{Na},\text{Ca})_4(\text{Al},\text{Si})_{12}\text{O}_{24}(\text{Cl},\text{CO}_3)$	tetragonal	1.54–1.59	0.004–0.037
ankerite	$\text{CaFe}(\text{CO}_3)_2$	hexagonal	1.54–1.75	0.202
autunite	$\text{Ca}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 10\text{H}_2\text{O}$	tetragonal	1.55–1.57	0.024
beryl	$\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$	hexagonal	1.56	0.006
rhodochrosite	$\text{MnCO}_3$	hexagonal	1.59–1.81	0.219
tourmaline	$\text{Na}(\text{Fe},\text{Mg},\text{Al},\text{Li})_3\text{Al}_6(\text{BO}_3)_3\text{Si}_6\text{O}_{18}(\text{OH})_4$	hexagonal	1.62–1.67	0.021–0.029
smithsonite	$\text{ZnCO}_3$	hexagonal	1.62–1.85	0.225
apatite	$\text{Ca}_5(\text{PO}_4)_3(\text{OH},\text{F},\text{Cl})$	hexagonal	1.63	0.003
siderite	$\text{FeCO}_3$	hexagonal	1.63–1.87	0.242
vesuvianite	$\text{Ca}_{10}(\text{Mg},\text{Fe})_2\text{Al}_4\text{Si}_9\text{O}_{34}(\text{OH})_4$	tetragonal	1.7	0.005
corundum	$\text{Al}_2\text{O}_3$	hexagonal	1.76	0.008
pyromorphite	$\text{Pb}(\text{PO}_4)_3\text{Cl}$	hexagonal	2.04–2.05	0.01
hausmannite	$\text{Mn}_3\text{O}_4$	tetragonal	2.1–2.4	0.31
wulfenite	$\text{PbMoO}_4$	tetragonal	2.28–2.4	0.121

**Uniaxial (–) Minerals (continued)**

<b>Mineral</b>	<b>Formula</b>	<b>Crystal System</b>	<b>Mean Refractive Index (<math>\bar{n}</math>)</b>	<b>Birefringence (<math>\delta</math>)</b>
vanadinite	Pb <sub>5</sub> (VO <sub>4</sub> ) <sub>3</sub> Cl	hexagonal	2.3–2.4	0.066
anatase	TiO <sub>2</sub>	tetragonal	2.48–2.56	0.073
proustite	Ag <sub>3</sub> AsS <sub>3</sub>	hexagonal	2.71–2.98	0.17
pyrargyrite	Ag <sub>3</sub> SbS <sub>3</sub>	hexagonal	2.88–3.08	0.2
hematite	Fe <sub>2</sub> O <sub>3</sub>	hexagonal	3–3.2	0.28

**Uniaxial (+) Minerals**

<b>Mineral</b>	<b>Formula</b>	<b>Crystal System</b>	<b>Mean Refractive Index (<math>\bar{n}</math>)</b>	<b>Birefringence (<math>\delta</math>)</b>
leucite	KAlSi <sub>2</sub> O <sub>6</sub>	tetragonal	1.51	0.001
apophyllite	KCa <sub>4</sub> Si <sub>8</sub> O <sub>20</sub> F•8H <sub>2</sub> O	tetragonal	1.53	0.002
quartz	SiO <sub>2</sub>	hexagonal	1.53–1.54	0.009
brucite	Mg(OH) <sub>2</sub>	hexagonal	1.57–1.58	0.02
alunite	KAl <sub>3</sub> (SO <sub>4</sub> ) <sub>2</sub> (OH) <sub>6</sub>	hexagonal	1.57–1.59	0.02
stishovite	SiO <sub>2</sub>	tetragonal	1.8–1.82	0.027
scheelite	CaWO <sub>4</sub>	tetragonal	1.92–1.93	0.014
zircon	ZrSiO <sub>4</sub>	tetragonal	1.93–1.99	0.06
zincite	ZnO	hexagonal	2.01–2.02	0.016
rutile	TiO <sub>2</sub>	tetragonal	2.61–2.9	0.29
cinnabar	HgS	hexagonal	2.9–3.25	0.35
cassiterite	SnO <sub>2</sub>	tetragonal	2–2.1	0.09

**Biaxial (–) Minerals**

<b>Mineral</b>	<b>Formula</b>	<b>Crystal System</b>	<b>2V°</b>	<b>Mean Refractive Index (<math>\bar{n}</math>)</b>	<b>Birefringence (<math>\delta</math>)</b>
niter	KNO <sub>3</sub>	orthorhombic	7	1.33–1.5	0.172
borax	Na <sub>2</sub> B <sub>4</sub> O <sub>5</sub> (OH) <sub>4</sub> •8H <sub>2</sub> O	monoclinic	40	1.44–1.47	0.025
kernite	Na <sub>2</sub> B <sub>4</sub> O <sub>6</sub> (OH) <sub>2</sub> •3H <sub>2</sub> O	monoclinic	80	1.45–1.48	0.034
stilbite	CaAl <sub>2</sub> Si <sub>7</sub> O <sub>18</sub> •7H <sub>2</sub> O	monoclinic	30–50	1.5	0.01
sepiolite	Mg <sub>4</sub> Si <sub>6</sub> O <sub>15</sub> (OH) <sub>2</sub> (H <sub>2</sub> O)•4H <sub>2</sub> O	orthorhombic	20–70	1.51–1.53	0.02
chalcanthite	CuSO <sub>4</sub> •5H <sub>2</sub> O	triclinic	56	1.51–1.54	0.029
microcline	KAlSi <sub>3</sub> O <sub>8</sub>	triclinic	77–84	1.52	0.01
orthoclase	KAlSi <sub>3</sub> O <sub>8</sub>	monoclinic	60–65	1.52	0.007
sanidine	(K,Na)AlSi <sub>3</sub> O <sub>8</sub>	monoclinic	80–85	1.52	0.007
strontianite	SrCO <sub>3</sub>	orthorhombic	7	1.52–1.66	0.148
witherite	BaCO <sub>3</sub>	orthorhombic	16	1.52–1.67	0.148
aragonite	CaCO <sub>3</sub>	orthorhombic	18	1.53–1.68	0.155
talc	Mg <sub>3</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub>	monoclinic	6–30	1.54–1.58	0.05
variscite	AlPO <sub>4</sub> •2H <sub>2</sub> O	orthorhombic	48–54	1.55–1.59	0.03
pyrophyllite	Al <sub>2</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub>	triclinic	52–62	1.55–1.6	0.047
kaolinite	Al <sub>2</sub> Si <sub>2</sub> O <sub>5</sub> (OH) <sub>4</sub>	triclinic	40	1.56	0.007
muscovite	KAl <sub>2</sub> (AlSi <sub>3</sub> O <sub>10</sub> )(OH) <sub>2</sub>	monoclinic	30–40	1.56–1.6	0.035

**Biaxial (–) Minerals (continued)**

<b>Mineral</b>	<b>Formula</b>	<b>Crystal System</b>	<b>2V°</b>	<b>Mean Refractive Index (<math>\bar{n}</math>)</b>	<b>Birefringence (<math>\delta</math>)</b>
chlorite	talc+brucite combinations	monoclinic	0–40	1.56–1.61	0.006–0.02
antigorite	Mg <sub>3</sub> Si <sub>2</sub> O <sub>5</sub> (OH) <sub>4</sub>	monoclinic	20–60	1.57	0.007
anorthite	CaAl <sub>2</sub> Si <sub>2</sub> O <sub>8</sub>	triclinic	78	1.57–1.59	0.013
biotite	K(Mg,Fe) <sub>3</sub> AlSi <sub>3</sub> O <sub>10</sub> (OH) <sub>2</sub>	monoclinic	0–32	1.57–1.61	0.04
amblygonite	LiAl(PO <sub>4</sub> )F	triclinic	52–90	1.59–1.62	0.03
anthophyllite	(Mg,Fe) <sub>7</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	orthorhombic	65–90	1.6–1.63	0.03
tremolite-actinolite	Ca <sub>2</sub> (Mg,Fe) <sub>5</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	monoclinic	85–90	1.61–1.63	0.022
lazulite	(Mg,Fe)Al <sub>2</sub> (PO <sub>4</sub> ) <sub>2</sub> (OH) <sub>2</sub>	monoclinic	70	1.61–1.64	0.031
wollastonite	CaSiO <sub>3</sub>	triclinic	39	1.62–1.63	0.014
erythrite	Co <sub>3</sub> (AsO <sub>4</sub> ) <sub>2</sub> • 8H <sub>2</sub> O	monoclinic	90	1.62–1.69	0.073
andalusite	Al <sub>2</sub> SiO <sub>5</sub>	orthorhombic	75–85	1.63–1.64	0.01
margarite	CaAl <sub>2</sub> (Al <sub>2</sub> Si <sub>2</sub> O <sub>10</sub> )(OH) <sub>2</sub>	monoclinic	45	1.63–1.65	0.013
monticellite	CaMgSiO <sub>4</sub>	orthorhombic	72–82	1.64–1.66	0.02
glaucomphane	Na <sub>2</sub> Mg <sub>3</sub> Al <sub>2</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	monoclinic	0–50	1.65–1.67	0.01
hornblende	(K,Na) <sub>0.1</sub> (Ca,Na,Fe,Mg) <sub>2</sub> (Mg,Fe,Al) <sub>5</sub> (Si,Al) <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	monoclinic	50–80	1.65–1.67	0.02
malachite	Cu <sub>2</sub> CO <sub>3</sub> (OH) <sub>2</sub>	monoclinic	43	1.65–1.9	0.254
clinozoisite	Ca <sub>2</sub> Al <sub>3</sub> Si <sub>3</sub> O <sub>12</sub> (OH)	monoclinic	14–90	1.67–1.73	0.005–0.015
triphylite	Li(Fe,Mn)PO <sub>4</sub>	orthorhombic	0–56	1.68–1.69	0.01
kaersutite	Ti-rich hornblende	monoclinic	68–82	1.68–1.73	0.02–0.08
kyanite	Al <sub>2</sub> SiO <sub>5</sub>	triclinic	82–83	1.71–1.72	0.016
epidote	Ca <sub>2</sub> (Al,Fe) <sub>3</sub> Si <sub>3</sub> O <sub>12</sub> (OH)	monoclinic	90–115	1.71–1.8	0.01–0.05
carnotite	K <sub>2</sub> U <sub>2</sub> O <sub>4</sub> (VO <sub>4</sub> ) <sub>2</sub> • 3H <sub>2</sub> O	monoclinic	38–44	1.75–1.95	0.2
cerussite	PbCO <sub>3</sub>	orthorhombic	9	1.8–2.07	0.274
atacamite	Cu <sub>2</sub> Cl(OH) <sub>3</sub>	orthorhombic	75	1.83–1.88	0.047
lepidocrocite	FeO(OH)	orthorhombic	83	1.94–2.51	0.57
goethite	FeO(OH)	orthorhombic	0–27	2.26–2.52	0.15
perovskite	CaTiO <sub>3</sub>	orthorhombic	90	2.3	0.002
realgar	AsS	monoclinic	41	2.5–2.8	0.166

**Biaxial (+) Minerals**

<b>Mineral</b>	<b>Formula</b>	<b>Crystal System</b>	<b>2V°</b>	<b>Mean Refractive Index (<math>\bar{n}</math>)</b>	<b>Birefringence (<math>\delta</math>)</b>
cryolite	Na <sub>3</sub> AlF <sub>6</sub>	monoclinic	43	1.33	0.001
epsomite	MgSO <sub>4</sub> • 7H <sub>2</sub> O	orthorhombic	52	1.43–1.46	0.028
carnallite	KMgCl <sub>3</sub> • 6H <sub>2</sub> O	orthorhombic	70	1.46–1.49	0.029
natrolite	Na <sub>2</sub> Al <sub>2</sub> Si <sub>3</sub> O <sub>10</sub> • 2H <sub>2</sub> O	orthorhombic	38–62	1.48	0.012
tridymite	SiO <sub>2</sub>	orthorhombic	70	1.48	0.003
ulexite	NaCaB <sub>5</sub> O <sub>6</sub> (OH) <sub>6</sub> • 5H <sub>2</sub> O	triclinic	73	1.49–1.52	0.029
heulandite	CaAl <sub>2</sub> Si <sub>7</sub> O <sub>18</sub> • 6H <sub>2</sub> O	monoclinic	35	1.5	0.005
albite	NaAlSi <sub>3</sub> O <sub>8</sub>	triclinic	77	1.52	0.011
gypsum	CaSO <sub>4</sub> • 2H <sub>2</sub> O	monoclinic	58	1.52	0.009
wavellite	Al <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> (OH) <sub>3</sub> • 5H <sub>2</sub> O	orthorhombic	72	1.52–1.55	0.027
cordierite	(Mg,Fe) <sub>2</sub> Al <sub>4</sub> Si <sub>5</sub> O <sub>18</sub>	orthorhombic	65–105	1.54–1.56	0.02

**Biaxial (+) Minerals (*continued*)**

Mineral	Formula	Crystal System	$2V^\circ$	Mean Refractive Index ( $\bar{n}$ )	Birefringence ( $\delta$ )
norbergite	Mg <sub>3</sub> SiO <sub>4</sub> (OH,F) <sub>2</sub>	orthorhombic	44–50	1.56–1.58	0.026
gibbsite	Al(OH) <sub>3</sub>	monoclinic	0–40	1.57–1.59	0.02
anhydrite	CaSO <sub>4</sub>	orthorhombic	44	1.57–1.61	0.044
vivianite	Fe <sub>3</sub> (PO <sub>4</sub> ) <sub>3</sub> • 8H <sub>2</sub> O	monoclinic	83	1.57–1.63	0.054
colemanite	CaB <sub>3</sub> O <sub>4</sub> (OH) <sub>3</sub> • H <sub>2</sub> O	monoclinic	56	1.58–1.61	0.028
coesite	SiO <sub>2</sub>	monoclinic	64	1.59	0.01
pectolite	NaCa <sub>2</sub> (SiO <sub>3</sub> ) <sub>3</sub> H	triclinic	35–63	1.59–1.63	0.04
clinohumite	Mg <sub>9</sub> (SiO <sub>4</sub> ) <sub>2</sub> (OH,F) <sub>2</sub>	monoclinic	73–76	1.59–1.64	0.03–0.04
chondrodite	Mg <sub>5</sub> Si <sub>2</sub> O <sub>4</sub> (OH,F) <sub>2</sub>	monoclinic	60–90	1.6–1.63	0.03
topaz	Al <sub>2</sub> SiO <sub>4</sub> (F,OH) <sub>2</sub>	orthorhombic	48–65	1.61–1.62	0.01
turquoise	CuAl <sub>6</sub> (PO <sub>4</sub> ) <sub>4</sub> (OH) <sub>8</sub> • 4H <sub>2</sub> O	triclinic	40	1.61–1.65	0.04
celestite	SrSO <sub>4</sub>	orthorhombic	51	1.62–1.63	0.009
prehnite	Ca <sub>2</sub> Al(AlSi <sub>3</sub> O <sub>10</sub> )(OH) <sub>2</sub>	orthorhombic	65–70	1.62–1.65	0.03
barite	BaSO <sub>4</sub>	orthorhombic	37	1.63–1.64	0.012
olivine	(Mg,Fe) <sub>2</sub> SiO <sub>4</sub>	orthorhombic	47–90	1.63–1.88	0.035–0.053
boracite	Mg <sub>3</sub> ClB <sub>7</sub> O <sub>13</sub>	orthorhombic	82	1.64–1.67	0.011
cummingtonite	Mg <sub>7</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	monoclinic	80–90	1.64–1.67	0.03
jadeite	NaAlSi <sub>2</sub> O <sub>6</sub>	monoclinic	70–75	1.65–1.67	0.02
spodumene	LiAlSi <sub>2</sub> O <sub>6</sub>	monoclinic	60–80	1.65–1.67	0.02
sillimanite	Al <sub>2</sub> SiO <sub>5</sub>	orthorhombic	20–30	1.65–1.68	0.022
hypersthene	(Mg,Fe) <sub>2</sub> Si <sub>2</sub> O <sub>6</sub>	orthorhombic	54	1.66	0.008
lawsonite	CaAl <sub>2</sub> Si <sub>2</sub> O <sub>7</sub> (OH) <sub>2</sub> • H <sub>2</sub> O	orthorhombic	76–86	1.66–1.68	0.02
diopside	Ca(Mg,Fe)Si <sub>2</sub> O <sub>6</sub>	monoclinic	56–64	1.66–1.75	0.03
sinhalite	MgAlBO <sub>4</sub>	orthorhombic	58	1.67–1.71	0.04
diaspore	AlO(OH)	orthorhombic	85	1.68–1.75	0.04
pigeonite	(Ca,Mg,Fe) <sub>2</sub> Si <sub>2</sub> O <sub>6</sub>	monoclinic	38–44	1.69–1.72	0.025
chloritoid	(Fe,Mg)Al <sub>2</sub> SiO <sub>5</sub> (OH) <sub>2</sub>	monoclinic	45–65	1.71–1.72	0.01
rhodonite	MnSiO <sub>3</sub>	triclinic	63–76	1.71–1.73	0.013
antlerite	Cu <sub>3</sub> SO <sub>4</sub> (OH) <sub>4</sub>	orthorhombic	53	1.72–1.78	0.063
azurite	Cu <sub>3</sub> (CO <sub>3</sub> ) <sub>2</sub> (OH) <sub>2</sub>	monoclinic	68	1.73–1.83	0.106
chrysoberyl	BeAl <sub>2</sub> O <sub>4</sub>	orthorhombic	45	1.74–1.75	0.01
staurolite	Fe <sub>2</sub> Al <sub>9</sub> Si <sub>4</sub> O <sub>20</sub> (O,OH) <sub>2</sub>	monoclinic	80–88	1.74–1.75	0.013
monazite	(Ce,La,Th)PO <sub>4</sub>	monoclinic	10–20	1.78–1.85	0.05
titanite (sphene)	CaTiSiO <sub>5</sub>	monoclinic	23–50	1.86–2.1	0.15
anglesite	PbSO <sub>4</sub>	orthorhombic	75	1.87–1.89	0.017
sulfur	S	orthorhombic	69	1.95–2.24	
wolframite	(Fe,Mn)WO <sub>4</sub>	monoclinic	73–79	2.1–2.5	0.13–0.15
manganite	MnO(OH)	monoclinic	small	2.2–2.5	0.29
columbite	(Fe,Mn)(Nb,Ta) <sub>2</sub> O <sub>6</sub>	orthorhombic	75	2.3–2.4	0.12
crocoite	PbCrO <sub>4</sub>	monoclinic	54	2.3–2.6	0.35
orpiment	As <sub>2</sub> S <sub>3</sub>	monoclinic	76	2.4–3	0.62
brookite	TiO <sub>2</sub>	orthorhombic	0–30	2.58–2.72	0.14

# APPENDIX

## Minerals Ordered by Birefringence and Interference Colors in Thin Section

Mineral	Formula	Crystal System	Optical Properties				
			System	Sign	2V°	Mean R.I. ( $\bar{n}$ )	Birefringence ( $\delta$ )
<b>Minerals with Very Low Birefringence</b> (Interference colors generally white and gray in thin section)							
cryolite	$\text{Na}_3\text{AlF}_6$	monoclinic	biaxial	+	43	1.33	0.001
leucite	$\text{KAlSi}_2\text{O}_6$	tetragonal	uniaxial	+		1.51	0.001
apophyllite	$\text{KCa}_4\text{Si}_8\text{O}_{20}\text{F} \cdot 8\text{H}_2\text{O}$	tetragonal	uniaxial	+		1.53	0.002
perovskite	$\text{CaTiO}_3$	orthorhombic	biaxial	-	90	2.3	0.002
apatite	$\text{Ca}_5(\text{PO}_4)_3(\text{OH},\text{F},\text{Cl})$	hexagonal	uniaxial	-		1.63	0.003
chabazite	$\text{Ca}_2\text{Al}_2\text{Si}_4\text{O}_{12} \cdot 6\text{H}_2\text{O}$	hexagonal	uniaxial	-		1.48	0.003
tridymite	$\text{SiO}_2$	orthorhombic	biaxial	+	70	1.48	0.003
nepheline	$(\text{Na},\text{K})\text{AlSiO}_4$	hexagonal	uniaxial	-		1.54	0.004
scapolite	$(\text{Na},\text{Ca})_4(\text{Al},\text{Si})_{12}\text{O}_{24}(\text{Cl},\text{CO}_3)$	tetragonal	uniaxial	-		1.54–1.59	0.004–0.037
heulandite	$\text{CaAl}_2\text{Si}_7\text{O}_{18} \cdot 6\text{H}_2\text{O}$	monoclinic	biaxial	+	35	1.5	0.005
vesuvianite	$\text{Ca}_{10}(\text{Mg},\text{Fe})_2\text{Al}_4\text{Si}_9\text{O}_{34}(\text{OH})_4$	tetragonal	uniaxial	-		1.7	0.005
clinozoisite	$\text{Ca}_2\text{Al}_3\text{Si}_3\text{O}_{12}(\text{OH})$	monoclinic	biaxial	-	14–90	1.67–1.73	0.005–0.015
beryl	$\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$	hexagonal	uniaxial	-		1.56	0.006
chlorite	talc+brucite combinations	monoclinic	biaxial	-	0–40	1.56–1.61	0.006–0.02
antigorite	$\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$	monoclinic	biaxial	-	20–60	1.57	0.007
cristobalite	$\text{SiO}_2$	tetragonal	uniaxial	-		1.48	0.007
kaolinite	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	triclinic	biaxial	-	40	1.56	0.007
orthoclase	$\text{KAlSi}_3\text{O}_8$	monoclinic	biaxial	-	60–65	1.52	0.007
sanidine	$(\text{K},\text{Na})\text{AlSi}_3\text{O}_8$	monoclinic	biaxial	-	80–85	1.52	0.007
corundum	$\text{Al}_2\text{O}_3$	hexagonal	uniaxial	-		1.76	0.008
hypersthene	$(\text{Mg},\text{Fe})_2\text{Si}_2\text{O}_6$	orthorhombic	biaxial	+	54	1.66	0.008
celestite	$\text{SrSO}_4$	orthorhombic	biaxial	+	51	1.62–1.63	0.009
gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	monoclinic	biaxial	+	58	1.52	0.009
quartz	$\text{SiO}_2$	hexagonal	uniaxial	+		1.53–1.54	0.009
<b>Minerals with Low Birefringence</b> (Displaying up to first-order yellow, brown, orange, or red interference colors in thin section)							
andalusite	$\text{Al}_2\text{SiO}_5$	orthorhombic	biaxial	-	75–85	1.63–1.64	0.01
chloritoid	$(\text{Fe},\text{Mg})\text{Al}_2\text{SiO}_5(\text{OH})_2$	monoclinic	biaxial	+	45–65	1.71–1.72	0.01
chrysoberyl	$\text{BeAl}_2\text{O}_4$	orthorhombic	biaxial	+	45	1.74–1.75	0.01
coesite	$\text{SiO}_2$	monoclinic	biaxial	+	64	1.59	0.01
microcline	$\text{KAlSi}_3\text{O}_8$	triclinic	biaxial	-	77–84	1.52	0.01
pyromorphite	$\text{Pb}(\text{PO}_4)_3\text{Cl}$	hexagonal	uniaxial	-		2.04–2.05	0.01
stilbite	$\text{CaAl}_2\text{Si}_7\text{O}_{18} \cdot 7\text{H}_2\text{O}$	monoclinic	biaxial	-	30–50	1.5	0.01
topaz	$\text{Al}_2\text{SiO}_4(\text{F},\text{OH})_2$	orthorhombic	biaxial	+	48–65	1.61–1.62	0.01
triphylite	$\text{Li}(\text{Fe},\text{Mn})\text{PO}_4$	orthorhombic	biaxial	-	0–56	1.68–1.69	0.01
glaucophane	$\text{Na}_2\text{Mg}_3\text{Al}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$	monoclinic	biaxial	-	0–50	1.65–1.67	0.01
epidote	$\text{Ca}_2(\text{Al},\text{Fe})_3\text{Si}_3\text{O}_{12}(\text{OH})$	monoclinic	biaxial	-	90–115	1.71–1.8	0.01–0.05
albite	$\text{NaAlSi}_3\text{O}_8$	triclinic	biaxial	+	77	1.52	0.011
boracite	$\text{Mg}_3\text{ClB}_7\text{O}_{13}$	orthorhombic	biaxial	+	82	1.64–1.67	0.011

