

Introduction to Earth Science (ES1101)

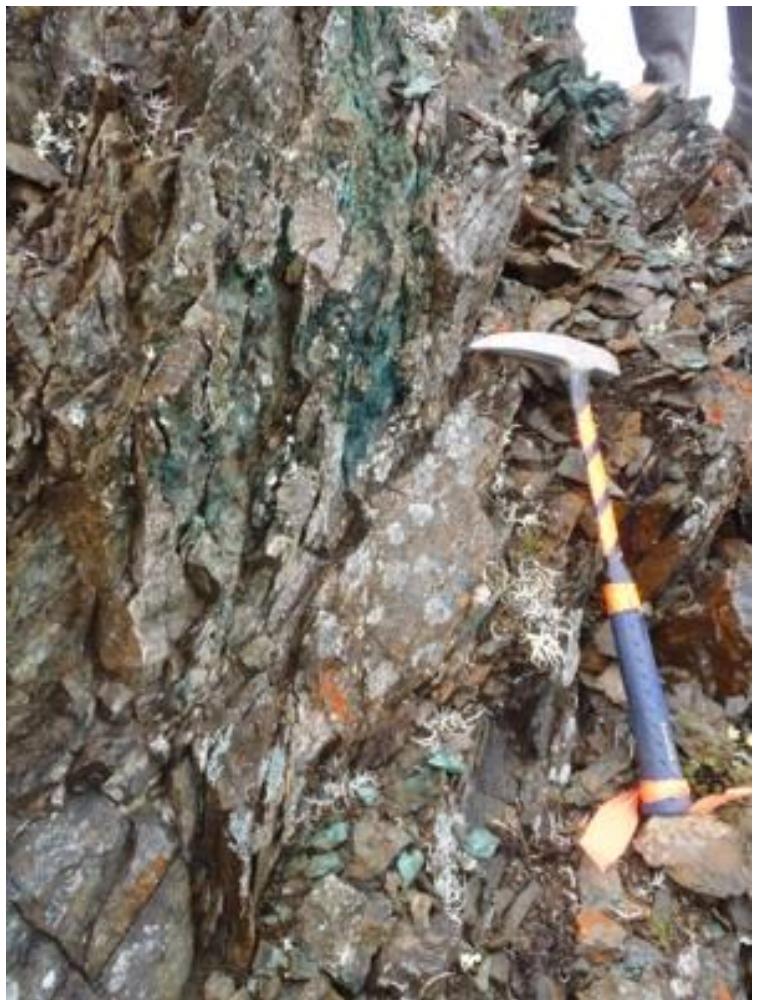
(Minerals: Crystallography and Crystal Chemistry)

Instructor: Gaurav Shukla

FIGURE 5.1 A royal crown containing a variety of valuable jewels.



Minerals and Rocks



Silver and copper mineralization in the Talkeetna Mountains. Green color is the copper mineral malachite. Photo credit: Evan Twelker, DGGS, taken 2014.



[Rocks & Minerals - Utah Geological Survey](#)

FIGURE 5.2 Copper ore is a useful mineral that serves as a source of copper metal.



(a) Malachite, a type of copper ore ($\text{Cu}_2[\text{CO}_3](\text{OH})_2$), contains copper plus other chemicals.



(b) The copper used for pots comes from copper ore.

What are minerals?

- Minerals are building blocks of rocks.
- Rock is a solid aggregate or mass of minerals.
- Understanding the behavior of minerals in response to changes in physical and chemical environment help us decipher the records of geological history.

What are minerals?