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Mineral	Formula	Crystal System	Optical Properties						
			System	Sign	2V°	Mean R.I. ( $\bar{n}$ )	Birefringence ( $\delta$ )		
<b>Minerals with Low Birefringence (continued)</b>									
(Displaying up to first-order yellow, brown, orange, or red interference colors in thin section)									
barite	$\text{BaSO}_4$	orthorhombic	biaxial	+	37	1.63–1.64	0.012		
natrolite	$\text{Na}_2\text{Al}_2\text{Si}_3\text{O}_{10} \cdot 2\text{H}_2\text{O}$	orthorhombic	biaxial	+	38–62	1.48	0.012		
anorthite	$\text{CaAl}_2\text{Si}_2\text{O}_8$	triclinic	biaxial	–	78	1.57–1.59	0.013		
margarite	$\text{CaAl}_2(\text{Al}_2\text{Si}_2\text{O}_{10})(\text{OH})_2$	monoclinic	biaxial	–	45	1.63–1.65	0.013		
rhodonite	$\text{MnSiO}_3$	triclinic	biaxial	+	63–76	1.71–1.73	0.013		
stauroelite	$\text{Fe}_2\text{Al}_9\text{Si}_4\text{O}_{23}(\text{OH})$	monoclinic	biaxial	+	80–88	1.74–1.75	0.013		
scheelite	$\text{CaWO}_4$	tetragonal	uniaxial	+		1.92–1.93	0.014		
wollastonite	$\text{CaSiO}_3$	triclinic	biaxial	–	39	1.62–1.63	0.014		
kyanite	$\text{Al}_2\text{SiO}_5$	triclinic	biaxial	–	82–83	1.71–1.72	0.016		
zincite	$\text{ZnO}$	hexagonal	uniaxial	+		2.01–2.02	0.016		
anglesite	$\text{PbSO}_4$	orthorhombic	biaxial	+	75	1.87–1.89	0.017		
<b>Minerals with Moderate Birefringence</b>									
(Displaying up to second-order interference colors in thin section)									
alunite	$\text{KAl}_3(\text{SO}_4)_2(\text{OH})_6$	hexagonal	uniaxial	+		1.57–1.59	0.02		
brucite	$\text{Mg}(\text{OH})_2$	hexagonal	uniaxial	+		1.57–1.58	0.02		
cordierite	$(\text{Mg},\text{Fe})_2\text{Al}_4\text{Si}_5\text{O}_{18}$	orthorhombic	biaxial	+/–	65–105	1.54–1.56	0.02		
gibbsite	$\text{Al}(\text{OH})_3$	monoclinic	biaxial	+	0–40	1.57–1.59	0.02		
hornblende	$(\text{K},\text{Na})_{0.1}(\text{Ca},\text{Na},\text{Fe},\text{Mg},\text{Mn})_2(\text{Mg},\text{Fe},\text{Al})_5(\text{Si},\text{Al})_8\text{O}_{22}(\text{OH})_2$	monoclinic	biaxial	–	50–80	1.65–1.67	0.02		
jadeite	$\text{NaAlSi}_2\text{O}_6$	monoclinic	biaxial	+	70–75	1.65–1.67	0.02		
lawsonite	$\text{CaAl}_2\text{Si}_2\text{O}_7(\text{OH})_2 \cdot \text{H}_2\text{O}$	orthorhombic	biaxial	+	76–86	1.66–1.68	0.02		
monticellite	$\text{CaMgSiO}_4$	orthorhombic	biaxial	–	72–82	1.64–1.66	0.02		
sepiolite	$\text{Mg}_4\text{Si}_6\text{O}_{15}(\text{OH})_2(\text{H}_2\text{O}) \cdot 4\text{H}_2\text{O}$	orthorhombic	biaxial	–	20–70	1.51–1.53	0.02		
spodumene	$\text{LiAlSi}_2\text{O}_6$	monoclinic	biaxial	+	60–80	1.65–1.67	0.02		
kaersutite	Ti-rich hornblende	monoclinic	biaxial	–	68–82	1.68–1.73	0.02–0.08		
tourmaline	$\text{Na}(\text{Fe},\text{Mg},\text{Al},\text{Li})_3\text{Al}_6(\text{BO}_3)_3\text{Si}_6\text{O}_{18}(\text{OH})_4$	hexagonal	uniaxial	–		1.62–1.67	0.021–0.029		
sillimanite	$\text{Al}_2\text{SiO}_5$	orthorhombic	biaxial	+	20–30	1.65–1.68	0.022		
tremolite-actinolite	$\text{Ca}_2(\text{Mg},\text{Fe})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	monoclinic	biaxial	–	85–90	1.61–1.63	0.022		
autunite	$\text{Ca}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 10\text{H}_2\text{O}$	tetragonal	uniaxial	-		1.55–1.57	0.024		
borax	$\text{Na}_2\text{B}_4\text{O}_5(\text{OH})_4 \cdot 8\text{H}_2\text{O}$	monoclinic	biaxial	-	40	1.44–1.47	0.025		
pigeonite	$(\text{Ca},\text{Mg},\text{Fe})_2\text{Si}_2\text{O}_6$	monoclinic	biaxial	+	38–44	1.69–1.72	0.025		
norbergite	$\text{Mg}_3\text{SiO}_4(\text{OH},\text{F})_2$	orthorhombic	biaxial	+	44–50	1.56–1.58	0.026		
stishovite	$\text{SiO}_2$	tetragonal	uniaxial	+		1.8–1.82	0.027		
wavellite	$\text{Al}_3(\text{PO}_4)_2(\text{OH})_3 \cdot 5\text{H}_2\text{O}$	orthorhombic	biaxial	+	72	1.52–1.55	0.027		
colemanite	$\text{CaB}_3\text{O}_4(\text{OH})_3 \cdot \text{H}_2\text{O}$	monoclinic	biaxial	+	56	1.58–1.61	0.028		
epsomite	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	orthorhombic	biaxial	+	52	1.43–1.46	0.028		
<b>Minerals with Moderate Birefringence</b>									
(Displaying up to second-order interference colors in thin section)									
carnallite	$\text{KMgCl}_3 \cdot 6\text{H}_2\text{O}$	orthorhombic	biaxial	+	70	1.46–1.49	0.029		
chalcanthite	$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$	triclinic	biaxial	–	56	1.51–1.54	0.029		
ulexite	$\text{NaCaB}_5\text{O}_6(\text{OH})_6 \cdot 5\text{H}_2\text{O}$	triclinic	biaxial	+	73	1.49–1.52	0.029		
amblygonite	$\text{LiAl}(\text{PO}_4)\text{F}$	triclinic	biaxial	–	52–90	1.59–1.62	0.03		

Mineral	Formula	Crystal System	Optical Properties						
			System	Sign	2V°	Mean R.I. ( $\bar{n}$ )	Birefringence ( $\delta$ )		
<b>Minerals with Moderate Birefringence (continued)</b>									
(Displaying up to second-order interference colors in thin section)									
anthophyllite	(Mg,Fe) <sub>7</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	orthorhombic	biaxial	–	65–90	1.6–1.63	0.03		
chondrodite	Mg <sub>5</sub> (SiO <sub>4</sub> ) <sub>2</sub> (OH,F) <sub>2</sub>	monoclinic	biaxial	+	60–90	1.6–1.63	0.03		
cummingtonite	Mg <sub>7</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	monoclinic	biaxial	+	80–90	1.64–1.67	0.03		
diopside	Ca(Mg,Fe)Si <sub>2</sub> O <sub>6</sub>	monoclinic	biaxial	+	56–64	1.66–1.75	0.03		
prehnite	Ca <sub>2</sub> Al(AlSi <sub>3</sub> O <sub>10</sub> )(OH) <sub>2</sub>	orthorhombic	biaxial	+	65–70	1.62–1.65	0.03		
variscite	AlPO <sub>4</sub> •2H <sub>2</sub> O	orthorhombic	biaxial	–	48–54	1.55–1.59	0.03		
clinohumite	Mg <sub>9</sub> (SiO <sub>4</sub> ) <sub>2</sub> (OH,F) <sub>2</sub>	monoclinic	biaxial	+	73–76	1.59–1.64	0.03–0.04		
lazulite	(Mg,Fe)Al <sub>2</sub> (PO <sub>4</sub> ) <sub>2</sub> (OH) <sub>2</sub>	monoclinic	biaxial	–	70	1.61–1.64	0.031		
kernite	Na <sub>2</sub> B <sub>4</sub> O <sub>6</sub> (OH) <sub>2</sub> •3H <sub>2</sub> O	monoclinic	biaxial	–	80	1.45–1.48	0.034		
muscovite	KAl <sub>2</sub> AlSi <sub>3</sub> O <sub>10</sub> (OH) <sub>2</sub>	monoclinic	biaxial	–	30–40	1.56–1.6	0.035		
<b>Minerals with Very Low Birefringence</b>									
(Interference colors generally white and gray in thin section)									
olivine	(Mg,Fe) <sub>2</sub> SiO <sub>4</sub>	orthorhombic	biaxial	+	47–90	1.63–1.88	0.035–0.053		
biotite	K(Mg,Fe) <sub>3</sub> AlSi <sub>3</sub> O <sub>10</sub> (OH) <sub>2</sub>	monoclinic	biaxial	–	0–32	1.57–1.61	0.04		
diaspore	AlO(OH)	orthorhombic	biaxial	+	85	1.68–1.75	0.04		
pectolite	NaCa <sub>2</sub> (SiO <sub>3</sub> ) <sub>3</sub> H	triclinic	biaxial	+	35–63	1.59–1.63	0.04		
sinhalite	MgAlBO <sub>4</sub>	orthorhombic	biaxial	+	58	1.67–1.71	0.04		
turquoise	CuAl <sub>6</sub> (PO <sub>4</sub> ) <sub>4</sub> (OH) <sub>8</sub> •4H <sub>2</sub> O	triclinic	biaxial	+	40	1.61–1.65	0.04		
anhydrite	CaSO <sub>4</sub>	orthorhombic	biaxial	+	44	1.57–1.61	0.044		
atacamite	Cu <sub>2</sub> Cl(OH) <sub>3</sub>	orthorhombic	biaxial	–	75	1.83–1.88	0.047		
pyrophyllite	Al <sub>2</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub>	triclinic	biaxial	–	52–62	1.55–1.6	0.047		
monazite	(Ce,La,Th)PO <sub>4</sub>	monoclinic	biaxial	+	10–20	1.78–1.85	0.05		
talc	Mg <sub>3</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub>	monoclinic	biaxial	–	6–30	1.54–1.58	0.05		
vivianite	Fe <sub>3</sub> (PO <sub>4</sub> ) <sub>3</sub> •8H <sub>2</sub> O	monoclinic	biaxial	+	83	1.57–1.63	0.054		
<b>Minerals with Very High Birefringence</b>									
(Displaying up to fourth-order and higher interference colors in thin section)									
zircon	ZrSiO <sub>4</sub>	tetragonal	uniaxial	+		1.93–1.99	0.06		
antlerite	Cu <sub>3</sub> SO <sub>4</sub> (OH) <sub>4</sub>	orthorhombic	biaxial	+	53	1.72–1.78	0.063		
vanadinite	Pb <sub>5</sub> (VO <sub>4</sub> ) <sub>3</sub> Cl	hexagonal	uniaxial	–		2.3–2.4	0.066		
anatase	TiO <sub>2</sub>	tetragonal	uniaxial	–		2.48–2.56	0.073		
erythrite	CO <sub>3</sub> (AsO <sub>4</sub> ) <sub>2</sub> •8H <sub>2</sub> O	monoclinic	biaxial	–	90	1.62–1.69	0.073		
cassiterite	SnO <sub>2</sub>	tetragonal	uniaxial	+		2–2.1	0.09		
azurite	Cu <sub>3</sub> (CO <sub>3</sub> ) <sub>2</sub> (OH) <sub>2</sub>	monoclinic	biaxial	+	68	1.73–1.83	0.106		
columbite	(Fe,Mn)(Nb,Ta) <sub>2</sub> O <sub>6</sub>	orthorhombic	biaxial	+		2.3–2.4	0.12		
wulfenite	PbMoO <sub>4</sub>	tetragonal	uniaxial	–		2.28–2.4	0.121		
wolframite	(Fe,Mn)WO <sub>4</sub>	monoclinic	biaxial	+	73–79	2.1–2.5	0.13–0.15		
brookite	TiO <sub>2</sub>	orthorhombic	biaxial	+	0–30	2.58–2.72	0.14		
strontianite	SrCO <sub>3</sub>	orthorhombic	biaxial	–	7	1.52–1.66	0.148		
witherite	BaCO <sub>3</sub>	orthorhombic	biaxial	–	16	1.52–1.67	0.148		
goethite	FeO(OH)	orthorhombic	biaxial	–	0–27	2.26–2.52	0.15		
titanite (sphene)	CaTiSiO <sub>5</sub>	monoclinic	biaxial	+	23–50	1.86–2.1	0.15		
aragonite	CaCO <sub>3</sub>	orthorhombic	biaxial	–	18	1.53–1.68	0.155		
realgar	AsS	monoclinic	biaxial	–	41	2.5–2.8	0.166		
proustite	Ag <sub>3</sub> AsS <sub>3</sub>	hexagonal	uniaxial	–		2.71–2.98	0.17		

Mineral	Formula	Crystal System	Optical Properties					
			System	Sign	2V°	Mean R.I. ( $\bar{n}$ )		
<b>Minerals with Very High Birefringence (continued)</b>								
(Displaying up to fourth-order and higher interference colors in thin section)								
calcite	$\text{CaCO}_3$	hexagonal	uniaxial	—	1.48–1.65	0.172		
niter	$\text{KNO}_3$	orthorhombic	biaxial	—	7	1.33–1.5		
dolomite	$\text{CaMg}(\text{CO}_3)_2$	hexagonal	uniaxial	—	1.5–1.67	0.179		
magnesite	$\text{MgCO}_3$	hexagonal	uniaxial	—	1.5–1.7	0.191		
carnotite	$\text{K}_2\text{U}_2\text{O}_4(\text{VO}_4)_2 \cdot 3\text{H}_2\text{O}$	monoclinic	biaxial	—	38–44	1.75–1.95		
pyrargyrite	$\text{Ag}_3\text{SbS}_3$	hexagonal	uniaxial	—	2.88–3.08	0.2		
ankerite	$\text{CaFe}(\text{CO}_3)_2$	hexagonal	uniaxial	—	1.54–1.75	0.202		
rhodochrosite	$\text{MnCO}_3$	hexagonal	uniaxial	—	1.59–1.81	0.219		
smithsonite	$\text{ZnCO}_3$	hexagonal	uniaxial	—	1.62–1.85	0.225		
siderite	$\text{FeCO}_3$	hexagonal	uniaxial	—	1.63–1.87	0.242		
nitratite	$\text{NaNO}_3$	hexagonal	uniaxial	—	1.33–1.58	0.251		
malachite	$\text{Cu}_2\text{CO}_3(\text{OH})_2$	monoclinic	biaxial	—	43	1.65–1.9		
cerussite	$\text{PbCO}_3$	orthorhombic	biaxial	—	9	1.8–2.07		
hematite	$\text{Fe}_2\text{O}_3$	hexagonal	uniaxial	—	3–3.2	0.28		
manganite	$\text{MnO(OH)}$	monoclinic	biaxial	+	small	2.2–2.5		
sulfur	S	orthorhombic	biaxial	+	69	1.95–2.24		
rutile	$\text{TiO}_2$	tetragonal	uniaxial	+	—	2.61–2.9		
hausmannite	$\text{Mn}_3\text{O}_4$	tetragonal	uniaxial	—	—	2.1–2.4		
cinnabar	HgS	hexagonal	uniaxial	+	—	2.9–3.25		
crocoite	$\text{PbCrO}_4$	monoclinic	biaxial	+	54	2.3–2.6		
lepidocrocite	$\text{FeO(OH)}$	orthorhombic	biaxial	—	83	1.94–2.51		
orpiment	$\text{As}_2\text{S}_3$	monoclinic	biaxial	+	76	2.4–3		

# APPENDIX

## Minerals Ordered by Hardness

Mineral	Formula	Specific Gravity ( <i>G</i> )	Hardness ( <i>H</i> )
talc	Mg <sub>3</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub>	2.8	1
molybdenite	MoS <sub>2</sub>	4.7	1–1½
pyrophyllite	Al <sub>2</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub>	2.8	1½
arsenic	As	5.7	1–2
erythrite	Co <sub>3</sub> (AsO <sub>4</sub> ) <sub>2</sub> •8H <sub>2</sub> O	3.06	1–2
graphite	C	2.1–2.2	1–2
nitratite	NaNO <sub>3</sub>	2.29	1–2
covellite	CuS	4.6	1½–2
orpiment	As <sub>2</sub> S <sub>3</sub>	3.49	1½–2
realgar	AsS	3.56	1½–2
sulfur	S	2.1	1½–2½
carnotite	K <sub>2</sub> U <sub>2</sub> O <sub>4</sub> (VO <sub>4</sub> ) <sub>2</sub> •3H <sub>2</sub> O	4.5	2
gypsum	CaSO <sub>4</sub> •2H <sub>2</sub> O	2.32	2
niter	KNO <sub>3</sub>	2.1	2
pyrargyrite	Ag <sub>3</sub> SbS <sub>3</sub>	5.85	2
stibnite	Sb <sub>2</sub> S <sub>3</sub>	4.6	2
sylvite	KCl	1.99	2
vivianite	Fe <sub>3</sub> (PO <sub>4</sub> ) <sub>3</sub> •8H <sub>2</sub> O	2.58	2
zinc	Zn	7.1	2
argentite (acanthite)	Ag <sub>2</sub> S	7.1	2–2½
autunite	Ca(UO <sub>2</sub> ) <sub>2</sub> (PO <sub>4</sub> ) <sub>2</sub> •10H <sub>2</sub> O	3.15	2–2½
borax	Na <sub>2</sub> B <sub>4</sub> O <sub>5</sub> (OH) <sub>4</sub> •8H <sub>2</sub> O	1.7–1.9	2–2½
cinnabar	HgS	8.1	2–2½
epsomite	MgSO <sub>4</sub> •7H <sub>2</sub> O	1.68	2–2½
galena	PbS	7.6	2–2½
kaolinite	Al <sub>2</sub> Si <sub>2</sub> O <sub>5</sub> (OH) <sub>4</sub>	2.6	2–2½
proustite	Ag <sub>3</sub> AsS <sub>3</sub>	5.5–7	2–2½
sepiolite	Mg <sub>4</sub> Si <sub>6</sub> O <sub>15</sub> (OH) <sub>2</sub> (H <sub>2</sub> O)•4H <sub>2</sub> O	2	2–2½
brucite	Mg(OH) <sub>2</sub>	2.4–2.5	2½
carnallite	KMgCl <sub>3</sub> •6H <sub>2</sub> O	1.6	2½
chalcanthite	CuSO <sub>4</sub> •5H <sub>2</sub> O	2.3	2½
chlorargerite	AgCl	1.55	2½
cryolite	Na <sub>3</sub> AlF <sub>6</sub>	2.97	2½
halite	NaCl	2.16	2½
muscovite	KAl <sub>2</sub> AlSi <sub>3</sub> O <sub>10</sub> (OH) <sub>2</sub>	2.8	2½
ulexite	NaCaB <sub>5</sub> O <sub>6</sub> (OH) <sub>6</sub> •5H <sub>2</sub> O	1.96	2½
chlorite	talc+brucite combinations	3	2–3
anglesite	PbSO <sub>4</sub>	6.38	2½–3
biotite	K(Mg,Fe) <sub>3</sub> AlSi <sub>3</sub> O <sub>10</sub> (OH) <sub>2</sub>	3	2½–3
bismuth	Bi	9.8	2½–3
boulangerite	Pb <sub>5</sub> Sb <sub>4</sub> S <sub>11</sub>	6–6.2	2½–3
chalcocite	Cu <sub>2</sub> S	5.8	2½–3
copper	Cu	8.7–8.9	2½–3
crocoite	PbCrO <sub>4</sub>	6	2½–3

Mineral	Formula	Specific Gravity (G)	Hardness (H)
gold	Au	15.6–19.3	2½–3
silver	Ag	10.1–10.5	2½–3
gibbsite	Al(OH) <sub>3</sub>	2.4	2½–3½
pyrolusite	MnO <sub>2</sub>	4.5–5	2½–6½
bornite	Cu <sub>5</sub> FeS <sub>4</sub>	6	3
calcite	CaCO <sub>3</sub>	2.71	3
enargite	Cu <sub>3</sub> AsS <sub>4</sub>	4.5	3
kernite	Na <sub>2</sub> B <sub>4</sub> O <sub>6</sub> (OH) <sub>2</sub> • 3H <sub>2</sub> O	1.9	3
vanadinite	Pb <sub>5</sub> (VO <sub>4</sub> ) <sub>3</sub> Cl	6.9	3
wulfenite	PbMoO <sub>4</sub>	6.7–7	3
antimony	Sb	6.7	3–3½
atacamite	Cu <sub>2</sub> Cl(OH) <sub>3</sub>	3.76	3–3½
barite	BaSO <sub>4</sub>	4.5	3–3½
celestite	SrSO <sub>4</sub>	3.97	3–3½
cerussite	PbCO <sub>3</sub>	6.55	3–3½
millerite	NiS	5.5	3–3½
witherite	BaCO <sub>3</sub>	4.29	3–3½
anhydrite	CaSO <sub>4</sub>	2.98	3½
strontianite	SrCO <sub>3</sub>	3.72	3½
antigorite	Mg <sub>3</sub> Si <sub>2</sub> O <sub>5</sub> (OH) <sub>4</sub>	2.6	3–4
tetrahedrite	Cu <sub>12</sub> Sb <sub>4</sub> S <sub>13</sub>	4.5–5.11	3–4
wavellite	Al <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> (OH) <sub>3</sub> • 5H <sub>2</sub> O	2.36	3–4
alunite	KAl <sub>3</sub> (SO <sub>4</sub> ) <sub>2</sub> (OH) <sub>6</sub>	2.6–2.9	3½–4
ankerite	CaFe(CO <sub>3</sub> ) <sub>2</sub>	3.1	3½–4
antlerite	Cu <sub>3</sub> SO <sub>4</sub> (OH) <sub>4</sub>	3.9	3½–4
aragonite	CaCO <sub>3</sub>	2.94	3½–4
azurite	Cu <sub>3</sub> (CO <sub>3</sub> ) <sub>2</sub> (OH) <sub>2</sub>	3.77	3½–4
chalcopyrite	CuFeS <sub>2</sub>	4.2	3½–4
cuprite	Cu <sub>2</sub> O	5.9–6.1	3½–4
dolomite	CaMg(CO <sub>3</sub> ) <sub>2</sub>	2.85	3½–4
heulandite	CaAl <sub>2</sub> Si <sub>7</sub> O <sub>18</sub> • 6H <sub>2</sub> O	2.15	3½–4
malachite	Cu <sub>2</sub> CO <sub>3</sub> (OH) <sub>2</sub>	3.7–4	3½–4
pentlandite	(Ni,Fe) <sub>9</sub> S <sub>8</sub>	5	3½–4
pyromorphite	Pb(PO <sub>4</sub> ) <sub>3</sub> Cl	7	3½–4
rhodochrosite	MnCO <sub>3</sub>	3.7	3½–4
sphalerite	ZnS	4	3½–4
stilbite	CaAl <sub>2</sub> Si <sub>7</sub> O <sub>18</sub> • 7H <sub>2</sub> O	2.15	3½–4
wurtzite	ZnS	4	3½–4
margarite	CaAl <sub>2</sub> (Al <sub>2</sub> Si <sub>2</sub> O <sub>10</sub> )(OH) <sub>2</sub>	3.1	3½–4½
pyrrhotite	Fe <sub>1-x</sub> S	4.6	3½–4½
fluorite	CaF <sub>2</sub>	3.18	4
magnesite	MgCO <sub>3</sub>	3	4
manganite	MnO(OH)	4.2–4.4	4
siderite	FeCO <sub>3</sub>	3.96	4
variscite	AlPO <sub>4</sub> • 2H <sub>2</sub> O	2.5	4
colemanite	CaB <sub>3</sub> O <sub>4</sub> (OH) <sub>3</sub> • H <sub>2</sub> O	2.42	4–4½
platinum	Pt	16.5–18	4–4½
smithsonite	ZnCO <sub>3</sub>	4.43	4–4½
wolframite	(Fe,Mn)WO <sub>4</sub>	7.2–7.6	4–4½

Appendix

<b>Mineral</b>	<b>Formula</b>	<b>Specific Gravity (G)</b>	<b>Hardness (H)</b>
zincite	ZnO	5.4–5.7	4–4½
chabazite	CaAl <sub>2</sub> Si <sub>4</sub> O <sub>12</sub> • 6H <sub>2</sub> O	2.1	4–5
apophyllite	KCa <sub>4</sub> Si <sub>8</sub> O <sub>20</sub> F • 8H <sub>2</sub> O	2.3	4½–5
pectolite	NaCa <sub>2</sub> (SiO <sub>3</sub> ) <sub>3</sub> H	2.9	4½–5
scheelite	CaWO <sub>4</sub>	6.11	4½–5
wollastonite	CaSiO <sub>3</sub>	3.1	4½–5
apatite	Ca <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> (OH,F,Cl)	3.2	5
columbite	(Fe,Mn)(Nb,Ta) <sub>2</sub> O <sub>6</sub>	6	5
lepidocrocite	FeO(OH)	4	5
titanite (sphene)	CaTiSiO <sub>5</sub>	3.5	5
brookite	TiO <sub>2</sub>	4.14	5–5½
goethite	FeO(OH)	4.3	5–5½
hausmannite	Mn <sub>3</sub> O <sub>4</sub>	4.86	5–5½
natrolite	Na <sub>2</sub> Al <sub>2</sub> Si <sub>3</sub> O <sub>10</sub> • 2H <sub>2</sub> O	2.23	5–5½
niccolite	NiAs	4.6	5–5½
triphylite	Li(Fe,Mn)PO <sub>4</sub>	3.5–5.5	5–5½
glaucophane	Na <sub>2</sub> Mg <sub>3</sub> Al <sub>2</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	3.1–3.2	5–6
hornblende	(Na,K) <sub>0–1</sub> (Ca,Na,Fe,Mg) <sub>2</sub> (Mg,Fe,Al) <sub>5</sub> (Si,Al) <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	3–3.5	5–6
hypersthene	(Mg,Fe) <sub>2</sub> Si <sub>2</sub> O <sub>6</sub>	3.2–3.5	5–6
ilmenite	FeTiO <sub>3</sub>	4.5–5	5–6
scapolite	(Na,Ca) <sub>4</sub> (Al,Si) <sub>12</sub> O <sub>24</sub> (Cl,CO <sub>3</sub> )	2.55–2.76	5–6
tremolite-actinolite	Ca <sub>2</sub> (Mg,Fe) <sub>5</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	3–3.3	5–6
uraninite	UO <sub>2</sub>	7–9.5	5–6
kyanite	Al <sub>2</sub> SiO <sub>5</sub>	3.6	5–7
analcime	NaAlSi <sub>2</sub> O <sub>6</sub> • H <sub>2</sub> O	2.26	5½
chromite	FeCr <sub>2</sub> O <sub>4</sub>	5.1	5½
cobaltite	CoAsS	6.3	5½
monazite	(Ce,La,Th)PO <sub>4</sub>	4.9–5.2	5½
monticellite	CaMgSiO <sub>4</sub>	3.15	5½
periclase	MgO	3.56	5½
perovskite	CaTiO <sub>3</sub>	4	5½
anatase	TiO <sub>2</sub>	3.9	5½–6
anthophyllite	(Mg,Fe) <sub>7</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	2.9–3.2	5½–6
arsenopyrite	FeAsS	6.1	5½–6
leucite	KAlSi <sub>2</sub> O <sub>6</sub>	2.48	5½–6
nepheline	(Na,K)AlSiO <sub>4</sub>	2.6	5½–6
rhodonite	MnSiO <sub>3</sub>	3.5–3.7	5½–6
skutterudite	(Co,Ni)As <sub>3</sub>	6.1–6.8	5½–6
sodalite	Na <sub>3</sub> Al <sub>3</sub> Si <sub>3</sub> O <sub>12</sub> • NaCl	2.3	5½–6
diopside	Ca(Mg,Fe)Si <sub>2</sub> O <sub>6</sub>	3.2–3.6	5½–6½
franklinite	ZnFe <sub>2</sub> O <sub>4</sub>	5.32	5½–6½
hematite	Fe <sub>2</sub> O <sub>3</sub>	4.9–5.3	5½–6½
magnetite	Fe <sub>3</sub> O <sub>4</sub>	5.2	5½–6½
amblygonite	LiAl(PO <sub>4</sub> )F	3	6
clinohumite	Mg <sub>9</sub> (SiO <sub>4</sub> ) <sub>2</sub> (OH,F) <sub>2</sub>	3.21–3.35	6
cummingtonite	Mg <sub>7</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	2.9–3.2	6
kaersutite	Ti-rich hornblende	3.2–3.3	6
lazulite	(Mg,Fe)Al <sub>2</sub> (PO <sub>4</sub> ) <sub>2</sub> (OH) <sub>2</sub>	3	6

Mineral	Formula	Specific Gravity (G)	Hardness (H)
microcline	KAlSi <sub>3</sub> O <sub>8</sub>	2.56	6
orthoclase	KAlSi <sub>3</sub> O <sub>8</sub>	2.56	6
pigeonite	(Ca,Mg,Fe) <sub>2</sub> Si <sub>2</sub> O <sub>6</sub>	3.4	6
sanidine	(K,Na)AlSi <sub>3</sub> O <sub>8</sub>	2.56	6
turquoise	CuAl <sub>6</sub> (PO <sub>4</sub> ) <sub>4</sub> (OH) <sub>8</sub> • 4H <sub>2</sub> O	2.7	6
albite	NaAlSi <sub>3</sub> O <sub>8</sub>	2.62	6–6 <sup>1</sup> / <sub>2</sub>
anorthite	CaAl <sub>2</sub> Si <sub>2</sub> O <sub>8</sub>	2.76	6–6 <sup>1</sup> / <sub>2</sub>
marcasite	FeS <sub>2</sub>	4.9	6–6 <sup>1</sup> / <sub>2</sub>
prehnite	Ca <sub>2</sub> Al(AlSi <sub>3</sub> O <sub>10</sub> )(OH) <sub>2</sub>	2.9	6–6 <sup>1</sup> / <sub>2</sub>
pyrite	FeS <sub>2</sub>	5.1	6–6 <sup>1</sup> / <sub>2</sub>
rutile	TiO <sub>2</sub>	4.24	6–6 <sup>1</sup> / <sub>2</sub>
chloritoid	(Fe,Mg)Al <sub>2</sub> SiO <sub>5</sub> (OH) <sub>2</sub>	3.5	6 <sup>1</sup> / <sub>2</sub>
chondrodite	Mg <sub>5</sub> (SiO <sub>4</sub> ) <sub>2</sub> (OH,F) <sub>2</sub>	3.16–3.26	6 <sup>1</sup> / <sub>2</sub>
clinozoisite	Ca <sub>2</sub> Al <sub>3</sub> Si <sub>3</sub> O <sub>12</sub> (OH)	3.1–3.4	6 <sup>1</sup> / <sub>2</sub>
epidote	Ca <sub>2</sub> (Al,Fe) <sub>3</sub> Si <sub>3</sub> O <sub>12</sub> (OH)	3.4–3.5	6 <sup>1</sup> / <sub>2</sub>
jadeite	NaAlSi <sub>2</sub> O <sub>6</sub>	3.3	6 <sup>1</sup> / <sub>2</sub>
norbergite	Mg <sub>3</sub> SiO <sub>4</sub> (OH,F) <sub>2</sub>	3.16	6 <sup>1</sup> / <sub>2</sub>
vesuvianite	Ca <sub>10</sub> (Mg,Fe) <sub>2</sub> Al <sub>4</sub> Si <sub>9</sub> O <sub>34</sub> (OH) <sub>4</sub>	3.4	6 <sup>1</sup> / <sub>2</sub>
cassiterite	SnO <sub>2</sub>	7	6–7
cristobalite	SiO <sub>2</sub>	2.33	6–7
sillimanite	Al <sub>2</sub> SiO <sub>5</sub>	3.23	6–7
tridymite	SiO <sub>2</sub>	2.28	6–7
diaspore	AlO(OH)	3.2–3.5	6 <sup>1</sup> / <sub>2</sub> –7
olivine	(Mg,Fe) <sub>2</sub> SiO <sub>4</sub>	3.2–3.4	6 <sup>1</sup> / <sub>2</sub> –7
sinhalite	MgAlBO <sub>4</sub>	3.42	6 <sup>1</sup> / <sub>2</sub> –7
spodumene	LiAlSi <sub>2</sub> O <sub>6</sub>	3.15	6 <sup>1</sup> / <sub>2</sub> –7
garnet	(Ca,Fe,Mg) <sub>3</sub> (Al,Fe) <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>	3.5–4.3	6 <sup>1</sup> / <sub>2</sub> –7 <sup>1</sup> / <sub>2</sub>
boracite	Mg <sub>3</sub> ClB <sub>7</sub> O <sub>13</sub>	2.95	7
cordierite	(Mg,Fe) <sub>2</sub> Al <sub>4</sub> Si <sub>5</sub> O <sub>18</sub>	2.5–2.8	7
quartz	SiO <sub>2</sub>	2.65	7
staurolite	Fe <sub>2</sub> Al <sub>9</sub> Si <sub>4</sub> O <sub>23</sub> (OH)	3.75	7–7 <sup>1</sup> / <sub>2</sub>
tourmaline	Na(Fe,Mg,Al,Li) <sub>3</sub> Al <sub>6</sub> (BO <sub>3</sub> ) <sub>3</sub> Si <sub>6</sub> O <sub>18</sub> (OH) <sub>4</sub>	2.9–3.3	7–7 <sup>1</sup> / <sub>2</sub>
andalusite	Al <sub>2</sub> SiO <sub>5</sub>	3.18	7 <sup>1</sup> / <sub>2</sub>
zircon	ZrSiO <sub>4</sub>	4.68	7 <sup>1</sup> / <sub>2</sub>
coesite	SiO <sub>2</sub>	2.93	7–8
lawsonite	CaAl <sub>2</sub> Si <sub>2</sub> O <sub>7</sub> (OH) <sub>2</sub> • H <sub>2</sub> O	3.1	7–8
beryl	Be <sub>3</sub> Al <sub>2</sub> Si <sub>6</sub> O <sub>18</sub>	2.7–2.9	7 <sup>1</sup> / <sub>2</sub> –8
spinel	MgAl <sub>2</sub> O <sub>4</sub>	3.5–4	7 <sup>1</sup> / <sub>2</sub> –8
topaz	Al <sub>2</sub> SiO <sub>4</sub> (F,OH) <sub>2</sub>	3.5–3.6	8
chrysoberyl	BeAl <sub>2</sub> O <sub>4</sub>	3.7–3.8	8 <sup>1</sup> / <sub>2</sub>
corundum	Al <sub>2</sub> O <sub>3</sub>	3.9–4.1	9
diamond	C	3.5	10

# APPENDIX

## Minerals Ordered by Specific Gravity

<b>Mineral</b>	<b>Formula</b>	<b>Specific Gravity (G)</b>	<b>Hardness (H)</b>
chlorargerite	AgCl	1.55	2 <sup>1/2</sup>
carnallite	KMgCl <sub>3</sub> •6H <sub>2</sub> O	1.6	2 <sup>1/2</sup>
epsomite	MgSO <sub>4</sub> •7H <sub>2</sub> O	1.68	2–2 <sup>1/2</sup>
borax	Na <sub>2</sub> B <sub>4</sub> O <sub>5</sub> (OH) <sub>4</sub> •8H <sub>2</sub> O	1.7–1.9	2–2 <sup>1/2</sup>
kernite	Na <sub>2</sub> B <sub>4</sub> O <sub>6</sub> (OH) <sub>2</sub> •3H <sub>2</sub> O	1.9	3
ulexite	NaCaB <sub>5</sub> O <sub>6</sub> (OH) <sub>6</sub> •5H <sub>2</sub> O	1.96	2 <sup>1/2</sup>
sylvite	KCl	1.99	2
sepiolite	Mg <sub>4</sub> Si <sub>6</sub> O <sub>15</sub> (OH) <sub>2</sub> (H <sub>2</sub> O)•4H <sub>2</sub> O	2	2–2 <sup>1/2</sup>
chabazite	CaAl <sub>2</sub> Si <sub>4</sub> O <sub>12</sub> •6H <sub>2</sub> O	2.1	4–5
niter	KNO <sub>3</sub>	2.1	2
sulfur	S	2.1	1 <sup>1/2</sup> –2 <sup>1/2</sup>
graphite	C	2.1–2.2	1–2
heulandite	CaAl <sub>2</sub> Si <sub>7</sub> O <sub>18</sub> •6H <sub>2</sub> O	2.15	3 <sup>1/2</sup> –4
stilbite	CaAl <sub>2</sub> Si <sub>7</sub> O <sub>18</sub> •7H <sub>2</sub> O	2.15	3 <sup>1/2</sup> –4
halite	NaCl	2.16	2 <sup>1/2</sup>
natrolite	Na <sub>2</sub> Al <sub>2</sub> Si <sub>3</sub> O <sub>10</sub> •2H <sub>2</sub> O	2.23	5–5 <sup>1/2</sup>
analcime	NaAlSi <sub>2</sub> O <sub>6</sub> •H <sub>2</sub> O	2.26	5 <sup>1/2</sup>
tridymite	SiO <sub>2</sub>	2.28	6–7
nitratite	NaNO <sub>3</sub>	2.29	1–2
apophyllite	KCa <sub>4</sub> Si <sub>8</sub> O <sub>20</sub> F•8H <sub>2</sub> O	2.3	4 <sup>1/2</sup> –5
chalcanthite	CuSO <sub>4</sub> •5H <sub>2</sub> O	2.3	2 <sup>1/2</sup>
sodalite	Na <sub>3</sub> Al <sub>3</sub> Si <sub>3</sub> O <sub>12</sub> •NaCl	2.3	5 <sup>1/2</sup> –6
gypsum	CaSO <sub>4</sub> •2H <sub>2</sub> O	2.32	2
cristobalite	SiO <sub>2</sub>	2.33	6–7
wavellite	Al <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> (OH) <sub>3</sub> •5H <sub>2</sub> O	2.36	3–4
gibbsite	Al(OH) <sub>3</sub>	2.4	2 <sup>1/2</sup> –3 <sup>1/2</sup>
brucite	Mg(OH) <sub>2</sub>	2.4–2.5	2 <sup>1/2</sup>
colemanite	CaB <sub>3</sub> O <sub>4</sub> (OH) <sub>3</sub> •H <sub>2</sub> O	2.42	4–4 <sup>1/2</sup>
leucite	KAlSi <sub>2</sub> O <sub>6</sub>	2.48	5 <sup>1/2</sup> –6
variscite	AlPO <sub>4</sub> •2H <sub>2</sub> O	2.5	4
cordierite	(Mg,Fe) <sub>2</sub> Al <sub>4</sub> Si <sub>5</sub> O <sub>18</sub>	2.5–2.8	7
scapolite	(Na,Ca) <sub>4</sub> (Al,Si) <sub>12</sub> O <sub>24</sub> (Cl,CO <sub>3</sub> )	2.55–2.76	5–6
microcline	KAlSi <sub>3</sub> O <sub>8</sub>	2.56	6
orthoclase	KAlSi <sub>3</sub> O <sub>8</sub>	2.56	6
sanidine	(K,Na)AlSi <sub>3</sub> O <sub>8</sub>	2.56	6
vivianite	Fe <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> •8H <sub>2</sub> O	2.58	2
antigorite	Mg <sub>3</sub> Si <sub>2</sub> O <sub>5</sub> (OH) <sub>4</sub>	2.6	3–4
kaolinite	Al <sub>2</sub> Si <sub>2</sub> O <sub>5</sub> (OH) <sub>4</sub>	2.6	2–2 <sup>1/2</sup>
nepheline	(Na,K)AlSiO <sub>4</sub>	2.6	5 <sup>1/2</sup> –6
alunite	KAl <sub>3</sub> (SO <sub>4</sub> ) <sub>2</sub> (OH) <sub>6</sub>	2.6–2.9	3 <sup>1/2</sup> –4
albite	NaAlSi <sub>3</sub> O <sub>8</sub>	2.62	6–6 <sup>1/2</sup>
quartz	SiO <sub>2</sub>	2.65	7
turquoise	CuAl <sub>6</sub> (PO <sub>4</sub> ) <sub>4</sub> (OH) <sub>8</sub> •4H <sub>2</sub> O	2.7	6
beryl	Be <sub>3</sub> Al <sub>2</sub> Si <sub>6</sub> O <sub>18</sub>	2.7–2.9	7 <sup>1/2</sup> –8

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Mineral	Formula	Specific Gravity (G)	Hardness (H)
calcite	$\text{CaCO}_3$	2.71	3
anorthite	$\text{CaAl}_2\text{Si}_2\text{O}_8$	2.76	6–6½
muscovite	$\text{KAl}_2\text{AlSi}_3\text{O}_{10}(\text{OH})_2$	2.8	2½
pyrophyllite	$\text{Al}_2\text{Si}_4\text{O}_{10}(\text{OH})_2$	2.8	1½
talc	$\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$	2.8	1
dolomite	$\text{CaMg}(\text{CO}_3)_2$	2.85	3½–4
pectolite	$\text{NaCa}_2(\text{SiO}_3)_3\text{H}$	2.9	4½–5
prehnite	$\text{Ca}_2\text{Al}(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$	2.9	6–6½
anthophyllite	$(\text{Mg},\text{Fe})_7\text{Si}_8\text{O}_{22}(\text{OH})_2$	2.9–3.2	5½–6
cummingtonite	$\text{Mg}_7\text{Si}_8\text{O}_{22}(\text{OH})_2$	2.9–3.2	6
tourmaline	$\text{Na}(\text{Fe},\text{Mg},\text{Al},\text{Li})_3\text{Al}_6(\text{BO}_3)_3\text{Si}_6\text{O}_{18}(\text{OH})_4$	2.9–3.3	7–7½
coesite	$\text{SiO}_2$	2.93	7–8
aragonite	$\text{CaCO}_3$	2.94	3½–4
boracite	$\text{Mg}_3\text{ClB}_7\text{O}_{13}$	2.95	7
cryolite	$\text{Na}_3\text{AlF}_6$	2.97	2½
anhydrite	$\text{CaSO}_4$	2.98	3½
amblygonite	$\text{LiAl}(\text{PO}_4)\text{F}$	3	6
biotite	$\text{K}(\text{Mg},\text{Fe})_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2$	3	2½–3
chlorite	talc+brucite combinations	3	2–3
lazulite	$(\text{Mg},\text{Fe})\text{Al}_2(\text{PO}_4)_2(\text{OH})_2$	3	6
magnesite	$\text{MgCO}_3$	3	4
erythrite	$\text{Co}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$	3.06	1–2
ankerite	$\text{CaFe}(\text{CO}_3)_2$	3.1	3½–4
lawsonite	$\text{CaAl}_2\text{Si}_2\text{O}_7(\text{OH})_2 \cdot \text{H}_2\text{O}$	3.1	7–8
margarite	$\text{CaAl}_2(\text{Al}_2\text{Si}_2\text{O}_{10})(\text{OH})_2$	3.1	3½–4½
wollastonite	$\text{CaSiO}_3$	3.1	4½–5
glaucomophane	$\text{Na}_2\text{Mg}_3\text{Al}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$	3.1–3.2	5–6
clinozoisite	$\text{Ca}_2\text{Al}_3\text{Si}_3\text{O}_{12}(\text{OH})$	3.1–3.4	6½
autunite	$\text{Ca}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 10\text{H}_2\text{O}$	3.15	2–2½
monticellite	$\text{CaMgSiO}_4$	3.15	5½
spodumene	$\text{LiAlSi}_2\text{O}_6$	3.15	6½–7
norbergite	$\text{Mg}_3\text{SiO}_4(\text{OH},\text{F})_2$	3.16	6½
chondrodite	$\text{Mg}_5(\text{SiO}_4)_2(\text{OH},\text{F})_2$	3.16–3.26	6½
andalusite	$\text{Al}_2\text{SiO}_5$	3.18	7½
fluorite	$\text{CaF}_2$	3.18	4
apatite	$\text{Ca}_5(\text{PO}_4)_3(\text{F},\text{Cl},\text{OH})$	3.2	5
kaersutite	Ti-rich hornblende	3.2–3.3	6
olivine	$(\text{Mg},\text{Fe})_2\text{SiO}_4$	3.2–3.4	6½–7
diaspore	$\text{AlO}(\text{OH})$	3.2–3.5	6½–7
hypersthene	$(\text{Mg},\text{Fe})_2\text{Si}_2\text{O}_6$	3.2–3.5	5–6
diopside	$\text{Ca}(\text{Mg},\text{Fe})\text{Si}_2\text{O}_6$	3.2–3.6	5½–6½
clinohumite	$\text{Mg}_9(\text{SiO}_4)_2(\text{OH},\text{F})_2$	3.21–3.35	6
sillimanite	$\text{Al}_2\text{SiO}_5$	3.23	6–7
jadeite	$\text{NaAlSi}_2\text{O}_6$	3.3	6½
pigeonite	$(\text{Ca},\text{Mg},\text{Fe})_2\text{Si}_2\text{O}_6$	3.4	6
vesuvianite	$\text{Ca}_{10}(\text{Mg},\text{Fe})_2\text{Al}_4\text{Si}_9\text{O}_{34}(\text{OH})_4$	3.4	6½
epidote	$\text{Ca}_2(\text{Al},\text{Fe})_3\text{Si}_3\text{O}_{12}(\text{OH})$	3.4–3.5	6½
sinhalite	$\text{MgAlBO}_4$	3.42	6½–7

**Appendix:**  
Specific Gravity

<b>Mineral</b>	<b>Formula</b>	<b>Specific Gravity (G)</b>	<b>Hardness (H)</b>
orpiment	As <sub>2</sub> S <sub>3</sub>	3.49	1½–2
chloritoid	(Fe,Mg)Al <sub>2</sub> SiO <sub>5</sub> (OH) <sub>2</sub>	3.5	6½
diamond	C	3.5	10
titanite (sphene)	CaTiSiO <sub>5</sub>	3.5	5
topaz	Al <sub>2</sub> SiO <sub>4</sub> (F,OH) <sub>2</sub>	3.5–3.6	8
rhodonite	MnSiO <sub>3</sub>	3.5–3.7	5½–6
spinel	MgAl <sub>2</sub> O <sub>4</sub>	3.5–4	7½–8
garnet	(Ca,Fe,Mg) <sub>3</sub> (Al,Fe) <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>	3.5–4.3	6½–7½
triphylite	Li(Fe,Mn)PO <sub>4</sub>	3.5–5.5	5–5½
periclase	MgO	3.56	5½
realgar	AsS	3.56	1½–2
kyanite	Al <sub>2</sub> SiO <sub>5</sub>	3.6	5–7
rhodochrosite	MnCO <sub>3</sub>	3.7	3½–4
chrysoberyl	BeAl <sub>2</sub> O <sub>4</sub>	3.7–3.8	8½
malachite	Cu <sub>2</sub> CO <sub>3</sub> (OH) <sub>2</sub>	3.7–4	3½–4
strontianite	SrCO <sub>3</sub>	3.72	3½
staurolite	Fe <sub>2</sub> Al <sub>9</sub> Si <sub>4</sub> O <sub>20</sub> (O,OH) <sub>2</sub>	3.75	7–7½
atacamite	Cu <sub>2</sub> Cl(OH) <sub>3</sub>	3.76	3–3½
azurite	Cu <sub>3</sub> (CO <sub>3</sub> ) <sub>2</sub> (OH) <sub>2</sub>	3.77	3½–4
anatase	TiO <sub>2</sub>	3.9	5½–6
antlerite	Cu <sub>3</sub> SO <sub>4</sub> (OH) <sub>4</sub>	3.9	3½–4
corundum	Al <sub>2</sub> O <sub>3</sub>	3.9–4.1	9
siderite	FeCO <sub>3</sub>	3.96	4
celestite	SrSO <sub>4</sub>	3.97	3–3½
tremolite-actinolite	Ca <sub>2</sub> (Mg,Fe) <sub>5</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	3–3.3	5–6
hornblende	(Na,K) <sub>0–1</sub> (Ca,Na,Fe,Mg) <sub>2</sub> (Mg,Fe,Al) <sub>5</sub> (Si,Al) <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	3–3.5	5–6
lepidocrocite	FeO(OH)	4	5
perovskite	CaTiO <sub>3</sub>	4	5½
sphalerite	ZnS	4	3½–4
wurtzite	ZnS	4	3½–4
brookite	TiO <sub>2</sub>	4.14	5–5½
chalcopyrite	CuFeS <sub>2</sub>	4.2	3½–4
manganite	MnO(OH)	4.2–4.4	4
rutile	TiO <sub>2</sub>	4.24	6–6½
witherite	BaCO <sub>3</sub>	4.29	3–3½
goethite	FeO(OH)	4.3	5–5½
stishovite	SiO <sub>2</sub>	4.3	
smithsonite	ZnCO <sub>3</sub>	4.43	4–4½
barite	BaSO <sub>4</sub>	4.5	3–3½
carnotite	K <sub>2</sub> U <sub>2</sub> O <sub>4</sub> (VO <sub>4</sub> ) <sub>2</sub> • 3H <sub>2</sub> O	4.5	2
enargite	Cu <sub>3</sub> AsS <sub>4</sub>	4.5	3
ilmenite	FeTiO <sub>3</sub>	4.5–5	5–6
pyrolusite	MnO <sub>2</sub>	4.5–5	2½–6½
tetrahedrite	Cu <sub>12</sub> Sb <sub>4</sub> S <sub>13</sub>	4.5–5.11	3–4
covellite	CuS	4.6	1½–2
niccolite	NiAs	4.6	5–5½
pyrrhotite	Fe <sub>1-x</sub> S	4.6	3½–4½
stibnite	Sb <sub>2</sub> S <sub>3</sub>	4.6	2