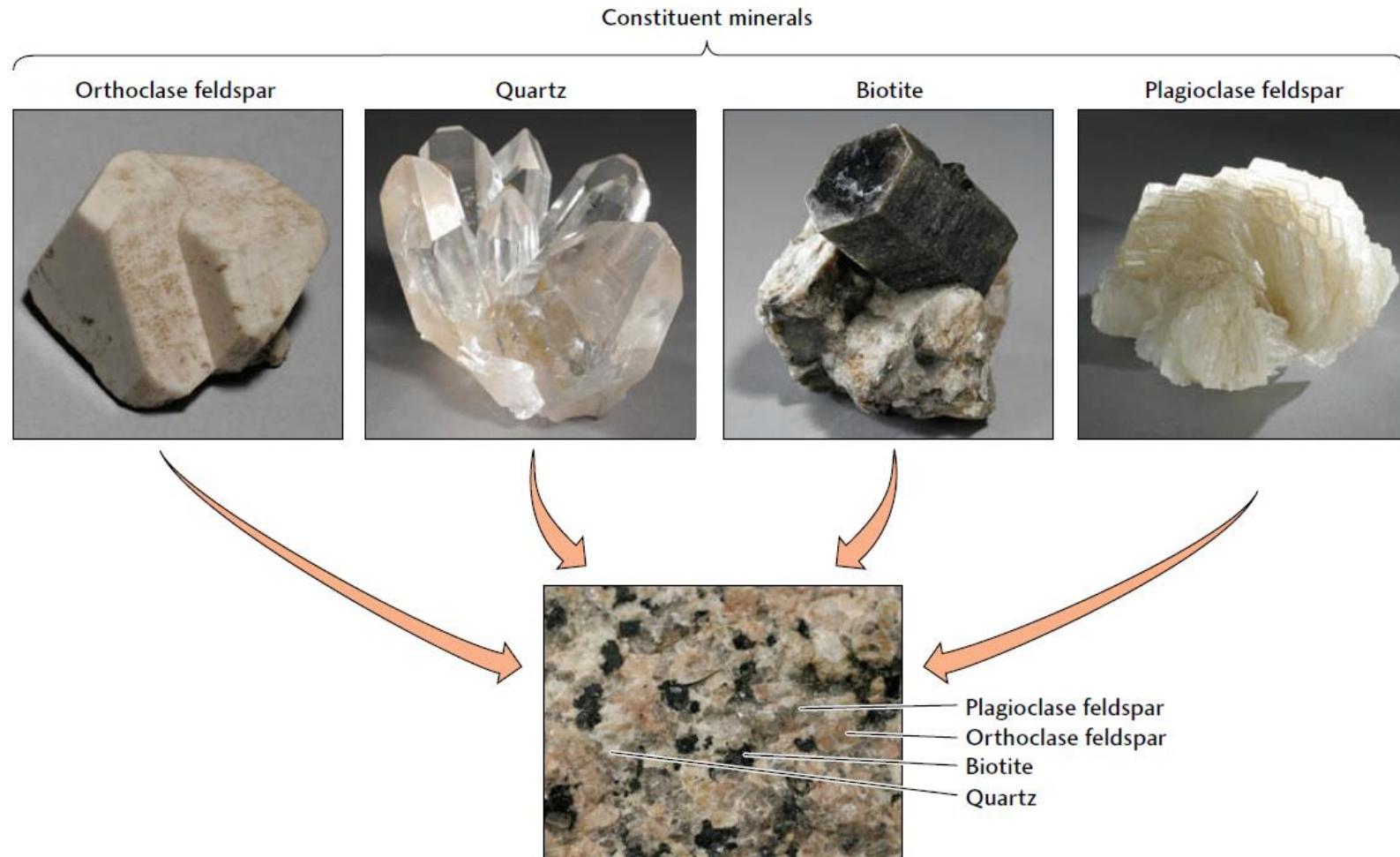


FIGURE 3.23 ■ Rocks are naturally occurring aggregates of minerals. [John Grotzinger/Ramón Rivera-Moret/Harvard Mineralogical Museum.]



Rock (granite)