Mineral	Formula	Specific Gravity (G)	Hardness (H)
zircon	ZrSiO <sub>4</sub>	4.68	7½
molybdenite	MoS <sub>2</sub>	4.7	1–1½
hausmannite	Mn <sub>3</sub> O <sub>4</sub>	4.86	5–5½
marcasite	FeS <sub>2</sub>	4.9	6–6½
monazite	(Ce,La,Th)PO <sub>4</sub>	4.9–5.2	5½
hematite	Fe <sub>2</sub> O <sub>3</sub>	4.9–5.3	5½–6½
pentlandite	(Ni,Fe) <sub>9</sub> S <sub>8</sub>	5	3½–4
chromite	FeCr <sub>2</sub> O <sub>4</sub>	5.1	5½
pyrite	FeS <sub>2</sub>	5.1	6–6½
magnetite	Fe <sub>3</sub> O <sub>4</sub>	5.2	5½–6½
franklinite	ZnFe <sub>2</sub> O <sub>4</sub>	5.32	5½–6½
zincite	ZnO	5.4–5.7	4–4½
millerite	NiS	5.5	3–3½
proustite	Ag <sub>3</sub> AsS <sub>3</sub>	5.5–7	2–2½
arsenic	As	5.7	1–2
chalcocite	Cu <sub>2</sub> S	5.8	2½–3
pyrargyrite	Ag <sub>3</sub> SbS <sub>3</sub>	5.85	2
cuprite	Cu <sub>2</sub> O	5.9–6.1	3½–4
bornite	Cu <sub>5</sub> FeS <sub>4</sub>	6	3
columbite	(Fe,Mn)(Nb,Ta) <sub>2</sub> O <sub>6</sub>	6	5
crocoite	PbCrO <sub>4</sub>	6	2½–3
arsenopyrite	FeAsS	6.1	5½–6
skutterudite	(Co,Ni)As <sub>3</sub>	6.1–6.8	5½–6
scheelite	CaWO <sub>4</sub>	6.11	4½–5
cobaltite	CoAsS	6.3	5½
anglesite	PbSO <sub>4</sub>	6.38	2½–3
cerussite	PbCO <sub>3</sub>	6.55	3–3½
antimony	Sb	6.7	3–3½
wulfenite	PbMoO <sub>4</sub>	6.7–7	3
vanadinite	Pb <sub>5</sub> (VO <sub>4</sub> ) <sub>3</sub> Cl	6.9	3
boulangerite	Pb <sub>5</sub> Sb <sub>4</sub> S <sub>11</sub>	6–6.2	2½–3
cassiterite	SnO <sub>2</sub>	7	6–7
pyromorphite	Pb(PO <sub>4</sub> ) <sub>3</sub> Cl	7	3½–4
argentite (acanthite)	Ag <sub>2</sub> S	7.1	2–2½
zinc	Zn	7.1	2
wolframite	(Fe,Mn)WO <sub>4</sub>	7.2–7.6	4–4½
galena	PbS	7.6	2–2½
uraninite	UO <sub>2</sub>	7–9.5	5–6
cinnabar	HgS	8.1	2–2½
copper	Cu	8.7–8.9	2½–3
bismuth	Bi	9.8	2½–3
silver	Ag	10.1–10.5	2½–3
gold	Au	15.6–19.3	2½–3
platinum	Pt	16.5–18	4–4½

Appendix:  
Specific Gravity

# Coordination Numbers and Effective Ionic Radii ( $\text{\AA}$ )\*

(H)	Metals												Semimetals												Non Metals												(He)
$\text{Li}^+$ 4 0.68 6 0.82	$\text{Be}^{2+}$ 3 0.25 4 0.35	$\text{Na}^+$ 4 1.07 6 1.08 9 1.40	$\text{Mg}^{2+}$ 4 0.66 6 0.80 8 0.97	$\text{K}^+$ 6 1.46 8 1.59 9 1.63 10 1.36 12 1.67 12 1.68	$\text{Ca}^{2+}$ 6 1.08 9 1.26 10 1.36 12 1.43	$\text{Sc}^{3+}$ 6 0.83 8 0.95	$\text{Ti}^{4+}$ 6 0.69	$\text{V}^{5+}$ 4 0.44 6 0.62	$\text{Cr}^{3+}$ 6 0.07 $\text{Cr}^{4+}$ 4 0.52 6 0.63 $\text{Cr}^{6+}$ 4 0.38	$\text{Mn}^{2+}$ 6 0.83 8 1.01	$\text{Fe}^{2+}$ 4 0.71 6 0.77	$\text{Co}^{2+}$ 4 0.65	$\text{Ni}^{2+}$ 6 0.77	$\text{Cu}^+$ 2 0.54 $\text{Cu}^{2+}$ 4 0.70 6 0.81	$\text{Zn}^{2+}$ 4 0.68 6 0.83	$\text{Ga}^{3+}$ 4 0.55 6 0.70	$\text{Ge}^{4+}$ 4 0.48 6 0.62	$\text{As}^{5+}$ 4 0.42 6 0.58	$\text{Se}^{2-}$ 6 1.88	$\text{Br}^-$ 6 1.88	$\text{(Kr)}$																
$\text{Rb}^+$ 6 1.57 8 1.68 12 1.81	$\text{Sr}^{2+}$ 6 1.21 8 1.33 10 1.40 12 1.48	$\text{Y}^{3+}$ 6 0.98 8 1.10 9 1.18	$\text{Zr}^{4+}$ 6 0.80 8 0.92	$\text{Nb}^{5+}$ 4 0.40 6 0.72	$\text{Mo}^{4+}$ 6 0.73 $\text{Mo}^{6+}$ 4 0.50	$\text{Tc}^{4+}$ 6 0.72	$\text{Ru}^{3+}$ 6 0.75 $\text{Ru}^{4+}$ 6 0.71	$\text{Rh}^{3+}$ 6 0.76 $\text{Rh}^{4+}$ 6 0.70	$\text{Pd}^{2+}$ 4 0.72 6 0.94	$\text{Ag}^+$ 4 1.10 6 1.23 8 1.38	$\text{Cd}^{2+}$ 4 0.88 6 1.03 8 1.15 12 1.39	$\text{In}^{3+}$ 6 0.88 8 1.00	$\text{Sn}^{4+}$ 6 0.77	$\text{Sb}^{3+}$ 4 0.85 $\text{Sb}^{5+}$ 6 0.69	$\text{(Te)}$	$\text{(I)}$	$\text{(Xe)}$																				
$\text{Cs}^+$ 6 1.78 8 1.86 10 1.89 12 1.68	$\text{Ba}^{2+}$ 6 1.44 8 1.50 10 1.60 12 1.40	$\text{La}^{3+}$ 6 1.13 8 1.26 10 1.36 12 1.40	$\text{Hf}^{4+}$ 6 0.79 8 0.91	$\text{Ta}^{5+}$ 6 0.72 8 0.77	$\text{W}^{4+}$ 6 0.73 $\text{W}^{6+}$ 4 0.50 6 0.68	$\text{Re}^{4+}$ 6 0.71 $\text{Re}^{6+}$ 6 0.60 $\text{Re}^{7+}$ 4 0.48	$\text{Os}^{4+}$ 6 0.71	$\text{Ir}^{3+}$ 6 0.81 $\text{Ir}^{4+}$ 6 0.71	$\text{Pt}^{2+}$ 6 0.68	$\text{Au}^{3+}$ 4 0.78	$\text{Hg}^{2+}$ 4 1.04 6 1.10 8 1.22	$\text{Tl}^{3+}$ 6 0.75	$\text{Pb}^{2+}$ 6 1.26 8 1.37 9 1.41 12 1.57	$\text{Bi}^{3+}$ 6 1.10 8 1.19	$\text{Po}^{4+}$ 8 1.16	$\text{(At)}$	$\text{(Rn)}$																				
$\text{(Fr)}$	$\text{Ra}^{2+}$ 8 1.48 12 1.64	$\text{(Ac)}$																																			

\*The first number in each entry is the coordination number; the second is the ionic radius in coordination with oxygen having a radius of 1.32 Å. Values for elements in parentheses were not determined. These values are modified from those in Zoltai and Stout (1984) *Mineralogy: Concepts and Principles*, Burgess Publishing Co., New York.

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## LIST OF MINERAL PROPERTIES

<b>Mineral</b>	<b>Formula</b>	<b>Specific Gravity (G)</b>	<b>Hardness (H)</b>	<b>Crystal System</b>
acanthite (see argentite)				
acmite (see aegirine)				
actinolite	$\text{Ca}_2(\text{Fe},\text{Mg})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	3.1–3.3	5–6	mon
adularia (variety of orthoclase)				
aegirine	$\text{Na}(\text{Al},\text{Fe})\text{Si}_2\text{O}_6$	3.5	6–6½	mon
åkermanite	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	2.94	5½	tet
alabandite	MnS	4.0	3½–4	cub
albite	$\text{NaAlSi}_3\text{O}_8$	2.62	6–6½	tri
alexandrite (gem chrysoberyl)				
allanite (Ce- and REE-rich variety of epidote)				
almandine	$\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	4.32	7	cub
alunite	$\text{KAl}_3(\text{SO}_4)_2(\text{OH})_6$	2.6–2.9	3½–4	hex
amazonite (blue-green variety of microcline)				
amblygonite	$\text{LiAl}(\text{PO}_4)\text{F}$	3	6	tri
amethyst (purple variety of quartz)				
amosite (asbestiform variety of cummingtonite)				
analcime	$\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$	2.26	5½	cub
anatase	$\text{TiO}_2$	3.9	5½–6	tet
andalusite	$\text{Al}_2\text{SiO}_5$	3.18	7½	orth
andradite	$\text{Ca}_3\text{Fe}_2\text{Si}_3\text{O}_{12}$	3.86	7	cub
anglesite	$\text{PbSO}_4$	6.38	2½–3	orth
anhydrite	$\text{CaSO}_4$	2.98	3½	orth
ankerite	$\text{CaFe}(\text{CO}_3)_2$	3.1	3½–4	hex
annite (Fe-biotite)				
anorthite	$\text{CaAl}_2\text{Si}_2\text{O}_8$	2.76	6–6½	tri
anorthoclase (variety of alkali feldspar)				
anthophyllite	$(\text{Mg},\text{Fe})_7\text{Si}_8\text{O}_{22}(\text{OH})_2$	2.9–3.2	5½–6	orth
antigorite	$\text{Mg}_6\text{Si}_4\text{O}_{10}(\text{OH})_8$	2.6	3–4	mon
antimony	Sb	6.7	3–3½	hex
antlerite	$\text{Cu}_3\text{SO}_4(\text{OH})_4$	3.9	3½–4	orth
apatite	$\text{Ca}_5(\text{PO}_4)_3(\text{OH},\text{F},\text{Cl})$	3.2	5	hex

## List of Mineral Properties

Mineral	Formula	Specific Gravity (G)	Hardness (H)	Crystal System
apophyllite	KCa <sub>4</sub> Si <sub>8</sub> O <sub>20</sub> F • 8H <sub>2</sub> O	2.3	4 <sup>1</sup> / <sub>2</sub> –5	tet
aquamarine (gem variety of beryl)				
aragonite	CaCO <sub>3</sub>	2.94	3 <sup>1</sup> / <sub>2</sub> –4	orth
argentite	Ag <sub>2</sub> S	7.1	2–2 <sup>1</sup> / <sub>2</sub>	cub
arsenic	As	5.7	1–2	hex
arsenopyrite	FeAsS	6.1	5 <sup>1</sup> / <sub>2</sub> –6	cub
asbestos (term given to asbestiform varieties of amphibole or serpentine)				
atacamite	Cu <sub>2</sub> Cl(OH) <sub>3</sub>	3.76	3–3 <sup>1</sup> / <sub>2</sub>	orth
augite	(Ca,Mg,Fé,Na)(Mg,Fe,Al)(Si,Al) <sub>2</sub> O <sub>6</sub>	3.2–3.4	5–6	mon
autunite	Ca(UO <sub>2</sub> ) <sub>2</sub> (PO <sub>4</sub> ) <sub>2</sub> • 10H <sub>2</sub> O	3.15	2–2 <sup>1</sup> / <sub>2</sub>	tet
azurite	Cu <sub>3</sub> (CO <sub>3</sub> ) <sub>2</sub> (OH) <sub>2</sub>	3.77	3 <sup>1</sup> / <sub>2</sub> –4	mon
barite	BaSO <sub>4</sub>	4.5	3–3 <sup>1</sup> / <sub>2</sub>	orth
bauxite (mixture of diaspore, boehmite and gibbsite)				
beryl	Be <sub>3</sub> Al <sub>2</sub> Si <sub>6</sub> O <sub>18</sub>	2.7–2.9	7 <sup>1</sup> / <sub>2</sub> –8	hex
biotite	K(Mg,Fe) <sub>3</sub> (AlSi <sub>3</sub> O <sub>10</sub> )(OH) <sub>2</sub>	3	2 <sup>1</sup> / <sub>2</sub> –3	mon
bismuth	Bi	9.8	2 <sup>1</sup> / <sub>2</sub> –3	hex
boehmite (polymorph of diaspore)	A1O(OH)			
boracite	Mg <sub>3</sub> ClB <sub>7</sub> O <sub>13</sub>	2.95	7	orth
borax	Na <sub>2</sub> B <sub>4</sub> O <sub>5</sub> (OH) <sub>4</sub> • 8H <sub>2</sub> O	1.7–1.9	2–2 <sup>1</sup> / <sub>2</sub>	mon
bornite	Cu <sub>5</sub> FeS <sub>4</sub>	6	3	cub
boulangerite	Pb <sub>5</sub> Sb <sub>4</sub> S <sub>11</sub>	6–6.2	2 <sup>1</sup> / <sub>2</sub> –3	mon
brookite	TiO <sub>2</sub>	4.14	5–5 <sup>1</sup> / <sub>2</sub>	orth
brucite	Mg(OH) <sub>2</sub>	2.4–2.5	2 <sup>1</sup> / <sub>2</sub>	hex
calcite	CaCO <sub>3</sub>	2.71	3	hex
carnallite	KMgCl <sub>3</sub> • 6H <sub>2</sub> O	1.6	2 <sup>1</sup> / <sub>2</sub>	orth
carnotite	K <sub>2</sub> (UO <sub>2</sub> ) <sub>2</sub> ,(VO <sub>4</sub> ) <sub>2</sub> • 3H <sub>2</sub> O	4.5	2	mon
cassiterite	SnO <sub>2</sub>	7	6–7	tet
celestite	SrSO <sub>4</sub>	3.97	3–3 <sup>1</sup> / <sub>2</sub>	orth
cerussite	PbCO <sub>3</sub>	6.55	3–3 <sup>1</sup> / <sub>2</sub>	orth
chabazite	CaAl <sub>2</sub> Si <sub>4</sub> O <sub>12</sub> • 6H <sub>2</sub> O	2.1	4–5	hex
chalcanthite	CuSO <sub>4</sub> • 5H <sub>2</sub> O	2.3	2 <sup>1</sup> / <sub>2</sub>	tri
chalcedony (microcrystalline variety of quartz)				

 List of  
Mineral  
Properties

## List of Mineral Properties

Mineral	Formula	Specific Gravity (G)	Hardness (H)	Crystal System
chalcocite	Cu <sub>2</sub> S	5.8	2½–3	mon
chalcopyrite	CuFeS <sub>2</sub>	4.2	3½–4	tet
chalk (fine grained variety of calcite)				
chert (microcrystalline variety of quartz)				
chlorargerite	AgCl	1.55	2½	cub
chlorite	talc + brucite combinations	3	2–3	mon
chloritoid	(Fe,Mg)Al <sub>2</sub> SiO <sub>5</sub> (OH) <sub>2</sub>	3.5	6½	mon
chondrodite	Mg <sub>5</sub> (SiO <sub>4</sub> ) <sub>2</sub> (OH,F) <sub>2</sub>	3.16–3.26	6½	mon
chromite	FeCr <sub>2</sub> O <sub>4</sub>	5.1	5½	cub
chrysoberyl	BeAl <sub>2</sub> O <sub>4</sub>	3.7–3.8	8½	orth
chrysotile	Mg <sub>6</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>8</sub>	2.5–2.6	4	mon
cinnabar	HgS	8.1	2–2½	hex
citrine (yellow variety of quartz)				
clinohumite	Mg <sub>9</sub> (SiO <sub>4</sub> ) <sub>4</sub> (OH,F) <sub>2</sub>	3.21–3.35	6	mon
clinopyroxene (pyroxene subgroup)				
clinozoisite	Ca <sub>2</sub> Al <sub>3</sub> Si <sub>3</sub> O <sub>12</sub> (OH)	3.1–3.4	6½	mon
cobaltite	CoAsS	6.3	5½	orth
coesite	SiO <sub>2</sub>	2.93	7–8	mon
colemanite	CaB <sub>3</sub> O <sub>4</sub> (OH) <sub>3</sub> ·H <sub>2</sub> O	2.42	4–4½	mon
collophane (variety of apatite)				
columbite	(Fe,Mn)Nb <sub>2</sub> O <sub>6</sub>	6	5	orth
copper	Cu	8.7–8.9	2½–3	cub
cordierite	(Mg,Fe) <sub>2</sub> Al <sub>4</sub> Si <sub>5</sub> O <sub>18</sub>	2.5–2.8	7	orth
corundum	Al <sub>2</sub> O <sub>3</sub>	3.9–4.1	9	hex
covellite	CuS	4.6	1½–2	hex
cristobalite	SiO <sub>2</sub>	2.33	6–7	tet
crocidolite (fibrous form of riebeckite)				
crocoite	PbCrO <sub>4</sub>	6	2½–3	mon
cryolite	Na <sub>3</sub> AlF <sub>6</sub>	2.97	2½	mon
cummingtonite	(Mg,Fe)Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	2.9–3.2	6	mon
cuprite	Cu <sub>2</sub> O	5.9–6.1	3½–4	cub
diamond	C	3.5	10	cub

## List of Mineral Properties

Mineral	Formula	Specific Gravity (G)	Hardness (H)	Crystal System
diaspore	$\text{AlO(OH)}$	3.2–3.5	$6\frac{1}{2}$ –7	orth
diopside	$\text{CaMgSi}_2\text{O}_6$	3.2–3.6	$5\frac{1}{2}$ – $6\frac{1}{2}$	mon
dolomite	$\text{CaMg(CO}_3)_2$	2.85	$3\frac{1}{2}$ –4	hex
emerald (deep green gem variety of beryl)				
enargite	$\text{Cu}_3\text{AsS}_4$	4.5	3	orth
enstatite	$\text{Mg}_2\text{Si}_2\text{O}_6$	3.2–3.5	5–6	orth
epidote	$\text{Ca}_2(\text{Al,Fe})_3\text{Si}_3\text{O}_{12}(\text{OH})$	3.4–3.5	$6\frac{1}{2}$	mon
epsomite	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	1.68	$2$ – $2\frac{1}{2}$	orth
erythrite	$\text{Co}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$	3.06	1–2	mon
fayalite	$\text{Fe}_2\text{SiO}_4$	3.4	$6\frac{1}{2}$	orth
ferrosilite (end member Fe-orthopyroxene)				
flint (microcrystalline variety of quartz)				
fluorite	$\text{CaF}_2$	3.18	4	cub
forsterite	$\text{Mg}_2\text{SiO}_4$	3.2	$6\frac{1}{2}$	orth
franklinite	$\text{ZnFe}_2\text{O}_4$	5.32	$5\frac{1}{2}$ – $6\frac{1}{2}$	cub
galena	$\text{PbS}$	7.6	$2$ – $2\frac{1}{2}$	cub
garnet	$(\text{Ca,Fe,Mg})_3(\text{Al,Fe})_2\text{Si}_3\text{O}_{12}$	3.5–4.3	$6\frac{1}{2}$ – $7\frac{1}{2}$	cub
gedrite (aluminous anthophyllite)				
gehlenite	$\text{Ca}_2\text{Al}_2\text{SiO}_7$	3.0	$5\frac{1}{2}$	tet
gibbsite	$\text{Al(OH)}_3$	2.4	$2\frac{1}{2}$ – $3\frac{1}{2}$	mon
glaucophane	$\text{Na}_2\text{Mg}_3\text{Al}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$	3.1–3.2	5–6	mon
goethite	$\text{FeO(OH)}$	4.3	$5$ – $5\frac{1}{2}$	orth
gold	$\text{Au}$	15.6–19.3	$2\frac{1}{2}$ –3	cub
graphite	$\text{C}$	2.1–2.2	1–2	hex
grossular	$\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	3.56	$6\frac{1}{2}$	cub
grunerite	$\text{Fe}_7\text{Si}_8\text{O}_{22}(\text{OH})_2$	3.1–3.6	6	mon
gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	2.32	2	mon
halite	$\text{NaCl}$	2.16	$2\frac{1}{2}$	cub
hausmannite	$\text{Mn}_3\text{O}_4$	4.86	$5$ – $5\frac{1}{2}$	tet
hedenbergite	$\text{CaFeSi}_2\text{O}_6$	3.55	5–6	mon
hematite	$\text{Fe}_2\text{O}_3$	4.9–5.3	$5\frac{1}{2}$ – $6\frac{1}{2}$	hex
heulandite	$\text{CaAl}_2\text{Si}_7\text{O}_{18} \cdot 6\text{H}_2\text{O}$	2.15	$3\frac{1}{2}$ –4	mon

 List of  
Mineral  
Properties

List of Mineral Properties

<b>Mineral</b>	<b>Formula</b>	<b>Specific Gravity (G)</b>	<b>Hardness (H)</b>	<b>Crystal System</b>
hornblende	$(\text{K}, \text{Na})_{0-1}(\text{Ca}, \text{Na}, \text{Fe}, \text{Mg})_2(\text{Mg}, \text{Fe}, \text{Al})_5(\text{Si}, \text{Al})_8\text{O}_{22}(\text{OH})_2$	3–3.5	5–6	mon
hypersthene	$(\text{Mg}, \text{Fe})_2\text{Si}_2\text{O}_6$	3.2–3.5	5–6	orth
idocrase (see vesuvianite)				
illite (micalike clay of variable composition)				
ilmenite	$\text{FeTiO}_3$	4.5–5	5–6	hex
jade (green variety of jadeite or tremolite)				
jadeite	$\text{NaAlSi}_2\text{O}_6$	3.3	$6\frac{1}{2}$	mon
jasper (red microcrystalline quartz)				
kaersutite	Ti-rich hornblende	3.2–3.3	6	mon
kaolinite	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	2.6	$2-2\frac{1}{2}$	tri
kernite	$\text{Na}_2\text{B}_4\text{O}_6(\text{OH})_2 \cdot 3\text{H}_2\text{O}$	1.9	3	mon
kyanite	$\text{Al}_2\text{SiO}_5$	3.6	5–7	tri
labradorite (a plagioclase feldspar of composition Ab50An5-Ab30An70)				
larnite				
laumontite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 4\text{H}_2\text{O}$	2.3	4	mon
lawsonite	$\text{CaAl}_2\text{Si}_2\text{O}_7(\text{OH})_2 \cdot \text{H}_2\text{O}$	3.1	7–8	orth
lazulite	$(\text{Mg}, \text{Fe})\text{Al}_2(\text{PO}_4)_2(\text{OH})_2$	3	6	mon
lepidocrocite	$\text{FeO}(\text{OH})$	4	5	orth
lepidolite	$\text{K}(\text{Li}, \text{Al})_{2-3}\text{AlSi}_3\text{O}_{10}(\text{OH})_2$	2.85	$2\frac{1}{2}-4$	mon
leucite	$\text{KAlSi}_2\text{O}_6$	2.48	$5\frac{1}{2}-6$	tet
limonite (mixture of hematite, goethite, and lepidocrocite)				
lizardite (a massive polymorph of serpentine)				
magnesite	$\text{MgCO}_3$	3	4	hex
magnetite	$\text{Fe}_3\text{O}_4$	5.2	$5\frac{1}{2}-6\frac{1}{2}$	cub
malachite	$\text{Cu}_2\text{CO}_3(\text{OH})_2$	3.7–4	$3\frac{1}{2}-4$	mon
manganite	$\text{MnO}(\text{OH})$	4.2–4.4	4	mon
marcasite	$\text{FeS}_2$	4.9	$6-6\frac{1}{2}$	orth
margarite	$\text{CaAl}_2(\text{Al}_2\text{Si}_2\text{O}_{10})(\text{OH})_2$	3.1	$3\frac{1}{2}-4\frac{1}{2}$	mon
marialite (end member sodic scapolite)				
meionite (end member calcic scapolite)				
microcline	$\text{KAlSi}_3\text{O}_8$	2.56	6	tri
millerite	$\text{NiS}$	5.5	$3-3\frac{1}{2}$	hex

## List of Mineral Properties

Mineral	Formula	Specific Gravity (G)	Hardness (H)	Crystal System
molybdenite	MoS <sub>2</sub>	4.7	1–1½	hex
monazite	(Ce,La,Th)PO <sub>4</sub>	4.9–5.2	5½	mon
monticellite	CaMgSiO <sub>4</sub>	3.15	5½	orth
montmorillonite	(Ca,Na) <sub>0.2–0.4</sub> (Al,Mg,Fe) <sub>2</sub> (Si,Al) <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub> ·nH <sub>2</sub> O	2.5	1–1½	mon
muscovite	KAl <sub>2</sub> (AlSi <sub>3</sub> O <sub>10</sub> )(OH) <sub>2</sub>	2.8	2½	mon
natrolite	Na <sub>2</sub> Al <sub>2</sub> Si <sub>3</sub> O <sub>10</sub> ·2H <sub>2</sub> O	2.23	5–5½	orth
nepheline	(Na,K)AlSiO <sub>4</sub>	2.6	5½–6	hex
nephrite (variety of actinolite)				
niccolite	NiAs	4.6	5–5½	hex
nickeline (see niccolite)				
niter	KNO <sub>3</sub>	2.1	2	orth
nitratite	NaNO <sub>3</sub>	2.29	1–2	hex
norbergite	Mg <sub>3</sub> SiO <sub>4</sub> (OH,F) <sub>2</sub>	3.16	6½	orth
olivine	(Mg,Fe) <sub>2</sub> SiO <sub>4</sub>	3.2–3.4	6½–7	orth
opal	SiO <sub>2</sub> ·nH <sub>2</sub> O	2.0–2.25	5–6	amorphous
orpiment	As <sub>2</sub> S <sub>3</sub>	3.49	1½–2	mon
orthoclase	KAlSi <sub>3</sub> O <sub>8</sub>	2.56	6	mon
orthopyroxene (pyroxene subgroup)				
paragonite	NaAl <sub>2</sub> (AlSi <sub>3</sub> O <sub>10</sub> )(OH) <sub>2</sub>	2.85	2	mon
pargasite (a sodic variety of hornblende)				
pectolite	NaCa <sub>2</sub> (SiO <sub>3</sub> ) <sub>3</sub> H	2.9	4½–5	tri
pentlandite	(Ni,Fe) <sub>9</sub> S <sub>8</sub>	5	3½–4	cub
periclase	MgO	3.56	5½	cub
peridot (gem olivine)				
perovskite	CaTiO <sub>3</sub>	4	5½	orth
perthite (intergrowth of K-feldspar and albite)				
phlogopite	KMg <sub>3</sub> (AlSi <sub>3</sub> O <sub>10</sub> )(OH) <sub>2</sub>	2.8	2½–3	mon
pigeonite	(Ca,Mg,Fe) <sub>2</sub> Si <sub>2</sub> O <sub>6</sub>	3.4	6	mon
plagioclase (feldspar having composition between albite and anorthite)				
platinum	Pt	16.5–18	4–4½	cub
pleonaste (Fe-rich spinel)				
prehnite	Ca <sub>2</sub> Al(AlSi <sub>3</sub> O <sub>10</sub> )(OH) <sub>2</sub>	2.9	6–6½	orth

 List of  
Mineral  
Properties

## List of Mineral Properties

Mineral	Formula	Specific Gravity (G)	Hardness (H)	Crystal System
proustite	Ag <sub>3</sub> AsS <sub>3</sub>	5.5–7	2–2½	hex
psilomelane (see romanechite)				
pyrargyrite	Ag <sub>3</sub> SbS <sub>3</sub>	5.85	2	hex
pyrite	FeS <sub>2</sub>	5.1	6–6½	cub
pyrolusite	MnO <sub>2</sub>	4.5–5	2½–6½	tet
pyromorphite	Pb(PO <sub>4</sub> ) <sub>3</sub> Cl	7	3½–4	hex
pyrope	Mg <sub>3</sub> Al <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>	3.54	7	cub
pyrophyllite	Al <sub>2</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub>	2.8	1½	tri
pyrrhotite	Fe <sub>1-x</sub> S	4.6	3½–4½	hex
quartz	SiO <sub>2</sub>	2.65	7	hex
realgar	AsS	3.56	11½–2	mon
rhodochrosite	MnCO <sub>3</sub>	3.7	3½–4	hex
rhodonite	MnSiO <sub>3</sub>	3.5–3.7	5½–6	tri
riebeckite (a bluish sodic amphibole)				
romanechite	BaMn <sub>9</sub> O <sub>16</sub> (OH) <sub>4</sub>	3.5–4.7	5–6	mon
ruby (red gem variety of corundum)				
rutile	TiO <sub>2</sub>	4.24	6–6½	tet
sanidine	(K,Na)AlSi <sub>3</sub> O <sub>8</sub>	2.56	6	mon
sapphire (gem variety of corundum)				
scapolite	(Na,Ca) <sub>4</sub> (Al,Si) <sub>12</sub> O <sub>24</sub> (Cl,CO <sub>3</sub> )	2.55–2.76	5–6	tet
scheelite	CaWO <sub>4</sub>	6.11	4½–5	tet
schorl (black variety of tourmaline)				
seLENite (variety of gypsum)				
sepiolite	Mg <sub>4</sub> Si <sub>6</sub> O <sub>15</sub> (OH) <sub>2</sub> (H <sub>2</sub> O)·4H <sub>2</sub> O	2	2–2½	orth
serpentine (mineral group)				
siderite	FeCO <sub>3</sub>	3.96	4	hex
sillimanite	Al <sub>2</sub> SiO <sub>5</sub>	3.23	6–7	orth
silver	Ag	10.1–10.5	2½–3	cub
sinhalite	MgAlBO <sub>4</sub>	3.42	6½–7	orth
skutterudite	(Co,Ni)As <sub>3</sub>	6.1–6.8	5½–6	cub

## List of Mineral Properties

Mineral	Formula	Specific Gravity (G)	Hardness (H)	Crystal System
smithsonite	ZnCO <sub>3</sub>	4.43	4–4½	hex
sodalite	Na <sub>3</sub> Al <sub>3</sub> Si <sub>3</sub> O <sub>12</sub> · NaCl	2.3	5½–6	cub
spessartine	Mn <sub>3</sub> Al <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>	4.19	7	cub
sphalerite	ZnS	4	3½–4	cub
sphene (see titanite)				
spinel	MgAl <sub>2</sub> O <sub>4</sub>	3.5–4	7½–8	cub
spodumene	LiAlSi <sub>2</sub> O <sub>6</sub>	3.15	6½–7	mon
staurolite	Fe <sub>2</sub> Al <sub>9</sub> Si <sub>4</sub> O <sub>23</sub> (OH)	3.75	7–7½	mon
stibnite	Sb <sub>2</sub> S <sub>3</sub>	4.6	2	orth
stilbite	CaAl <sub>2</sub> Si <sub>7</sub> O <sub>18</sub> · 7H <sub>2</sub> O	2.15	3½–4	mon
stishovite	SiO <sub>2</sub>	4.3		tet
strontianite	SrCO <sub>3</sub>	3.72	3½	orth
sulfur	S	2.1	1½–2½	orth
sylvite	KCl	1.99	2	cub
talc	Mg <sub>3</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub>	2.8	1	mon
tephroite (manganese-rich variety of olivine)				
tetrahedrite	Cu <sub>12</sub> Sb <sub>4</sub> S <sub>13</sub>	4.5–5.11	3–4	cub
titanite	CaTiSiO <sub>5</sub>	3.5	5	mon
topaz	Al <sub>2</sub> SiO <sub>4</sub> (F,OH) <sub>2</sub>	3.5–3.6	8	orth
tourmaline	(Na,Ca)(Fe,Mg,Al,Li) <sub>3</sub> Al <sub>6</sub> (BO <sub>3</sub> ) <sub>3</sub> Si <sub>6</sub> O <sub>18</sub> (OH) <sub>4</sub>	2.9–3.3	7–7½	hex
tremolite	Ca <sub>2</sub> Mg <sub>5</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	3–3.3	5–6	mon
tridymite	SiO <sub>2</sub>	2.28	6–7	orth
triphylite	Li(Fe,Mn)PO <sub>4</sub>	3.5–5.5	5–5½	orth
trona	Na <sub>3</sub> H(CO <sub>3</sub> ) <sub>2</sub> · 2H <sub>2</sub> O	2.13	3	mon
turquoise	CuAl <sub>6</sub> (PO <sub>4</sub> ) <sub>4</sub> (OH) <sub>8</sub> · 4H <sub>2</sub> O	2.7	6	tri
ulexite	NaCaB <sub>5</sub> O <sub>6</sub> (OH) <sub>6</sub> · 5H <sub>2</sub> O	1.96	2½	tri
uraninite	UO <sub>2</sub>	7–9.5	5–6	cub
vanadinite	Pb <sub>5</sub> (VO <sub>4</sub> ) <sub>3</sub> Cl	6.9	3	hex
variscite	AlPO <sub>4</sub> · 2H <sub>2</sub> O	2.5	4	orth
vermiculite (one of the clays of the smectite group)				

## List of Mineral Properties

Mineral	Formula	Specific Gravity (G)	Hardness (H)	Crystal System
vesuvianite	$\text{Ca}_{10}(\text{Mg},\text{Fe})_2\text{Al}_4\text{Si}_9\text{O}_{34}(\text{OH})_4$	3.4	$6\frac{1}{2}$	tet
vivianite	$\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$	2.58	2	mon
wavellite	$\text{Al}_3(\text{PO}_4)_2(\text{OH})_3 \cdot 5\text{H}_2\text{O}$	2.36	3–4	orth
witherite	$\text{BaCO}_3$	4.29	3– $3\frac{1}{2}$	orth
wolframite	$(\text{Fe},\text{Mn})\text{WO}_4$	7.2–7.6	4– $4\frac{1}{2}$	mon
wollastonite	$\text{CaSiO}_3$	3.1	$4\frac{1}{2}$ –5	tri
wulfenite	$\text{PbMoO}_4$	6.7–7	3	tet
wurtzite	$\text{ZnS}$	4	$3\frac{1}{2}$ –4	hex
xanthophyllite	$\text{Ca}(\text{Mg},\text{Al})_{2-3}(\text{Al}_2\text{Si}_2\text{O}_{10})(\text{OH})_2$	3–3.1	$3\frac{1}{2}$	mon
zinc	$\text{Zn}$	7.1	2	hex
zincite	$\text{ZnO}$	5.4–5.7	4– $4\frac{1}{2}$	hex
zircon	$\text{ZrSiO}_4$	4.68	$7\frac{1}{2}$	tet
zoisite	$\text{Ca}_2\text{Al}_3\text{Si}_3\text{O}_{12}(\text{OH})$	3.5	6	orth

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# PERIODIC TABLE OF THE ELEMENTS

# Periodic Table of the Elements

### Lanthanide series:

1.12	3,4	1.13	3,4	1.14	3	1.13	3	1.17	2,3	1.2	2,3	1.20	3	1.2	3,4	1.22	3	1.23	3	1.24	3	1.25	2,3	1.1	2,3	1.27	3
58	59	Pr	60	Nd	Pm	61	Sm	62	Eu	63	Gd	64	Tb	65	Dy	66	Ho	67	Er	68	Tm	69	Yb	70	Lu	71	3
Ce																											
140.12		140.91		144.24	(147)		150.36		151.97		157.25		158.93		162.50		164.93		167.26		168.93		173.04		174.97		
1.3	4	1.5	4,5	1.38	3,4,5,6	1.36	3,4,5,6	1.28	3,4,5,6	1.3	3,4,5,6	1.3	3,4,5,6	1.3	3,4	1.3	3	1.3	3	1.3	3	1.3	2,3	1.3	2,3	1.3	3
90	91	Pa	92	U	Np	93	Pu	94	Am	95	Cm	96	Bk	97	Cf	98	Es	99	Fm	100	Md	101	No	102	Lr	103	3
Th																											
(232)		(231)		(238)	(237)		(244)		(243)		(247)		(247)		(251)		(252)		(257)		(258)		(259)		(260)		

### Actinide series:

140.12	140.91	144.24	(147)	150.36	151.97	157.25	158.93	162.50	164.93	167.26	168.93	173.04	174.97													
1.3	4	1.5	4,5	1.38	3,4,5,6	1.36	3,4,5,6	1.28	3,4,5,6	1.3	3,4,5,6	1.3	3,4,5,6	1.3	3,4	1.3	3	1.3	3	1.3	3	1.3	2,3	1.3	2,3	3
90	91	92	93	94	95	96	97	98	99	100	101	102	103													
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr													
(232)	(231)	(238)	(237)	(244)	(243)	(247)	(247)	(251)	(252)	(257)	(258)	(259)	(260)													

\*The mass number of an important radioactive isotope—not the atomic mass—is shown in parenthesis for an element with no stable isotopes.  
\*\*Element 112 has a proposed name of Copernicium which is, at the time of this publication, under review by IUPAC.

# Index

Page references followed by "f" indicate illustrated figures or photographs; followed by "t" indicates a table.

## A

Aa, 263, 315, 326, 368  
Abrasion, 82, 182  
Absolute location, 310-311  
Absolute magnitude, 280  
Absolute temperature, 205  
Absorption, 1-2, 10, 13, 20, 22, 40, 72, 109, 339-340  
Acid mine drainage, 220  
Acidity, 174  
Afghanistan, 230  
Africa, 75, 138, 186, 193, 218, 221-222, 226, 230-231  
Age, 2, 25-26, 37, 59, 181, 184, 186, 354, 367  
Aggregate, 1, 4-5, 7, 12, 15, 20, 74, 76, 165, 169, 385, 437, 476  
Agriculture, 218  
AIDS, 177  
Algae, 224  
Alkali feldspars, 50, 58, 142-145, 147, 372, 375  
Alkaline, 1, 31-32, 35-36, 42, 134, 139, 157, 172, 349, 356, 377-378, 385, 387-388, 398, 469, 499, 509-510, 517, 554  
Alluvial fan, 185  
Alluvium, 1, 231  
Alps, 212  
Aluminum, 2, 11, 31, 39, 55, 61, 82, 137, 148, 161, 175, 218-219, 221, 224, 230, 233, 356-357, 384, 388, 444, 447, 462, 503, 509, 515-517  
industry, 218, 233  
reserves, 218  
Aluminum ore, 2, 175  
Amphibole, 35, 39, 52, 55, 76, 78, 109, 123-125, 136-137, 149, 152-153, 173-174, 197, 200, 203, 363, 366, 367, 375, 382-384, 392, 395-400, 412, 414, 416, 488, 498, 501, 504-505, 507, 509-511, 515, 544, 549  
Amphiboles, 2, 6, 10, 43, 58, 78, 109, 115, 125, 149, 152-154, 195, 200, 354, 357, 359, 361, 383, 387, 396-400, 504, 507, 509-510  
Amphibolite, 1, 173, 195, 197-198, 200, 338  
Amplitude, 104, 106  
Andalusite, 3, 58, 82, 86-87, 125, 127, 130, 196, 199, 204, 206-208, 210-211, 355-356, 410-413, 441, 474, 488, 501, 514, 516-517, 527, 529, 536, 538, 543  
Andesite, 1, 156-160  
Angle of incidence, 1, 4, 111, 325, 330  
Angles, 4-5, 8, 13, 17, 19-21, 54, 81, 107, 110-111, 117-118, 120, 125, 150, 154, 244, 249-251, 263, 269, 274-275, 278, 280, 283-284, 286-287, 292, 306-311, 322, 324-328, 330-333, 340, 369, 373, 381, 396-400, 403, 501, 504, 507-508, 511  
Angola, 231  
Animals, 61, 175, 239, 241  
Anion, 1, 9, 17, 29, 36, 51, 62, 135, 179, 181, 345-347, 349, 352-354, 356, 444  
Anions, 9, 12-13, 29-31, 34-36, 39-40, 49, 51-52, 61-62, 177, 181, 227, 344-350, 352-353, 355-357, 359, 378  
Antarctica, 193  
Apatite, 15, 23, 39, 55, 58, 62, 73, 76, 82-83, 86, 103, 115, 155, 159, 181, 183-184, 355, 359, 377-378, 381, 403, 414, 464-467, 469-470, 491, 498, 525, 529, 535, 538, 543, 545  
Apollo, 161  
Aragonite, 2, 16, 57, 59, 88, 116, 184, 203, 208-209, 275-276, 368, 378, 395, 400, 416, 447-448, 452-454, 456, 490, 498, 526, 531, 534, 538, 544  
Argon, 29, 346  
Aristotle, 25, 239  
Arizona, 165, 169, 407, 462, 476

Arkose, 1, 185

Arsenic, 18, 225-226, 418, 421, 429, 431-432, 489, 499, 521, 533, 540, 544  
Asbestos, 1, 52, 71, 78, 217, 219, 382-383, 500, 509, 544

Asteroids, 38

Atlantic Ocean, 185

Mediterranean Sea, 185

Atmosphere, 1, 38-39, 55, 60, 133, 186, 224

composition, 1, 39, 55, 60, 133

density, 133

early, 38, 186

movement, 133

oceans and, 186

origin of, 224

physical properties, 1, 186, 224

planets, 38

temperature, 60, 133

Atom, 2-4, 6, 8-12, 14, 17-18, 22, 27-29, 33, 36, 40-41, 44, 52-53, 61, 84, 104, 109, 225, 282-283, 301, 306, 310-311, 322, 344, 346, 349, 351, 356, 426, 447

Atomic mass, 2, 33

Atomic number, 2, 6, 28-29, 31, 33, 339, 346

Atomic structure, 1, 4, 10, 13, 15, 19, 23, 40, 48-49, 52, 62-63, 70, 79, 82, 85, 105, 110, 144, 148, 151-152, 177, 205, 231, 239-240, 244, 271, 274, 290, 292, 296, 301, 311, 320, 322, 324, 326, 328-330, 332, 334, 336, 338, 340, 343-357, 359-366, 367, 470

Augite, 55, 150-151, 153, 164, 169, 392-395, 398, 476, 483, 488, 499, 501, 508, 511, 513, 544

Aureole, 2, 4, 19, 192, 202

Australia, 92, 97, 175, 179, 186, 188, 189, 218, 221, 230-231, 379, 454, 473, 481

mining, 186, 218, 221, 231

mining in, 231

size, 175, 186

## B

Backscatter, 2, 18, 336-337

Bacteria, 175

Bar, 193, 205, 212, 229, 246, 269, 311-312

Bars, 78, 229, 312, 337

Basal cleavage, 2, 79, 147, 425, 507, 518

Basalt, 2, 7-8, 135-136, 156-160, 165, 169, 200, 211, 376, 379, 391-392, 402, 407, 459, 476, 504-505

formation, 2, 7

hotspot, 157

Basaltic composition, 7, 9

Base, 152, 231, 258-259, 283, 285, 288, 416, 499

Basin, 183, 185

Basins, 185

Batholiths, 157, 159

Bauxite, 2, 175, 218-219, 224, 444, 447, 495, 544

Beach, 185, 369, 465, 523

deposits, 185, 523

shoreline, 185

Beaches, 186

Bedrock, 162

Beds, 7, 55, 175, 179-180, 183-185, 217, 418, 421, 433, 439, 452, 456, 458-459

Bentonite, 2, 20, 177, 384

Big Sur, 354

Biological activity, 174, 176

Biological processes, 2

Biotite, 1, 5, 8, 11, 13, 16-18, 20-21, 39, 50-51, 55, 76,

79-80, 86, 89, 92, 97-98, 109, 120, 127-128,

129-131, 137, 147-149, 158-160, 162, 165,

169, 173-174, 194, 196, 199-201, 203, 208,

212, 235, 237, 293, 338, 355, 357, 359-360,

366, 377, 386-388, 390, 399, 412-413,

474-477, 482-483, 487, 494, 496-497, 516,

518, 527, 531, 533, 538, 543-544

Blueschist facies, 2, 197-198, 203, 395, 400, 416, 452

Boiling point, 85

Bolivia, 218, 221

Bonding, 5, 10-11, 13-14, 20-22, 34-36, 44, 51, 62, 76, 79, 83-85, 147, 175, 219, 226-227, 340,

344-346, 354, 359, 432

Boston, 303, 318

Boundaries, 52-53, 105, 125, 144, 173, 205, 354, 374

Europe, 354

physical, 374

plate, 52-53, 125, 144, 374

water, 173

Boyle, Robert, 26

Branch, 15, 21, 102

Brazil, 3, 50, 66, 67, 90-92, 95, 97, 136, 163, 165, 167, 169, 199, 213, 215, 218, 221, 230-231, 360, 369, 381, 403, 466, 471-473, 476, 478, 479-481, 483

Breaks, 4, 20, 70-71, 79-80, 148, 179, 207, 345, 402, 496, 523

Breccia, 3, 181-182, 185

Buoyancy, 133

Burial metamorphism, 3, 17, 192

## C

Calcite, 6, 11-12, 16, 19, 21, 23-24, 35, 53-59, 62, 71, 73-74, 76, 80, 82-83, 86-88, 92, 97, 103, 112-113, 115, 118, 125, 127-128, 129-130, 135, 161, 165, 169, 174-175, 177-179, 182-184, 188, 189, 196, 201-204, 208-209, 213, 215, 217, 226, 268, 274-276, 288, 290, 301, 309, 345, 355, 366, 368, 372, 376-377, 379-380, 387, 391-393, 398, 401-402, 405, 408-409, 420, 424, 426, 429-431, 433-437, 441, 445, 447-453, 455, 458-460, 473-476, 481-483, 490, 498-499, 502, 525, 532, 534, 538, 544-545

Calcium, 15, 19, 23, 26-27, 39, 54, 86, 137, 147, 150, 161, 174, 208-209, 218, 345, 512, 514

Calcium carbonate, 23, 54, 209

California, 78, 91, 96-97, 164, 168, 183, 198, 203, 223-224, 337, 354, 385, 415, 416, 456-458, 472-473, 480-481

Calorie, 205

Cambodia, 230

Canada, 50, 92-93, 97-98, 165, 169, 193, 218, 221, 230-231, 235-236, 237-238, 284, 303, 318, 414, 425, 446, 473, 476-478, 481, 483-485

agriculture, 218

Cancer, 78, 354

Carbon, 3, 10, 14, 22, 26, 30, 33, 39, 59-60, 83-85, 160, 177, 208, 226-227, 339, 420

Carbon dioxide, 3, 22, 59, 160, 177

Carbonate deposits, 184

Carbonates, 10-11, 13, 62, 84, 125, 134, 152, 175, 177-179, 183-184, 186, 195, 200, 202, 224, 228, 275, 354, 359-360, 366, 368, 375, 383, 398, 417, 421-422, 431, 437-438, 441, 445, 447-451, 453-456, 458, 490

Carbonation, 3, 204

Cation, 3, 12, 17-18, 29, 36, 38, 41, 51-52, 62, 103, 135, 147, 177, 228, 292, 344, 346-348, 352-357, 406, 432, 440, 460

Caves, 456, 461

Cementation, 3, 11, 171, 174-175

Chain, 3, 6, 10, 19, 34, 58, 63, 149, 152, 357-358, 361, 367, 392, 396, 398, 400, 488

Chalk, 185, 499, 516-517, 545

Chemical bond, 4, 10, 12, 340, 344, 354, 366

Chemical bonds, 76, 79, 344

covalent, 344

ion, 344

ionic, 76, 79, 344

Chemical compounds, 18, 23

Chemical energy, 51

Chemical sedimentary rock, 3, 6-7, 11-12, 15, 172, 183

Chemical sedimentary rocks, 10, 171-172, 182-184,

- chert, 172, 183, 186  
 dolostone, 183  
 evaporites, 171, 183  
 identification of, 183  
 limestone, 172, 183  
 Chemistry, 1, 7, 21, 23, 26-27, 40, 44, 61, 65, 70, 137, 143, 152-154, 157, 173, 186, 191, 202, 205, 211, 221, 271, 303, 318, 335-336, 338, 344, 354, 364, 366, 367, 384, 390, 394, 396, 400-401, 411, 446, 458, 465  
 chemical bonds, 344  
 electron, 40, 336, 338  
 Chert, 2-3, 140, 172, 180-181, 183, 185-186, 369, 449, 516-517, 545  
 Chicago, 24  
 Chile, 218, 434, 462  
 China, 25-26, 177, 218, 230  
 Chlorine, 26-27, 35, 49-50, 135, 179  
 Chlorine (Cl), 27, 35  
 Chromium, 26-27, 72, 138, 218-219, 221, 393, 495, 500, 509, 518  
 Chrysotile, 1, 62, 71, 76, 78-79, 92, 97, 213, 215, 382-384, 473, 481, 487, 500, 504, 545  
 Classification, 1, 13, 15, 31, 38, 47-66, 67, 70, 103, 155-157, 162, 171, 181-182, 186, 212, 367, 382  
 Clastic sedimentary rocks, 8, 186  
 Clasts, 3-4, 171, 181  
 Clay, 2-4, 7, 11-13, 15-16, 20, 36, 40, 71, 147, 171-172, 175-177, 181-182, 184, 191, 193, 195, 199, 219, 361, 367, 384-385, 433, 444, 449, 462, 487, 496, 547  
 Clay minerals, 7, 11, 36, 147, 172, 175-176, 181, 184, 195, 199, 361, 384-385, 444, 462  
 Clays, 4, 8, 11, 15, 19-20, 36, 58, 78-79, 147-148, 172-177, 182, 186, 194, 197, 199, 217, 384-385, 459, 487, 496, 499, 523, 550  
 Cleavage, 2, 4-5, 7-8, 10, 14-16, 20, 35-36, 71, 75, 79-82, 84-85, 89, 108, 110, 118-119, 123-125, 128, 130-131, 147-150, 154, 162, 173, 180, 201, 239, 290, 318, 368-402, 404-446, 448-470, 475, 482, 493, 495-524  
 Climate, 24, 223  
 world, 24  
 Climatologists, 223  
 Clouds, 322, 345  
 Coal, 23-24, 172, 177, 185, 219, 233, 428, 443, 449, 504  
 Coast, 183  
 Cold War, 218  
 Color, 1, 3-4, 8-10, 15, 18, 20, 22, 25, 40-41, 50, 52, 55, 67, 70-73, 75-76, 88-89, 104, 108-110, 114-115, 119, 121, 124, 127, 129-130, 134, 136, 138, 147, 154-155, 159, 167, 177, 180, 183, 189, 193, 200, 215, 226, 228, 230-231, 237, 336, 338, 368-402, 404-470, 474, 479, 493-494, 496, 498, 507-524  
 Columbia River, 157  
 Combines, 18, 30, 456  
 Community, 28  
 Compaction, 11, 171, 174-175  
 Composition, 1-5, 7-22, 23, 36, 39-40, 42-44, 50-55, 57, 59-60, 62-63, 65, 70, 72, 85, 87, 102, 109, 133-137, 142-148, 150-154, 157-159, 162, 171, 173, 175-177, 179, 191, 193, 195, 197, 202, 204-206, 208, 210, 221, 223, 225-226, 228-229, 274-276, 306-307, 309, 319, 328, 331, 336-337, 339, 359, 368-470, 487, 502, 510, 513, 517, 547-548  
 Compounds, 10-11, 18-20, 23, 25-26, 33-36, 38-39, 59, 83, 135, 209, 230, 275, 333, 335, 346, 353-354, 446  
 Compression, 192  
 Concentration, 2, 4, 8, 14-15, 50, 54, 57, 218-220, 233, 339  
 Conduction, 18, 87-88  
 Conglomerate, 4, 171-172, 181-182, 185  
 Congo, 75  
 Continental crust, 157  
 Continental environments, 185  
 Continental rifts, 133-134, 157  
 Continental shelf, 185  
 Continental slope, 185  
 Continents, 16, 185, 221  
 Continuous spectrum, 321  
 Copper, 26, 35-36, 38, 62, 72, 79, 83, 86-87, 93, 98, 103, 217-219, 221-222, 224-226, 229, 233, 235, 238, 320-322, 340, 347, 349, 390  
 Coquina, 4, 172, 185  
 Corals, 4  
 Core, 4, 22, 38-39, 50  
 of Earth, 39  
 Cores, 37, 223  
 Correlation, 276, 357  
 Covalent bond, 4, 35  
 Covalent bonds, 35-36, 84-85, 345  
 Craton, 16  
 Crocidolite, 1, 52, 74, 78-79, 382, 384, 399, 500, 545  
 Crust, 24, 31, 36, 38-39, 58-59, 62, 64-65, 87, 133, 138, 140-141, 157, 162, 171, 192-193, 204, 217-219, 226, 356, 366, 368, 371-372, 375, 455  
 Crystal, 1-22, 24-25, 35-36, 44, 48-54, 56, 61-62, 65, 70-71, 74-77, 79, 81, 83, 85, 88-89, 107-122, 124-125, 136, 139, 142, 145-146, 150-151, 162, 173, 221, 223, 226, 230-231, 233, 239-271, 274-277, 279, 283-284, 286, 290-294, 296, 298-303, 306-318, 319-320, 322, 324-328, 330-334, 340, 344-345, 347, 349, 353-357, 359, 364, 366, 368, 371-372, 375, 376, 378-381, 384, 402-406, 411, 413, 415, 429-430, 434, 436, 438, 440, 457, 459-461, 463-466, 469, 493, 516, 525-528, 529-532, 543-551  
 structures, 2-3, 6, 11, 14, 20, 24, 36, 51-52, 61-62, 79, 83, 85, 139, 151, 221, 226, 231, 233, 239, 250, 252, 275-276, 279, 292, 296, 298-299, 302, 306, 319, 322, 325, 328, 330-332, 344-345, 347, 349, 353-357, 359, 364, 366, 376, 378-381, 384, 402-403, 415, 436  
 Crystal form, 5-6, 9, 15-16, 19-21, 35, 74, 88, 302, 318, 404-406, 411, 413, 429-430, 436, 438, 460, 469, 493  
 Crystal lattice, 2, 5  
 Crystal settling, 146  
 Crystal shape, 20, 70-71, 74, 108, 125, 239, 275, 302, 314, 375, 381, 413, 415, 465  
 Crystal structures, 11, 24, 51, 62, 151, 221, 231, 233, 239, 250, 276, 279, 296, 299, 302, 306, 319, 322, 330-332, 344, 347, 353-355, 357, 359, 364, 366  
 Crystalline, 2, 4-5, 13, 16-17, 19, 23-24, 40, 48-49, 51, 54, 59, 80, 133, 333, 341, 369, 434, 467, 502, 523  
 Crystals, 1-2, 4-12, 14-17, 19-21, 25, 33, 35-36, 48-57, 61, 65-66, 70-71, 74-76, 79, 81, 85, 90-91, 95-97, 104-105, 109, 111-112, 114-123, 125-126, 133-134, 136-139, 142, 146, 150, 155, 159, 162, 164-165, 168-169, 177-178, 180, 184-185, 189, 193-195, 199, 204-205, 222-223, 225-227, 231, 239-244, 246, 248-256, 259, 261-263, 268-271, 274-276, 290, 292-294, 296, 298-302, 306-314, 316-318, 319-320, 322, 324, 330-334, 340, 344-347, 354, 366, 368-382, 385-397, 399-402, 404-469, 471-473, 476, 478, 479-481, 485, 494-524  
 disseminated, 6, 387-389, 393, 420, 424, 426-429, 441, 452  
 shapes of, 276  
 Cyanide, 5, 226  
 Cyprus, 419
- D**  
 Dating, 37, 415  
 Deformation, 14, 52, 76, 82, 194, 204  
 brittle, 76  
 ductile, 76  
 elastic, 76  
 Delta, 185  
 Density, 5, 9, 11, 18, 33, 70, 83-84, 86, 125, 133, 209, 301, 312, 327, 330, 415, 420-423, 426-429, 431, 437-439, 442, 450, 452-453, 465, 467, 469, 493, 499, 502-503  
 ice, 9  
 Denver, 79  
 Deposition, 2-3, 5, 20, 174, 184-186, 200, 222, 224  
 streams, 174, 185, 224  
 Deserts, 185  
 Desiccation, 11  
 Destructive interference, 5, 7, 105, 114, 322, 328  
 Detrital sedimentary rocks, 1, 171-172, 181-182  
 breccia, 181-182  
 conglomerate, 171-172, 181-182  
 sandstone, 1, 171-172, 181-182  
 shale, 171-172, 181-182  
 Detrital sediments, 5, 174, 181  
 Detritus, 5, 172  
 Development, 21, 23, 26-27, 30, 176, 191, 319, 335-336, 344  
 uneven, 21  
 Diagenesis, 3, 5, 57, 174-177, 192-193, 197  
 Diamond mine, 231  
 Diamonds, 1, 23, 25, 56, 60, 71, 75, 91, 96, 110, 161, 164, 168, 175, 189, 218, 221, 226, 230-231, 233, 472, 480  
 Diaspora, 446  
 Diatoms, 172  
 Diffraction, 3, 5, 7, 9-10, 14, 16, 18-19, 22, 319-335, 337, 339-341, 344-345, 354, 493  
 Diffusion, 19, 51-52, 57, 60, 138, 380  
 Dikes, 157, 159, 221  
 Diorite, 5, 135, 156, 159-160, 399  
 Disseminated deposit, 6, 221  
 Dissolution, 3, 6, 19, 172, 174-175  
 Distance, 5, 17, 79, 114, 143, 185, 239-240, 252, 278, 285-286, 298, 306, 310, 312, 320, 322, 324-325, 345-347, 350, 400  
 Distribution, 16, 20, 29, 36, 52, 220, 239, 246, 275, 337, 350, 354, 424  
 Divide, 41, 58, 62, 71, 102-103, 134, 155, 171, 197, 210-211, 217, 224, 250, 302, 315, 327, 366, 373, 392, 403, 435, 447, 458  
 DNA, 335  
 Dolomites, 417  
 Dolostone, 3, 6, 179, 183, 185, 201-202  
 Dome, 6, 18, 257, 264, 269  
 Domes, 183-184, 256, 433  
 Doppler effect, 340  
 Double refraction, 2, 6-7, 14, 19, 112-115, 125, 499  
 Drainage, 220  
 acid mine, 220  
 Dry climates, 172
- E**  
 Earth, 1-3, 7, 9-11, 15, 17, 22, 23-25, 30-31, 36-39, 50-51, 58-60, 62, 64-65, 84-85, 87, 104, 133-134, 136, 138, 140-141, 144, 157-162, 171, 173, 175-176, 181, 183-184, 186, 191-193, 203, 209, 217-222, 224, 226, 320, 349, 356, 366, 368, 372, 375, 404, 416, 432, 463-465, 515  
 chemical, 3, 7, 9-11, 15, 17, 22, 23, 25, 31, 38, 50-51, 58-60, 62, 64-65, 87, 133-134, 138, 141, 161-162, 171, 173, 175-176, 183-184, 186, 193, 217-219, 222, 224, 356, 366  
 core, 22, 38-39, 50  
 crust, 24, 31, 36, 38-39, 58-59, 62, 64-65, 87, 133, 138, 140-141, 157, 162, 171, 192-193, 217-219, 226, 356, 366, 368, 372, 375  
 crust of, 24, 133  
 hot spots, 133, 157  
 interior, 9-10, 17, 37, 39, 50  
 internal processes of, 38  
 magnetic field, 7, 87  
 orientation, 10, 15, 17  
 radius of, 10, 356  
 rotation of, 2  
 spheres, 9, 15, 349  
 structure, 1, 3, 7, 9-11, 15, 22, 23, 25, 36, 38, 62, 84-85, 87, 140, 144, 175-176, 320, 349, 356, 366, 372, 375, 404, 416, 432, 463-465  
 temperature of, 7, 141, 175  
 Economics, 219, 224, 234  
 Education, 1, 23, 47, 67, 69, 89, 95, 101, 129, 133, 167, 171, 189, 191, 215, 217, 237, 239, 273, 305, 319, 336, 343, 367, 479, 487, 493, 525, 529, 533, 537, 541, 543, 553  
 Egypt, 25, 230  
 Electric field, 87  
 Electrical charge, 17, 498  
 Electricity, 12-13, 18, 36, 85, 87, 231, 339  
 Electromagnetic radiation, 6, 8, 10, 19, 21-22, 28, 104, 109, 320, 322  
 Electromagnetic spectrum, 10, 22, 104  
 Electron, 6, 9, 14, 16, 18, 22, 28-31, 33, 35-36, 40, 52, 78, 138-139, 151, 176, 255, 322, 336-340, 345, 361, 370-371  
 Electron cloud, 6, 29, 33, 345

- Electrons, 1-4, 6, 10-12, 14, 17-18, 21-22, 27-31, 33-37, 39, 44, 72, 85-87, 109, 319, 321-322, 327, 336-337, 339, 344-346
- Elements, 1, 3-4, 6, 8-18, 20-22, 23-31, 33-45, 49-52, 54, 56, 58-62, 65, 72-73, 85, 134-139, 141-142, 150, 152-155, 162, 171-172, 175, 199, 208-209, 217-219, 221-222, 224-226, 228, 233, 244, 246, 248, 254, 256, 259, 261, 263, 274-276, 280, 283, 286, 292, 294, 296, 299, 302, 314, 317, 322, 328, 331, 335-341, 346-347, 349, 353, 356-357, 359, 369, 382, 390, 394, 413, 415-420, 422-423, 426, 429, 432, 447, 463, 465, 515, 553
- minerals as, 24
- Periodic Table of, 1, 9-10, 13, 15, 21, 30, 44, 553
- trace, 1, 10, 12-13, 21, 40-42, 44, 52, 72, 369, 382, 429, 447
- Emission spectrum, 337
- Emissions, 339
- Energy, 2, 4-10, 12, 14-15, 17-22, 28-29, 33-34, 37, 49, 51, 54, 59-60, 73, 85, 104-106, 109, 185, 204-205, 208-209, 211, 217, 219, 234, 319-323, 336-340, 357
- kinds of, 17, 22, 59, 73, 185, 217, 319, 336-337
- kinetic, 49, 51, 54
- levels, 2, 4, 28-29, 34, 321
- mechanical, 5, 12, 204
- potential, 15, 321
- resources, 217, 219, 234
- Energy resources, 217, 219, 234
- England, 461
- Entropy, 3, 7, 205, 209-210
- Environment, 10, 78, 185-186, 219, 224, 233-234, 493-494, 498, 507-524
- Environmental law, 233-234
- Environmental Protection Agency (EPA), 78
- Equator, 259-260
- Equilibrium, 7-8, 12, 14-15, 20, 22, 59-60, 136-138, 140-141, 146, 162, 183, 193-194, 197, 204-206, 208-209, 211
- metastable, 8, 12, 22, 60, 205, 209
- Era, 59
- Erosion, 184, 224
- stream, 224
- Estonia, 218
- Europe, 175, 193, 217, 354, 384, 468
- Evaporation, 7, 183, 185, 224, 345
- Evaporite deposits, 184, 224, 233, 456, 461
- Evaporite minerals, 89, 180, 183, 186, 455
- Evaporites, 3, 171, 183, 185, 187, 495, 497-499, 505
- Evolution, 37, 44, 193
- Extinction, 7, 10-11, 14, 20, 108, 114, 118-119, 123, 127-128, 129, 131, 328, 330, 369, 379-380, 383, 387-389, 392-397, 400-402, 410, 446, 448, 452, 458, 461, 474-475, 482
- mass, 10
- Extrusive, 1-2, 5, 7, 11, 18, 21-22, 51, 54, 133-134, 154, 157, 159, 370
- Extrusive igneous rock, 1-2, 5, 11, 18, 21, 133
- Extrusive igneous rocks, 51, 133, 154, 157, 370
- Eye, 1, 3-4, 18, 21, 53-54, 72, 74, 81, 104, 107, 114, 133, 138, 144, 184, 195, 239, 245-246, 259-261, 360, 369, 372, 385, 387-388, 443
- F**
- Facies, 1-3, 6-8, 11-12, 16-18, 22, 184-186, 197-198, 200, 203, 211-212, 390, 393, 395, 400, 416, 452
- Fault, 20, 198, 222
- Faulting, 192
- Faults, 52, 192
- normal, 52
- Feldspar, 1-2, 5, 7-8, 11-13, 18, 20-21, 24, 41, 43-44, 50-51, 53, 55, 58, 61-65, 74, 80, 82, 87, 102-103, 115, 123, 133, 136-137, 140-147, 150-152, 155-162, 165, 169, 171-175, 177, 181-182, 186, 194-197, 199-200, 203-204, 208, 211, 307, 357, 359-360, 367, 372-375, 377-378, 382, 385, 388-390, 395-396, 403-405, 411, 414, 416, 435-436, 440, 443, 463, 466-467, 476, 478, 483-484, 487, 493, 503, 507-508, 511-514, 543, 547-548
- Feldspar group, 7, 65, 141, 367, 372
- Feldspars, 1, 3, 15, 39, 50, 53-54, 58, 63-65, 74, 86-87, 125, 137, 139-145, 147, 150-152, 155, 158-160, 172-173, 175, 194, 357, 359-360, 368, 371-378, 381, 387-388, 390, 413, 487, 507, 512-514
- Felsic rocks, 134
- Ferromagnesian, 390
- Fertilizer, 217-219
- Fertilizers, 184
- Fine particles, 74
- Fine-grained texture, 495
- Fires, 177
- First law of thermodynamics, 205
- Fish, 220, 243, 276, 278
- Fissility, 7, 19, 181
- Fissure, 11
- Fissures, 133
- Flood basalts, 157, 160
- Florida, 176
- Fluorescence, 7, 22, 73, 322, 339, 463, 469, 493, 499
- Focus, 71, 103, 107, 112-113, 120, 204, 218, 338
- Fold, 6, 20-21, 241-242, 244-256, 259-263, 268-269, 271, 276, 278-280, 282, 284, 288-289, 292-294, 296-299, 302, 308, 314, 317, 331, 345, 347-348, 352-353, 356, 364, 369, 410, 413, 425-427, 435, 440, 448, 457, 464-465
- Folds, 249, 263
- Foliated metamorphic rock, 2, 8, 15, 18-19
- Foliation, 7, 19, 194, 199, 201, 203
- Forests, 234
- Fossils, 37, 59, 184, 499, 519, 524
- Precambrian, 59, 184
- Fraction, 37, 110, 143, 297
- Fracture, 4, 7-8, 10, 21, 49, 71, 79-80, 83, 89, 162, 223, 368, 370-402, 404-446, 448-470, 495, 498, 500, 503, 505, 508-513, 515-519, 521, 523-524
- zones, 7, 223, 394, 419-420, 423, 427, 434, 439, 444, 452, 462, 467, 495
- Fractures, 35, 55, 79-80, 90-91, 95-96, 163-164, 167-168, 179, 222, 418, 461, 472, 480, 493
- conchoidal, 35, 79-80, 90, 95, 163, 167, 461, 472, 480
- rock, 179, 461, 493
- France, 384, 447, 469
- Freshwater, 174
- Fronts, 322-324
- Fumaroles, 226, 418, 421, 461-462
- Fusion, 37
- G**
- Gabbro, 2, 8, 42-43, 135, 156-160, 201, 392
- Galena, 20, 35-36, 57, 73, 76-77, 79, 86, 93, 98, 179, 220, 223, 226, 235, 237, 418, 421-424, 427-431, 433, 435, 443, 447, 449, 453-454, 459-460, 463-464, 470, 477, 484, 489, 519, 533, 540, 546
- Gamma radiation, 340
- Gamma rays, 8, 13, 104, 320-321
- Garnet, 6, 16, 21, 39, 58, 72, 74, 76, 85, 87, 103, 110, 128, 131, 172, 181, 193-194, 196, 198-203, 208, 210-211, 230, 268, 292-294, 299-300, 333, 335, 338, 355, 359, 362, 366, 367, 376, 378, 382, 393, 395, 397, 401, 403-404, 406-407, 411-413, 417, 441, 475, 482, 488, 510, 516-518, 525, 536, 539, 546
- Gases, 29, 31-32, 35-36, 38, 502, 554
- General Electric, 231
- Geochemistry, 44, 366
- Geode, 8, 56, 90, 95, 163, 167, 471
- Geological Society of America, 162, 186, 212
- Geology, 186, 197, 212, 218, 220, 234
- environmental, 220, 234
- Georgia, 92, 97, 164, 169, 473, 481
- Geothermal gradient, 3, 17
- Germany, 38, 42-43, 218, 319, 383, 404
- Gibraltar, 185
- Glacial deposits, 21
- tilt, 21
- Glaciers, 172, 185
- tidal, 185
- Glass, 4, 8, 10, 13, 16, 21-22, 23-24, 49, 51, 55, 59, 79, 82-83, 88, 102, 108, 110, 114, 133, 157, 177, 198, 319, 321, 332, 339, 370, 439, 493-494, 512
- Globe, 221, 407
- Gneiss, 2, 8, 194-195, 198, 200-201, 203, 212
- Gold, 7, 16, 25, 36, 70, 73, 86, 92-93, 98, 103, 217, 219-221, 223-226, 233, 235-236, 237-238, 339, 347, 349, 351, 382, 415, 418-420, 422, 428-432, 477-478, 483-485, 489, 493, 496, 519-520, 524, 534, 540, 546
- concentrations of, 224, 339
- Gold mines, 219
- Gold Rush, 223
- Gradient, 3, 17
- Grain size, 3, 108, 133-134, 171, 181-182, 186, 194, 202, 204-205
- Granite, 8, 18, 24, 48, 61, 133-135, 147-148, 156, 158-159, 173, 191, 211, 222, 375, 414, 416
- Granodiorite, 5, 8, 156, 158, 222, 462
- Granules, 8
- Grapes, 3, 76
- Graphite, 13, 22, 36, 60, 73, 76, 82-86, 194, 204, 209, 218, 226-227, 231, 339, 418, 420, 425, 489, 493, 519, 533, 537, 546
- Gravel, 4, 8, 23, 182
- Gravity, 2, 5, 11, 16, 19, 83-88, 172-174, 219, 221, 223, 334, 368, 370-402, 404-470, 495, 498-499, 501-506, 508-509, 515, 519-521, 523-524, 533-536, 537-540, 543-551
- specific, 2, 11, 16, 19, 83-88, 334, 368, 370-402, 404-470, 495, 498-499, 501-506, 508-509, 515, 519-521, 523-524, 533-536, 537-540, 543-551
- Graywacke, 1, 8
- Great circle, 253
- Great Salt Lake, 224
- Green River Formation, 55
- Groundmass, 16, 155, 194
- Groundwater, 55-56, 186, 495
- hot springs, 56, 495
- wells, 186
- zones of, 495
- Gulf coast, 183
- Gypsum, 1, 7, 9, 15, 19, 54-56, 62, 71, 74, 76-77, 79, 82-83, 86, 92, 97, 103, 108, 177, 179-180, 183-185, 188, 189, 217, 224, 226, 268, 421, 431, 433, 445, 452, 456, 458-461, 473, 481, 490, 495, 527, 529, 533, 537, 546, 549
- H**
- Habitat, 1, 3, 9, 74-78, 89, 91, 96, 108, 110, 119, 164, 168, 251, 274, 300-302, 368-470, 473, 481
- Habitat, 233
- Hail, 379
- Halite, 5, 7, 18, 35-36, 55-56, 62, 74, 76, 79-80, 86-87, 103, 179-181, 183-185, 217, 223-224, 226, 239-240, 268, 275, 282-283, 292-294, 300, 344-345, 349, 352-353, 377, 424, 432-434, 437, 447-448, 456, 459-460, 489, 495, 497, 525, 533, 537, 546
- Halos, 382, 415, 432
- Hardness, 1, 9, 13, 17, 35-36, 49, 70-71, 73, 77, 82-83, 89, 91, 96, 244, 368, 370-402, 404-470, 473, 481, 493-524, 533-536, 537-540, 543-551
- Head, 448
- Heat, 3-4, 11-13, 18, 21, 36, 55-56, 133, 175, 177, 183, 191-192, 205, 222, 231, 321, 494-497, 499, 501, 503, 521-524
- Heat flow, 56
- oceanic, 56
- Helium, 29, 37
- Hematite, 30, 43, 60, 73, 77, 86, 173-175, 180, 184, 186, 195, 220, 223, 228, 397, 426, 432, 435-439, 443, 446-447, 489, 501, 511, 523, 526, 532, 535, 540, 546-547
- High pressure, 2, 11, 22, 85, 197, 203-206, 209
- Highlands, 198, 212
- Horn, 398
- Hornblende, 1, 5, 8, 11, 13, 17-18, 20-21, 40, 55, 87, 103, 125, 127-128, 130-131, 149-150, 153-154, 158-161, 196, 198, 200-201, 203, 338, 359, 361, 378, 393-394, 396-399, 402, 463, 474-475, 482, 488, 501, 511, 517, 530, 535, 538-539, 547-548
- Hornfels, 9, 17, 194, 197-198, 203
- Hot spots, 133, 157
- Hot springs, 21, 56, 91, 96, 164, 168, 174, 231-232, 472, 480, 495-496, 499
- Hubble, Edwin, 37
- Human activities, 13
- Hydration, 9, 204
- Hydrogen, 5, 9-10, 14, 26, 28-30, 36-37, 39, 79, 230, 322, 413, 456, 502, 504
- Hydrogen bonds, 36, 79, 413, 456
- Hydrolysis, 9, 172-173
- Hydrothermal deposits, 56, 177, 222, 233, 418-419, 495-496, 498-505, 507-508, 511, 513, 515, 519-524
- Hypotheses, 60, 319, 344
- Hypothesis, 9, 18

- I**
- Ice, 9, 23, 51, 103, 223, 435
    - ground, 9, 23
    - intrusive, 51
  - Ice cores, 223
  - Iceland, 448
  - Igneous activity, 221
  - Igneous processes, 54, 193, 200
  - Igneous rocks, 2, 7, 21, 38, 49-51, 54-55, 57-58, 62, 133-165, 167, 171, 173, 177, 186-187, 195, 199-203, 211-212, 221, 226, 369-370, 373-383, 386-388, 391-394, 397, 399, 402-403, 405-406, 408, 412-413, 415, 418, 420, 424-425, 436-438, 441, 448, 461-463, 465-466, 499, 502, 505, 510, 513-514, 517, 524
    - compositions, 7, 21, 51, 54-55, 62, 134-135, 137-138, 142-148, 150-155, 159-160, 162, 171, 177, 186, 202, 211-212, 221, 375, 378, 392-393, 397, 466, 514
    - extrusive, 2, 7, 21, 51, 54, 133-134, 154, 157, 159, 370
    - felsic, 7, 134, 137, 373, 505, 510, 514, 517
    - mafic, 2, 21, 134, 136-138, 140, 147-149, 153-155, 157-162, 173, 177, 195, 200-203, 221, 226, 375, 378-380, 383, 386, 391-394, 397, 399, 406, 420, 424-425, 436, 441, 461, 510, 513-514
    - plutonic, 54, 133-135, 147, 156-161, 394
    - textures, 199
  - ultramafic, 21, 134, 137-138, 148, 154-155, 157-158, 160-161, 177, 195, 202, 211, 221, 226, 383, 386, 393, 406, 408, 420, 502, 510, 513, 517
  - Impact craters, 87, 140, 371
  - Inclusions, 42, 73-74, 123, 180, 193, 223, 370, 382, 412, 420, 519
  - India, 26, 90, 95, 163, 167, 218, 230-231, 471
  - Indonesia, 175, 218
  - Industrial minerals, 186, 217, 234
  - Industrial Revolution, 26, 181
  - Infrared radiation, 104-105, 320, 340
  - Intensity, 3-4, 12, 21, 104-106, 108, 114, 321, 326-328, 330, 332-333, 336-339
  - Interface, 1, 110-112
  - Intermediate composition, 1, 5, 11, 13, 20-21, 145, 151, 275, 399
  - Internal processes, 38
  - International Mineralogical Association, 70
  - International Union of Geological Sciences, 162, 186, 212
  - Intrusions, 138, 157-158, 198, 221, 231, 501
  - Intrusive, 2, 5-6, 8, 10, 13, 15, 17, 20-21, 51, 133-134, 201, 494, 501, 514, 524
  - Intrusive igneous rocks, 51, 201, 514, 524
  - Iodine, 27
  - Ionic bond, 10, 36, 345, 353
  - Ionic bonds, 1, 6, 34-36, 344-345, 357, 432
  - Ionic compounds, 83
  - Iran, 218
  - Iraq, 218
  - Ireland, 218
  - Iridium, 138
  - Iron, 2, 7, 10-12, 16, 19, 21, 23, 26, 29-30, 33, 37-39, 43, 50, 55, 59-60, 72, 82, 86-87, 102, 137-138, 161, 173, 175, 177, 183-184, 186, 195, 202, 218-219, 224-226, 229, 233, 321, 337, 351, 356, 369, 393, 402, 418, 423, 428, 437-438, 440, 442, 446-447, 449, 451-452, 462, 478, 485, 497-498, 501-502, 508-511, 513, 516-518, 521, 523
  - Island arcs, 157
  - Islands, 62
  - Isotopes, 11, 17, 33-34, 184, 339
    - radioactive, 17, 34, 184
  - Israel, 231
- J**
- Japan, 198, 219
  - Jasper, 180, 195, 369, 516-517, 547
  - Joints, 402
- K**
- Kaolinite, 4, 61, 71, 86, 172-173, 176-177, 196, 204, 207-208, 347, 349, 361, 384-385, 444, 462, 469, 487, 496, 526, 529, 533, 537, 547
  - Kazakhstan, 218
- L**
- Land reclamation, 233
  - Laterite, 11, 175, 224, 495
  - Lava, 7, 11, 22, 133, 135, 160
    - Lava flows, 160
  - Leaching, 17, 175, 224, 444
  - Lead, 13, 24-26, 50, 54-55, 58-59, 65, 70, 73, 85, 89, 92, 98, 155, 209, 219, 223-224, 235, 237, 241, 251, 300, 320, 328, 333, 372, 418, 420, 423, 425, 427, 429-430, 432, 453-454, 464, 477, 483, 495-496, 498-499, 503-506, 519, 523
  - Light, 1-2, 4-18, 20-22, 49-50, 60, 70-74, 102-120, 122, 124-125, 128, 130-131, 134, 139, 144, 159-160, 193-195, 199-201, 232-233, 320, 322, 324, 330, 336-337, 339-340, 345, 356, 369, 381, 385-386, 393-394, 396-397, 399, 401, 405, 409-410, 412, 416-418, 425, 434, 436, 443, 445, 449-450, 456, 459-460, 463, 468-469, 475, 482, 494-505, 507-516, 519, 521, 524
  - Lightning, 512
    - strikes, 512
  - Limestone, 3-4, 11, 21, 56-57, 59, 172, 178-180, 183, 185, 195, 201-202, 219, 442, 449, 451, 459, 462, 521
  - Limestones, 3, 56, 58, 62, 171, 177, 183-184, 201-202, 223, 414, 417, 429, 435, 448, 452-453, 461, 499-500, 502-507, 509-512, 514, 516-517, 519, 521, 523-524
  - Linnaeus, Carolus, 61
  - Lithification, 3, 5, 11, 18, 172, 174-175, 200
  - Location, 9-10, 29, 37, 42-43, 141, 206, 246, 252, 280, 285, 290, 296, 300, 309-313, 315, 322, 326
    - mathematical, 29
  - London, 44, 162, 186, 212, 234, 341, 366
  - Low pressure, 194, 198, 205-206, 516
  - Lung cancer, 78
  - Lungs, 89
  - Luster, 1, 6, 8, 12-13, 15, 19-20, 22, 70-74, 81, 89, 102, 110, 177, 368, 370-402, 404-470, 493-524
- M**
- Macedonia, 441
  - Mafic, 2, 8, 10, 12, 14-15, 19, 21, 39, 42-43, 59, 134, 136-138, 140, 147-149, 153-155, 157-162, 173, 175, 177, 195, 197, 200-203, 205, 221, 226, 375, 378-380, 383, 386, 390-394, 397-399, 404, 406-407, 416-417, 420, 424-425, 436, 441, 445, 449, 461, 494, 497-498, 504, 507, 510, 513-514, 521-522
  - Mafic rocks, 59, 147, 155, 158-160, 197, 200, 203, 205, 392-393, 398-399, 416-417, 445, 497-498, 507
  - Magma, 3, 5, 8-9, 11-15, 17, 22, 49-52, 54, 59, 102-103, 133-138, 143, 146-147, 158, 162, 173, 193, 198, 204, 221, 467
    - chambers, 133, 221
      - crystallization of, 3, 8, 14-15, 136, 221
  - Magnesium, 12, 21, 38-39, 50, 61, 86, 102, 137, 147, 161, 173, 179, 185, 202, 218, 349, 351, 356, 383-384, 387, 445, 510, 513, 517-518
  - Magnetic field, 7, 87-88
  - Magnetite, 43, 55, 60, 73, 86-87, 103, 155, 159, 172-173, 181, 184, 186, 195-196, 220-221, 227-228, 356, 383, 397, 406, 422, 424, 428, 437-442, 446-447, 465, 490, 523, 535, 540, 547
  - Magnitude, 5, 9, 18, 20, 280, 285, 287, 299, 320, 322
  - Manganese, 39, 72, 86, 175, 184, 218-219, 346, 402, 445, 447, 450, 497, 500, 502, 504, 509, 511, 513-514, 517, 550
  - Mantle, 6, 38-39, 62, 133, 138, 162, 204, 226, 371, 418, 420
    - lower, 133, 138, 226
    - upper, 133, 162
  - Maps, 337
  - Marble, 12, 24, 42-43, 155, 165, 169, 195, 201, 213, 215, 348-350, 393, 476, 483
  - Marine organisms, 59
  - Mars, 38
  - Mass number, 12
  - Matter, 5, 25-26, 30, 33, 37, 59-60, 110, 119, 181, 248, 260, 274, 278, 291, 301-302, 311-312, 314, 319, 324
  - Mechanical weathering, 3, 5, 12, 172
  - Melt, 5, 35, 49, 55, 134-138, 141, 145-146, 154-155, 177, 193, 195, 197, 221-222, 230-231, 357
  - Mercury, 23-24, 26, 38, 221, 225, 426, 495, 521
  - Metallic bonds, 34-36, 87, 225, 344
  - Metallic minerals, 71-72, 74, 431, 493
  - Metals, 1, 5, 11, 16, 18, 20, 30-31, 34-36, 55, 72, 84, 87, 89, 138, 147, 217-219, 221, 224-226, 228, 234, 320, 339-340, 347, 349, 351, 367, 418, 430, 466, 541
  - Metamorphic environments, 175, 198
    - regional, 198
  - Metamorphic facies, 1-2, 6, 8, 11-12, 17-18, 22, 197-198
  - Metamorphic rocks, 2, 39, 57, 61, 65, 87, 102-103, 140, 143, 148, 152-155, 162, 175, 177, 186, 191-213, 215, 223, 226-227, 231, 356, 373-374, 378, 380, 386-388, 390, 393, 395-397, 400-406, 408, 410, 412-415, 418, 420, 428-429, 435-436, 438, 449-450, 452, 466, 468, 498-499, 501, 504-505, 508-509, 511, 516-519, 521-524
    - foliated, 2, 194, 199-200, 387, 390, 413, 420
  - Metamorphic textures, 194
    - foliation, 194
  - Metamorphic zones, 191-192, 199
  - Metamorphism, 1, 3-6, 8, 12, 16-17, 19, 23, 57, 59, 174-175, 191-195, 197-200, 202-203, 205-206, 210-211, 222, 382, 391, 417, 497
    - agents, 174-175, 191
    - contact, 4, 19, 191-192, 194, 197-198, 200, 202, 211, 222, 382, 417
    - shock, 3, 6, 19, 192
  - Metasomatism, 12, 19, 57, 191, 202, 206
  - Metastable equilibrium, 12, 60, 205
  - Meteor, 19, 87, 371
  - Meteorites, 38, 59, 225-226, 228, 370, 418, 509, 521
  - Methane, 38
  - Mexico, 90, 92, 95, 97, 184, 189, 218, 230, 235, 237, 369, 409, 419, 471, 477, 479
  - Mica, 1, 8, 12, 55, 61, 136, 147-148, 193, 195, 204, 219, 367, 384, 386, 388-389, 411, 414, 440, 443, 445, 487, 494-496, 502, 508, 517
  - Micas, 2, 9, 11, 15, 18-19, 22, 43, 58, 74, 79-80, 118, 147-148, 155, 175-176, 181, 194-195, 199-200, 204, 217, 333, 357, 359, 361, 373-374, 384, 386-390, 404-405, 411-412, 444, 487, 495-496, 508
  - Mid-ocean ridge, 134
  - Mid-ocean ridges, 133, 157, 222
  - Migration, 19
    - chain, 19
  - Mineral classes, 13, 35, 62, 65, 84
  - Mineral resources, 219, 224, 233-234
  - Mineral species, 22, 64, 89, 148, 367
  - Minerals, 1-9, 11-22, 23-31, 33-45, 47-66, 67, 70-76, 78-89, 99, 102-103, 105, 107-126, 133-155, 157-165, 167, 171-188, 189, 191-213, 215, 217-236, 237-238, 239, 241, 251, 260-261, 263, 271, 275, 292-294, 300-303, 307-308, 313, 318, 319-320, 328, 330, 332-333, 335, 337-341, 344-345, 347, 349, 351, 353-357, 359-362, 364, 366, 367-478, 479, 485, 487, 493-524, 525-528, 529-532, 533, 537
    - compositional variations in, 135, 155
    - evaporite, 7, 89, 180, 183-184, 186, 224, 233, 421, 433, 455-456, 459, 461
    - groups, 4, 15, 17, 19, 21, 27, 31, 36, 38, 40, 59, 61-63, 65, 70-71, 85, 103, 139, 147, 149, 155, 161, 171, 177-179, 217, 219, 228, 233, 263, 271, 293-294, 300, 302, 318, 345, 347, 357, 360, 362, 364, 366, 367, 376, 378, 384, 390, 392, 403, 412, 415-416, 421, 429-430, 440, 443, 447-448, 452, 454-458, 462-463
    - nonsilicate, 134, 173, 175
    - nonsilicates, 58, 359, 364
    - phosphates, 62, 134, 183, 224, 440, 464-466, 470, 497
    - rock-forming, 50, 57, 102, 126, 385, 433, 448-449, 458, 461
    - salt, 7, 18, 49, 55, 172, 180, 183-185, 217-219, 224, 344, 432-433, 495
    - samples, 12, 34, 61, 70, 74-75, 83, 86-87, 89, 102, 107, 140, 159, 226, 239, 332-333, 338-340, 378, 384, 399-400, 414, 435, 439, 496
    - silicate, 2-3, 5-6, 8, 11, 13-15, 18-20, 38-40, 54,

- 58-59, 62-64, 133-155, 157-165, 167, 175, 182-183, 219, 227, 338, 354-357, 359-360, 364, 366, 367, 387-388, 413, 415-417, 468, 487  
 silicates, 3-8, 11, 13-15, 18-20, 35-36, 38, 58, 61-65, 73, 84, 138-140, 142, 147, 149, 152, 154-155, 161, 173-176, 183-184, 186, 200, 202, 206, 219, 224, 227, 354, 356-357, 359-362, 364, 366, 367-368, 378-379, 381-385, 387-388, 390, 392, 396, 400, 402-403, 409-410, 412, 415-417, 437, 441, 464, 466, 487  
 Mines, 184, 219-220, 233-234, 470  
     copper, 219, 233  
     gold, 219-220, 233  
 Mining, 4, 57, 86, 186, 217-219, 221, 224, 231, 233-234, 470  
 Model, 2, 18, 27-30, 38, 44, 49, 136-137, 193, 198, 204, 290, 325, 344-345, 347, 349, 351-352  
 Mohs scale, 82, 89  
 Mojave Desert, 224  
 Molecules, 2, 10, 13, 16, 19, 25-26, 33, 39, 50-51, 274, 354, 376, 378, 380, 461, 469  
 Molybdenum, 26, 221-222, 321  
 Montmorillonite, 2, 4, 40, 172, 176, 384, 487, 496, 548  
 Moon, 37, 59, 161  
     history, 161  
     phases, 59  
 Mountain belts, 157, 159  
 Mountain building, 191, 198  
     subduction and, 191  
 Mountain ranges, 172  
 Mud, 13  
 Mudstone, 13, 171, 181-182  
 Muscovite, 50, 55, 61, 71, 76, 86, 103, 127-128, 130-131, 136-137, 147-148, 158, 173-174, 177, 193, 196, 199, 204, 208, 212, 218, 355, 357, 359-360, 385-390, 396, 413-414, 439, 474-475, 482, 487, 493, 496, 526, 531, 533, 538, 548  
 Music, 278  
 Myanmar, 230
- N**
- Namibia, 50, 218, 230-231  
 Natural processes, 219  
 Nebula, 37  
 Neutral, 13, 31  
 Neutrons, 2, 11-13, 27-29, 33, 44, 322  
 New Mexico, 184  
 New Zealand, 42-43  
 Newton, Isaac, 27  
 Nickel, 37, 44, 55, 65, 89, 162, 175, 187, 212, 218-219, 221, 224, 234, 271, 303, 318, 341, 366, 418, 424-426, 428, 470, 494, 519, 521, 524  
 Nitrates, 62, 219, 224, 354, 447, 456  
 Nitric acid, 498-499, 502, 505, 515, 519-521, 524  
 Nitrogen, 26, 39, 219  
 Nonmetallic minerals, 71-72, 493, 499  
 Nonsilicates, 58, 359, 364  
 North America, 78, 172, 198, 221, 231  
 North Korea, 218  
 Northwest Territories, 231  
 Norway, 41, 66, 67, 163, 167, 218, 235, 237, 429, 471, 478, 484  
 Nuclear weapons, 354  
 Nucleus, 2, 6, 13, 28-29, 31, 33, 345-346  
     atomic, 2, 6, 13, 28-29, 31, 33, 345-346
- O**
- Observations, 11, 37-38, 60, 103, 173, 209, 274, 301  
 Obsidian, 13, 49, 51, 59, 80, 110, 133, 370  
 Ocean, 7, 133-134, 157, 184-185, 222, 224  
     color, 134  
     depth, 133, 224  
     margins, 224  
 Ocean floor, 7  
 Oceanic crust, 157  
 Oceans, 157, 184, 186  
 Offshore, 186  
 Oil, 8, 17, 24, 71, 108, 177, 218-219, 233  
     price of, 233  
 Olivine, 2, 5-6, 8, 11, 14-15, 17, 35, 39-44, 54-55, 59, 86, 102, 127, 129-130, 133, 136-137, 140, 147, 154-155, 158-162, 165, 169, 173-174, 176, 196, 202, 230, 268, 354-358, 362, 367, 375, 383, 393, 399-400, 404, 406-410,
- 419-420, 440-443, 474, 476, 488, 510, 513, 528, 531, 536, 538, 548, 550  
 Ontario, 50, 92-93, 97-98, 165, 169, 186, 221, 235-236, 237-238, 414, 425, 446, 473, 476-478, 481, 483-485  
 Opaque, 5, 14, 17, 35, 50, 55, 72, 102-103, 108, 128, 131, 387, 418-430, 437-443, 445-447, 463, 475, 482, 494, 496, 499-501, 503-507, 511-512, 514-516, 518-524  
 Ore, 2, 5-6, 8-9, 12-14, 16-17, 19-20, 26, 36, 56-57, 86, 93, 98, 138, 175, 179, 184, 202, 217-236, 237-238, 380, 382, 406, 419, 422-423, 425-428, 435, 437-439, 441-442, 446, 452, 454, 459, 461-463, 477-478, 484-485, 493, 521  
     deposits of, 179, 223-224, 226  
 Organisms, 2, 59, 174  
     first, 174  
 Outcrops, 173, 465  
 Oxidation, 14, 30, 73, 340, 451, 494-497, 499, 503  
 Oxides, 2, 10, 16, 26, 30, 35-37, 41, 56, 58-59, 62, 84, 135, 137, 175, 177, 183-184, 186, 202, 217, 224, 227-228, 346, 349, 368, 383, 435, 439-440, 442, 444-447, 455, 470, 489-490  
 Oxygen, 3, 14, 19, 26, 30-31, 33, 35, 39, 41, 43, 54, 59-62, 64, 134-135, 139, 173, 186, 208, 218, 220, 230, 338, 346-347, 353-357, 360-363, 368, 392, 396, 398, 413, 415, 443, 456, 462  
     diatomic, 35  
     molecular, 354, 360
- P**
- Pakistan, 230  
 Parallel, 4-5, 7, 11, 14-16, 18, 21-22, 74, 76, 79, 81, 105-106, 109-110, 113-116, 118-125, 172, 181, 194, 200-201, 203-204, 240-241, 244, 252-253, 256, 261-263, 269, 297-299, 301, 306, 309, 311-315, 317, 322-325, 330, 333, 361, 374, 379-380, 382, 387, 392-393, 396-398, 400-403, 410-414, 416-417, 421, 426, 429-430, 446, 448, 452, 458, 461, 464, 466, 499, 501, 516-517
- Parallels, 311  
 Paris, 15, 183  
 Partial melting, 1, 12, 14, 159, 193, 195, 200  
 Peat, 185  
 Pegmatites, 49-51, 136-137, 148, 152, 162, 221, 375, 382, 386, 389, 395-396, 403, 405, 412, 414, 424, 426, 429, 436, 438-440, 443, 447, 464, 466-468, 495-498, 500, 502-510, 512-519, 521-524  
 Peridotite, 11, 15, 42-43, 135, 160-161  
 Period, 15, 25, 27, 31-32, 354, 554  
 Periodic Table, 1, 9-10, 13, 15, 21, 26-27, 30-31, 34-36, 44, 225, 346, 553  
 Periods, 23-24, 31, 34, 87  
 Permeability, 184  
 Phenocrysts, 11, 16, 51, 134, 138, 155, 373, 394, 407, 512, 514  
 Phosphates, 62, 134, 183, 224, 440, 464-466, 470, 497  
 Phosphorite, 15, 172, 184, 468  
 Phosphorus, 39, 50, 58, 155  
 Photons, 340  
 Phyllite, 15, 195, 200  
 Pipe, 15, 221, 231  
 Place, 2-3, 16-17, 37, 52, 57, 85, 107, 114, 120, 133, 136, 138, 143, 162, 174, 185, 194, 202, 207-208, 226-227, 231, 253, 260, 302, 330, 348, 442, 455, 494, 496  
 Placer deposits, 223-224, 226, 233, 418-420, 440, 493, 503, 506-508, 515-516, 518-519, 521, 524  
 Placers, 223, 226, 438-439, 441-443  
 Plagioclase feldspars, 143, 372, 374-375  
 Planets, 37-38  
 Plants, 61, 184, 241  
 Plasma, 10, 339-340  
 Plastic deformation, 52  
 Plates, 2, 15, 52, 67, 71-72, 75-76, 81, 95, 108-109, 112, 115, 117, 119-121, 129, 138, 140, 150, 167, 183, 189, 215, 225-226, 237, 332, 368-369, 374-375, 382-383, 387, 393, 399, 402, 419-421, 424-425, 428, 448, 450, 469, 479  
 Platinum, 16, 26, 86, 138, 218-219, 221, 225-226, 233, 349, 351, 418-420, 489, 521, 534, 540, 548  
 Pluton, 192-193, 202, 222
- Plutonic, 10, 15, 54, 133-135, 147, 156-161, 394  
 Plutonic rocks, 134, 156-158  
 Plutons, 9, 133, 157, 159, 192, 222, 414, 508, 510  
 PM, 32, 300, 554  
 Point sources, 322  
 Polarizing microscope, 102-103, 105, 107-108, 110, 125  
 Pollution, 233  
 Polymerization, 16, 356-357, 360  
 Polymorphs, 16, 62, 65, 84-85, 139-142, 144, 175-176, 192, 202, 204, 206-207, 276, 340, 360-361, 368-374, 382, 384-385, 387-390, 392, 401, 410-413, 421, 426, 428, 431, 436, 439, 444, 446, 448, 452-453  
 Pore space, 175  
 Porosity, 184  
 Porphyry, 16, 134, 222, 426  
 Portugal, 218  
 Potassium, 26-27, 39, 49, 64-65, 133, 136, 171, 174, 218-219, 222, 356, 433, 487, 496, 498, 512-514  
 Power, 6, 107, 184, 320  
 Precious metals, 16, 219, 225  
 Precipitation, 3, 7, 14, 21-22, 50, 55-56, 59, 65, 89, 171-172, 174, 224, 336  
 Prediction, 207, 328  
 Preservation, 59  
 Process, 5-6, 9-14, 17, 23-24, 28, 30, 37, 41-42, 49-51, 56-57, 71, 108, 135-138, 144, 146, 151, 158, 162, 174-175, 177, 183, 185, 200, 219, 221, 230-231, 233, 260, 322, 331, 333, 335, 340, 493  
 Projections, 245, 256, 259-260, 310  
 Proteins, 354  
 Protons, 2, 11-13, 27-31, 33-34, 44, 322, 344, 346  
 Protoplanets, 38  
 Pyrite, 7, 55, 57, 62, 66, 70-73, 76, 81, 86, 90-92, 95-98, 103, 155, 159, 164, 168, 174, 186, 220, 226-229, 235, 237, 251, 253, 255, 268, 301, 418, 422-424, 426-431, 435, 446, 449, 463, 471-473, 477, 479-481, 483, 489, 502, 512, 521, 523-524, 536, 540, 549  
 Pyroxenes, 4, 10, 19, 54, 58, 87, 109, 137, 149-152, 161, 179, 354, 357, 359, 361, 366, 392-397, 399-402, 407, 493, 507-509, 511, 513, 515
- Q**
- Quarrying, 217  
 Quartz, 1, 3-5, 8, 11, 13, 17-18, 20-22, 23-24, 33, 39-40, 48-51, 53, 55-59, 61-64, 70-75, 77, 79-80, 82-84, 86-87, 89-91, 93, 95-96, 99, 103, 108, 115, 117, 119, 121, 124, 127-128, 129-131, 133, 136-137, 139-141, 143, 147, 155-160, 162-165, 167-169, 171-175, 178, 180-186, 189, 192-200, 202-204, 207-208, 211, 217, 219, 222, 224-227, 230-233, 236, 238, 241, 243, 268, 274-275, 301, 337-338, 355-357, 359-360, 368-375, 377, 381-382, 385, 387-390, 393, 395-396, 398-399, 402-405, 411-414, 416, 418, 422-426, 430-431, 434-436, 438-440, 443, 448, 451, 459, 462-463, 466, 472, 474-476, 478, 480, 482-484, 487, 493-494, 501, 511, 514, 516-517, 519, 524, 526, 529, 536, 537, 543-547, 549  
 Quartz sandstone, 233  
 Quartzite, 17, 195, 199, 369  
 Quebec, 78, 393
- R**
- Radiation, 3-6, 8-11, 13, 18-19, 21-22, 28, 34, 73, 104-105, 109, 319-322, 324, 327, 331, 337-338, 340, 493  
     electromagnetic, 6, 8, 10, 19, 21-22, 28, 104, 109, 320, 322  
     exposure to, 321  
     gamma, 8, 13, 104, 320-321, 340  
 Radio waves, 6, 104, 320  
 Radioactive decay, 5, 14, 17, 443  
 Radioactive waste, 184  
 Radioactivity, 17, 34, 88, 443, 465, 469-470, 493  
 Radioisotopes, 34  
 Radiometric dating, 415  
 Rainbow, 10, 110, 232  
 Rainbows, 110  
 Ratio, 1-2, 10, 17, 43, 51, 62-63, 84, 102, 110, 135, 137, 143, 174, 219, 229, 350, 352-353, 357, 382-383, 410, 414, 456

- Recrystallization, 11, 17, 57, 175, 180, 191, 194, 204  
 Red Sea, 414  
 Reflection, 8, 10, 12, 17, 72, 91, 96, 106, 111, 164, 168, 239, 241, 276, 296, 298-299, 322, 325-327, 337, 357, 472, 480  
 Refraction, 1-2, 4, 6-7, 9-10, 14, 17, 19, 60, 110-116, 125, 376, 381, 388-389, 401, 407-408, 441, 449, 453, 458, 499, 525  
 Regions, 6, 15, 37, 50, 56, 125, 133, 139, 141, 191, 221, 455, 457  
 Relief, 17, 108, 110-112, 124-125, 127-128, 129, 131, 161, 369-370, 372, 374, 376-377, 381, 389-391, 402, 404-406, 410, 412-417, 421, 432-433, 436-438, 446, 448, 457-458, 461, 465-466, 474-475, 482  
 Reserve, 386  
 Reserves, 17, 218  
     mineral, 17, 218  
 Residual deposits, 450  
 Resources, 44, 65, 89, 126, 162, 186-187, 212, 217, 219, 224, 233-234, 271, 303, 318, 341, 366, 493  
     metallic, 217, 219, 493  
     nonmetallic, 217, 219, 493  
 Response, 4, 12, 15-17, 73, 191, 193-194, 222  
 Revolution, 26, 181  
 Rhyolite, 8, 18, 133-134, 156-159, 222, 373, 375, 414  
 Ridges, 133, 157, 222  
 Rings, 5, 18, 52, 81, 84, 117, 121, 124, 162, 302, 361-362, 376-382, 391, 402-403, 416, 431-432, 437, 458  
 Rio Grande, 157  
 Ripple marks, 182  
 Rivers, 185, 223  
 Rock, 1-22, 24, 34, 42-44, 48, 50, 54, 57-61, 65, 86-87, 89, 102, 108, 126, 133-138, 147, 152, 155-162, 171-175, 178-184, 186-187, 191-195, 197-208, 210-212, 217, 219, 221, 224, 226, 231, 233-234, 271, 303, 318, 322-323, 336, 339, 341, 364, 366, 384-385, 394, 410, 414, 420, 433, 442, 448-449, 457-458, 461, 466, 468, 478, 485, 493, 496, 503, 514, 521, 524  
     bedrock, 162  
     crystalline, 2, 4-5, 13, 16-17, 19, 24, 48, 54, 59, 133, 341  
     igneous, 1-2, 4-5, 7-11, 13, 15-16, 18-22, 50, 54, 57-59, 61, 65, 102, 133-138, 147, 152, 155-162, 171-173, 175, 186-187, 191, 193, 195, 199-203, 211-212, 221, 226, 231, 394, 414, 420, 448, 461, 466, 514, 524  
     sedimentary, 1-8, 10-13, 15, 17-19, 57, 59, 61, 65, 102, 147, 162, 171-175, 178-184, 186-187, 195, 200, 202, 212, 221, 224, 226, 433, 461, 493, 503, 514, 521, 524  
 Rock cycle, 200  
 Rock-forming minerals, 50, 57, 126  
 Rocks, 1-3, 5, 7-8, 10, 12-13, 15, 18, 20-21, 25, 34, 37-39, 49-51, 54-59, 61-62, 65, 78, 87-88, 102-103, 108, 133-165, 167, 171-188, 189, 191-213, 215, 221-224, 226-228, 231, 233, 323, 338-340, 356, 366, 368-371, 373-383, 385-388, 390-420, 424-426, 428-429, 435-438, 441-443, 445, 448-450, 452, 454, 460-463, 465-466, 468-469, 493-494, 496-505, 507-511, 513-514, 516-519, 521-524  
     deformation, 194, 204  
     extrusive igneous, 1-2, 5, 18, 21, 51, 133, 154, 157, 370  
     intrusive igneous, 2, 5, 8, 13, 15, 20-21, 51, 133, 201, 501, 514, 524  
     metamorphic, 1-2, 7-8, 10, 12, 15, 18, 39, 49, 56-58, 61, 65, 87, 102-103, 140, 142-143, 147-148, 152-155, 162, 171-172, 175-177, 186-187, 191-213, 215, 221, 223, 226-227, 231, 356, 369, 373-375, 377-378, 380, 386-388, 390, 393, 395-397, 400-408, 410-416, 418, 420, 428-429, 435-438, 441, 449-450, 452, 466, 468, 498-499, 501, 504-505, 507-509, 511, 514, 516-519, 521-524  
     parent, 34, 38  
     rhylitic, 134  
     source, 12-13, 103, 139, 158, 162, 172, 175, 185-186, 221-223, 340, 468  
 Rotation, 2, 10, 14, 16, 18, 20-21, 107, 112, 114, 118-122, 128, 130, 241-242, 244-252,  
     254-255, 259, 263, 269, 276, 278-279, 281-284, 286, 289, 292, 296-299, 302, 314, 448, 475, 482  
 Russia, 218, 230-231, 388, 406, 438
- S**
- Salt, 7, 18, 49, 55, 172, 180, 183-185, 217-219, 224, 344, 432-433, 495  
 Salt deposits, 184  
 Salt domes, 183-184, 433  
 Salt flats, 433  
 Salts, 56, 182-183, 185, 223-224, 292, 345, 432-433, 448, 456, 461, 493, 495  
 San Francisco, 65, 126, 186  
 Sand, 1, 18, 23, 49, 177, 182, 219, 407, 448, 465, 512  
 Sand deposits, 512  
 Sandstone, 1, 3, 12, 16-18, 61, 140, 160, 171-172, 178, 181-182, 185, 211, 233, 369, 439  
 Scale, 2, 11, 13, 17, 33, 52, 55, 82-83, 89, 103, 107, 140-141, 145, 159, 192, 306, 338, 348, 383, 389, 493  
 Scales, 53, 225, 413, 418-420  
 Scattering, 17-18, 74, 322, 340  
 Schist, 7, 18, 92, 98, 194-195, 198, 200, 203, 215, 235, 237, 477-478, 483, 485  
 Schistosity, 8, 15, 18, 200, 211  
 Schists, 193-195, 197, 226, 380, 382, 411, 413, 420, 441, 443, 445, 449, 494-497, 500-505, 507-512, 514-519, 521, 524  
 Scientific method, 60  
 Sea level, 186  
 Seas, 55, 185, 224  
 Seawater, 50, 185, 224  
     pH, 50  
 Second law of thermodynamics, 205  
 Sections, 38, 76, 102, 108-110, 112, 115, 118, 123-125, 199, 241, 296, 338, 340, 373, 378, 394, 396, 399-400, 402-403, 411, 413-414, 493  
 Sediment, 1-3, 5, 11-13, 15, 18-19, 171-172, 174-176, 182, 184-185, 222, 224, 384, 493  
     sources, 175-176, 184  
     transport, 11  
 Sedimentary environments, 175, 184-185  
 Sedimentary rock, 2-7, 11-13, 15, 18-19, 61, 172, 174, 183-184  
     detrital, 5, 12, 18, 172, 174, 184  
     lithification, 3, 5, 11, 18, 172, 174  
 Sedimentary rocks, 1-2, 5, 8, 10, 39, 49, 57, 59, 65, 140-142, 147-148, 171-188, 189, 202, 226, 356, 375, 415, 426, 441, 443, 460-461, 493, 503, 514, 517, 521, 524  
     clastic, 8, 171-172, 175, 177, 181, 184, 186  
     diagenesis, 5, 57, 174-177  
     organic, 59, 171-172, 174, 181, 184, 226, 443  
 Serpentine, 19, 59, 62, 76-78, 92, 97, 161, 195-196, 202, 206, 213, 215, 360-361, 367, 382-386, 406-408, 473, 481, 487, 498, 500-501, 504, 544, 547, 549  
 Shale, 3, 7, 19, 59, 171-172, 181-182, 185, 195, 199-200, 429, 449  
 Shallow marine, 184  
 Shields, 157, 172, 191, 224  
 Shock metamorphism, 3, 6, 19, 192  
 Shoreline, 185-186  
 Shorelines, 185  
 Sierra Nevada, 224  
 Silicate, 2-3, 5-6, 8, 10-11, 13-15, 18-20, 38-40, 54, 58-59, 62-64, 133-155, 157-165, 167, 175, 182-183, 219, 227, 338, 354-357, 359-360, 364, 366, 367, 387-388, 413, 415-417, 468, 487-488  
 Silicate minerals, 3, 5-6, 8, 11, 13-15, 18-20, 39, 54, 59, 62, 133-155, 157-165, 167, 175, 182, 219, 227, 354-357, 359  
 Silicates, 3-8, 10-11, 13-15, 18-20, 35-36, 38, 58, 61-65, 73, 84, 138-140, 142, 147, 149, 152, 154-155, 161, 173-176, 183-184, 186, 200, 202, 206, 219, 224, 227, 354, 356-362, 364, 366, 367-368, 378-379, 381-385, 387-388, 390, 392, 396, 400, 402-403, 409-410, 412, 415-417, 437, 441, 464, 466, 487-488  
 Silicon, 12, 14, 21, 31, 33, 38-39, 54, 59, 64, 134, 139, 171, 173, 202, 218, 356-357, 360, 362, 390  
 Sill, 42-43, 158  
 Silt, 3, 13, 19, 182  
 Siltstone, 3, 19, 181-182, 185  
 Silver, 16, 25-26, 35-36, 86, 93, 98, 217-219, 221, 224-226, 233, 236, 238, 349, 351, 388-389, 418-420, 423-425, 427-434, 478, 484, 489, 495-496, 499, 504, 515, 519-521, 523-524, 534, 540, 549  
 Sites, 5, 21, 51, 53, 57, 139, 149-150, 292, 347, 349-350, 356-357, 359-362, 365, 376-378, 387, 392-393, 396, 398, 400, 416, 422-425, 427, 431, 435, 437, 440, 443-444, 465  
 Slate, 19, 195, 198, 200  
 Slide, 8, 21, 108, 113, 331-332, 493  
 Slides, 70, 88, 102, 332  
 Slope, 3, 185, 205, 209-210  
 Slopes, 210, 259  
     stability of, 210  
 Smelting, 12, 19, 38  
 Snake River, 160  
 Snow, 435  
 Snowflakes, 370  
 Sodium, 23, 26-27, 35, 39, 147, 161, 171, 174, 218-219, 222, 381, 496-498, 500, 502-504, 511-514  
 Soil, 11, 177, 186, 220, 233, 495  
     chemistry, 186  
     degradation, 233  
     horizons, 186  
     properties, 11, 177, 186, 233  
 Soil horizons, 186  
 Soil pollution, 233  
 Soils, 179, 224, 369, 385, 456, 459, 496, 502  
     color of, 459  
     residual, 459  
 Solar nebula, 37  
 Solar system, 34, 37  
     planets and, 37  
 Soot, 463  
 Source region, 162  
 Source regions, 139  
 South Africa, 138, 186, 193, 218, 221-222, 226, 230-231  
 Soviet Union, 218  
 Space, 2, 5-6, 10-11, 14-15, 19, 37, 104, 141, 175, 197, 206-207, 210-211, 254, 274, 276, 278-279, 284-291, 296, 298-303, 313, 315, 318, 330, 333-334, 347, 352, 369-470  
 Species, 11, 17, 22, 62, 64-65, 84-85, 89, 144-145, 148, 175, 177, 179, 183, 206, 345-346, 367, 378, 390, 392, 396, 404-406, 419, 440, 447, 490, 517-518, 525, 536, 487-491  
 Specific gravity, 2, 11, 16, 19, 83-88, 334, 368, 370-402, 404-470, 495, 498-499, 501-506, 508-509, 515, 519-521, 523-524, 533-536, 537-540, 543-551  
 Spectroscopy, 2, 6, 10, 13, 17, 19, 22, 337-340  
 Speed of light, 320  
 Speleothem, 20  
 Spinel, 39, 54, 72, 76, 82, 103, 110, 140, 161, 202-203, 228, 230, 268, 292-294, 300, 353, 359, 382-383, 404, 407, 409, 412, 419, 440-442, 444, 447, 490, 517-518, 525, 536, 539, 548, 550  
 Spreading centers, 157  
 Springs, 7, 21, 56, 91, 96, 164, 168, 174, 231-232, 472, 480, 495-496, 499  
 Stalactite, 20, 76  
 Stalactites, 496  
 Stars, 37-38, 44  
     evolution, 37, 44  
 States, 2, 9, 11, 31, 55, 78, 138, 183, 187, 205, 212, 218, 221, 223, 230-231, 234, 255, 274, 312, 322, 350, 354-356  
     elongated, 230  
     federal, 218  
 Steno, Nicolaus, 274-275  
 Stocks, 157  
 Strain, 20, 204  
 Streak, 20, 70, 73, 82, 89, 369-402, 404-470, 493-515, 517, 519-524  
 Streak plate, 20, 73, 82  
 Streams, 174, 185, 220, 224  
     channels, 174  
     deposition, 174, 185, 224  
 Stress, 76, 82, 204  
 Strike, 321, 326  
 Strikes, 18, 72, 110, 322-324, 332, 336, 512  
     lightning, 512  
 Subduction and mountain building, 191  
 Subduction zone, 2, 134, 222  
 Subduction zones, 133, 154, 157, 198  
 Subsoil, 11  
 Sulfates, 13, 62, 84, 175, 179, 182-183, 186, 228, 275,

- 353-354, 421, 458-459, 461, 463, 466, 523  
 Sulfide gas, 504  
 Sulfides, 10-11, 35, 56, 58, 62, 72, 84, 179, 186, 217, 219-220, 222, 224, 226-227, 349, 367, 418-423, 425, 427-428, 435, 437, 442, 448, 489, 515  
 Sulfur, 13, 19-20, 26-27, 38-39, 56, 71, 73, 86, 135, 179-180, 184, 219, 221-222, 224, 226-229, 268, 353, 364, 418, 420-421, 423, 427, 431, 433, 459, 464, 489, 496-497, 519, 528, 532, 533, 537, 550  
 Sulfur dioxide, 519  
 Sulfuric acid, 220, 496, 498, 505-506, 508, 519-520, 523  
 Sun, 22, 37, 177  
 Supersaturation, 3  
 Surface water, 56  
 Suspended, 86  
 Sweden, 26, 165, 169, 409, 476  
 Swell, 374, 496  
 System, 3-15, 19-22, 27-28, 34, 37-38, 43-44, 59-61, 65, 136, 141, 152, 205-207, 211, 228-229, 261-263, 268-270, 274, 276, 286, 290-291, 293-294, 298, 300, 302, 306-309, 313-314, 317-318, 325, 331, 334, 359, 525-528, 529-532, 543-551  
 Systems, 2, 4, 20-21, 43, 49, 51, 59-60, 86, 141, 152, 206, 211, 259-260, 263, 268-269, 276, 283, 286, 291, 293-294, 298, 301-302, 306-308, 311-314, 317, 324-326, 334  
 equilibrium, 20, 59-60, 141, 206, 211  
 open, 20, 259-260
- T**
- Temperature, 2-3, 6-8, 10-12, 15-19, 22, 23, 35, 37, 49-52, 54, 56-57, 59-60, 83-84, 87, 133-134, 136-138, 140-147, 150-152, 154-155, 160, 162, 173-175, 177, 179, 184, 191-194, 197-199, 202-207, 209-211, 221, 227, 231, 357, 368, 370, 372-375, 377, 382, 392-394, 401, 410, 412, 421-424, 426, 428-429, 431, 435, 437, 441, 448, 453, 463-464, 496-497, 499, 505, 508, 512, 514, 518-519, 521, 523  
 apparent, 17-18, 22, 84  
 base, 152, 231, 499  
 controls, 35, 221, 357  
 data, 18, 211, 372, 374, 392-394, 410  
 extremes, 193  
 indices, 2, 10-11, 19, 453  
 inversion, 8, 10, 16, 18-19  
 Tenacity, 6-7, 12, 18, 20, 76, 395  
 Terrane, 9-10, 12, 16, 22, 138, 199  
 Terrestrial planets, 38  
 Tertiary, 59  
 Test, 83, 319, 344  
 Testing, 354  
 Texture, 7, 52, 151, 155, 183, 191, 193-194, 204, 495  
 Thailand, 230-231  
 Theories, 26-27, 60, 344  
 Theory, 18, 25-27, 249, 319, 340, 344  
 Thin section, 13, 15-17, 21, 45, 65, 89, 102, 107-109, 115, 118, 120, 123-124, 126-128, 130-131, 139, 142, 144-145, 151, 154, 161-162, 176, 187-188, 189, 194, 201, 212, 234, 271, 303, 318, 336, 338-341, 366, 369-370, 372, 374-376, 380-383, 386-396, 398-402, 404-414, 421, 432-434, 436-438, 441, 444-446, 448-453, 456-462, 465-466, 474-475, 482, 529-532
- Till, 21, 231  
 Time, 3, 7, 10, 14, 16-17, 20, 23-26, 33, 37, 51, 54, 57, 59-60, 70, 78, 87, 104, 124-125, 133-134, 136, 138, 140, 144, 146, 173-174, 177, 181, 183-184, 186, 194, 207, 209, 223-224, 226, 253, 274, 291, 320, 323, 336, 338, 349, 354, 359, 512  
 Tin, 26, 50, 138, 218-219, 221-222, 224, 233, 414, 428, 430, 438-439, 509, 519, 523
- Titanium, 27, 39, 72, 138, 161, 218, 224, 366, 413  
 Topography, 17, 337  
 Trace elements, 1, 40, 42, 44, 72, 382  
 Transitional environments, 185  
 Translucent, 5, 21, 72, 370, 372-386, 389-402, 404-417, 421, 426, 431-438, 440-442, 444-446, 448-470, 495-518, 524
- Transmission, 52, 361  
 Transparency, 35, 368, 370-402, 404-470  
 Transparent, 5, 21, 35, 50, 70, 72, 368, 370-371, 373, 376-382, 386-391, 393-401, 404-411,
- 413-417, 420-421, 426, 432-436, 438, 441-442, 444-445, 448-455, 457-467, 469-470, 495-518, 524  
 Transportation, 174, 182, 218  
 Travertine, 21, 56, 174, 183  
 Tropical climates, 224  
 Tuff, 2, 59  
 Tungsten, 218, 221-222, 321, 463, 509, 523
- U**
- Ultramafic rocks, 78, 137, 148, 155, 157, 160-161, 177, 202, 211, 221, 386, 404, 407, 419, 442, 496, 498, 500, 504, 507, 517, 521, 523  
 Ultraviolet radiation, 104-105
- Unit cells, 16, 18, 21, 25, 33, 74, 274, 276-288, 290-294, 296-298, 300-302, 305-318, 324, 327-328, 330, 344, 351
- United Kingdom, 218  
 United Nations, 354  
 United States, 55, 78, 138, 183, 187, 212, 218, 221, 223, 230-231, 234, 255, 354  
 concentration, 218
- Universe, 17, 37  
 expanding, 37
- Upper mantle, 133, 162  
 Ur, 27, 111  
 Uranium, 34, 50, 155, 219, 221, 469-470, 494-495, 497, 515, 519
- V**
- Valence electrons, 1, 11, 17, 21, 28, 31, 33, 36, 39, 85, 336  
 Van der Waals bonds, 36, 84  
 Vapor, 22, 135, 147, 204, 207-208, 223  
 Vegetation, 220  
 Vein deposits, 224, 424, 426  
 Vent, 11  
 Vesicles, 135, 160, 370  
 Vesuvius, 417  
 Virgo, 37  
 Viscosity, 22, 135  
 Visible light, 6, 10, 21-22, 73, 104-105, 115, 117, 320, 322, 324, 340, 418  
 Volatiles, 3, 38, 50, 135, 161  
 Volcanic ash, 2, 177, 384, 496  
 Volcanic pipes, 231  
 Volcanic rock, 7, 22, 133, 157, 160-161, 394  
 Volcanoes, 160, 226  
 Hawaii, 160  
 Volume, 3, 5-6, 10, 13, 15, 33, 53, 58, 83-84, 158, 171, 175, 185, 205, 209-210, 219, 226, 307, 336-337, 364
- W**
- Wash, 439  
 Water, 1, 7-9, 15, 18-20, 22, 23, 25, 35, 38, 40, 49-51, 54-56, 59, 71, 84-86, 88-89, 110-111, 133, 135-137, 160, 171-175, 177, 179, 182-183, 186, 193, 207-208, 217, 220-222, 224, 228, 231, 233, 321-323, 345, 357, 360, 378, 381, 385, 412, 415, 437, 446-447, 455-458, 469, 493-500, 505, 510  
 boiling point, 85  
 conductivity, 35, 217  
 fresh, 160, 173, 183, 495, 499  
 hardness of, 493-500, 505, 510  
 hydrogen bonds, 456
- Water vapor, 208  
 Wave fronts, 322-324  
 Wavelength, 3, 8, 12-13, 19, 22, 73, 104-105, 110, 114-115, 117, 320-324, 336, 338, 340
- Waves, 4-6, 10, 14, 22, 104-106, 172, 320, 322-324  
 dispersion, 6  
 frequency, 104, 320  
 height, 104  
 height of, 104  
 length, 5, 10, 14  
 length of, 10, 14  
 orbital, 4, 14  
 wavelength, 22, 104-105, 320, 322-324
- Weathering, 3-5, 8-9, 12, 17-18, 22, 55, 103, 142, 148, 172-176, 179, 181, 183, 186, 200, 224, 227, 357, 384-385, 444, 446, 448, 494, 501-503
- granite, 8, 18, 148, 173  
 ore deposits, 179, 224, 227  
 products of, 173-174, 227, 384  
 silicate minerals, 3, 5, 8, 18, 142, 148, 175, 227,

357

Welded tuff, 59  
 Wells, 162, 186, 212, 332  
 Wind, 22, 172-174

**X**

Xenoliths, 204, 371  
 X-rays, 6, 8-9, 15, 19, 22, 28, 34, 104, 319-324, 326-328, 331, 334, 336-340

**Z**

Zimbabwe, 218  
 Zinc, 13, 36, 221, 223, 225-226, 349, 351, 418, 429, 442, 450, 494, 496, 501, 504, 506, 515, 517, 523, 533, 540, 551