Structure of Minerals

Most abundant elements in the crust

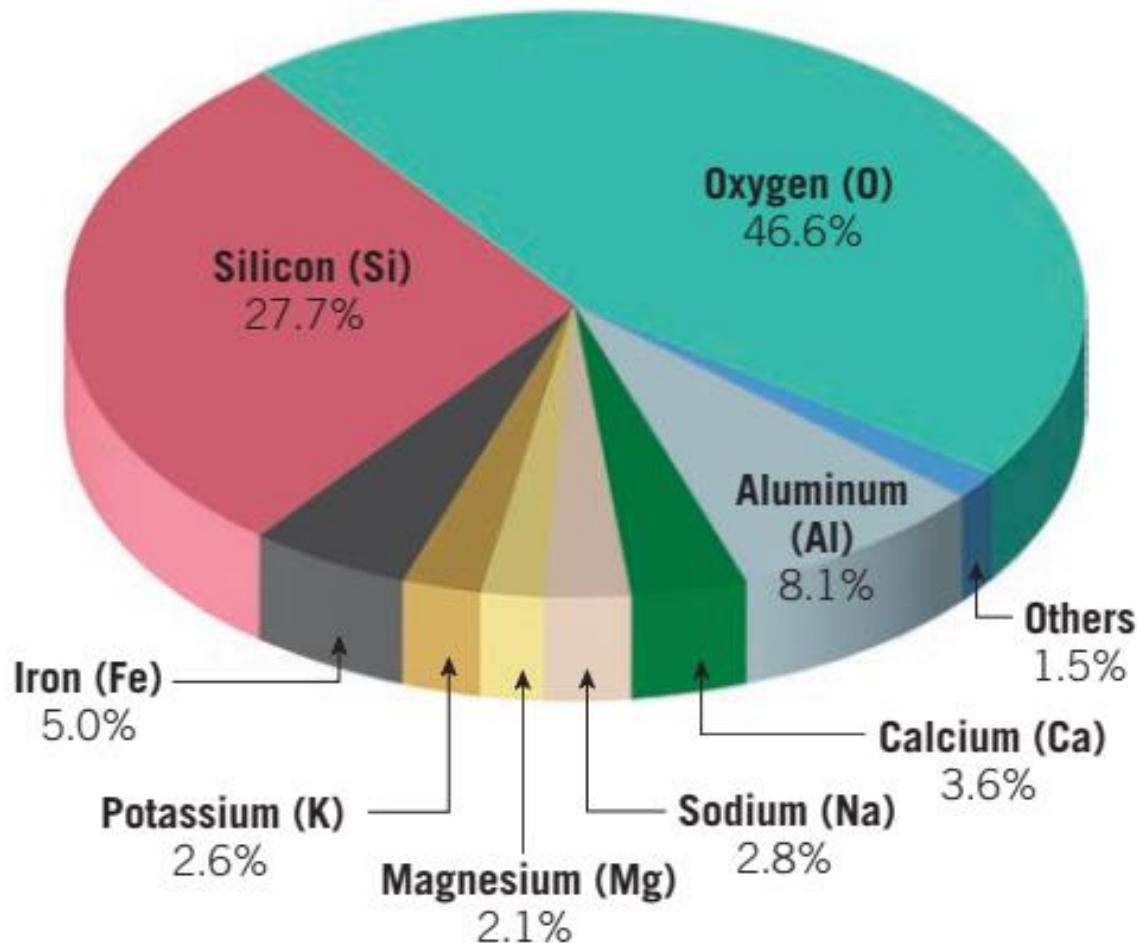


Figure 3.30
The eight most abundant elements in the continental crust

Minerals Classification

- More than 4000 minerals have been identified, and several new ones are identified each year.
- Common minerals that make up most of the Earth's crust are only a few dozens and known as rock-forming minerals.
- As we have seen that the oxygen and silicon are the most common elements in the Earth's crust, so the silicate minerals account for more than 90% of the crust.

Definition of Minerals:

A mineral is a **naturally** occurring crystalline (inorganic) **solid** with a **definite, but not necessarily a fixed, chemical composition.**

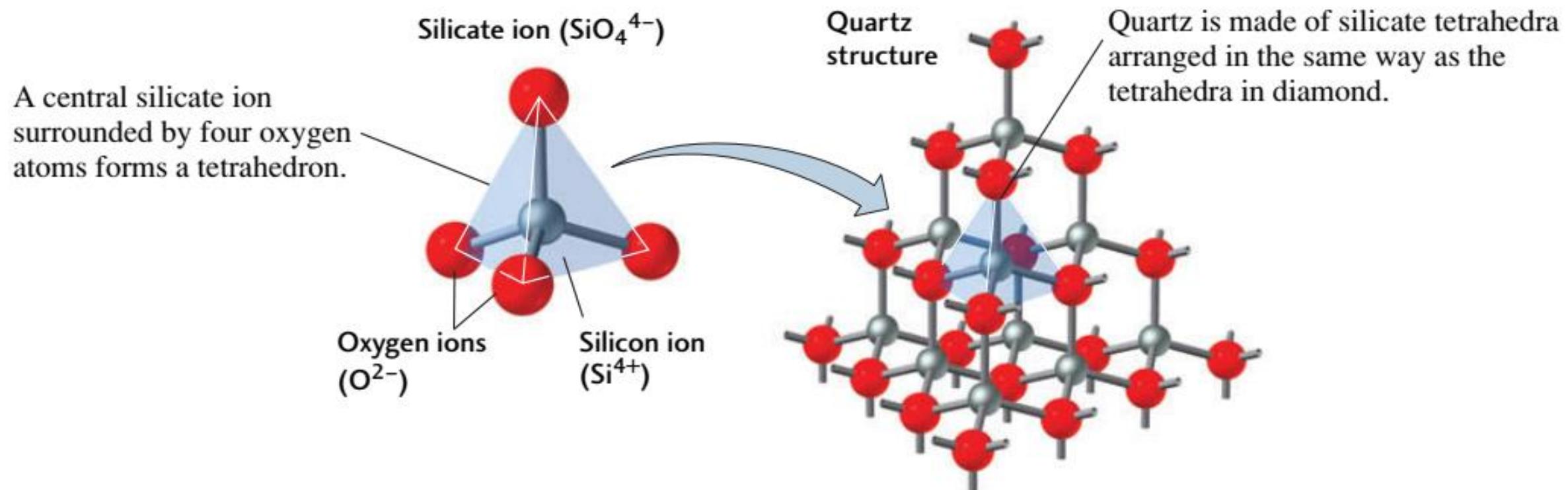
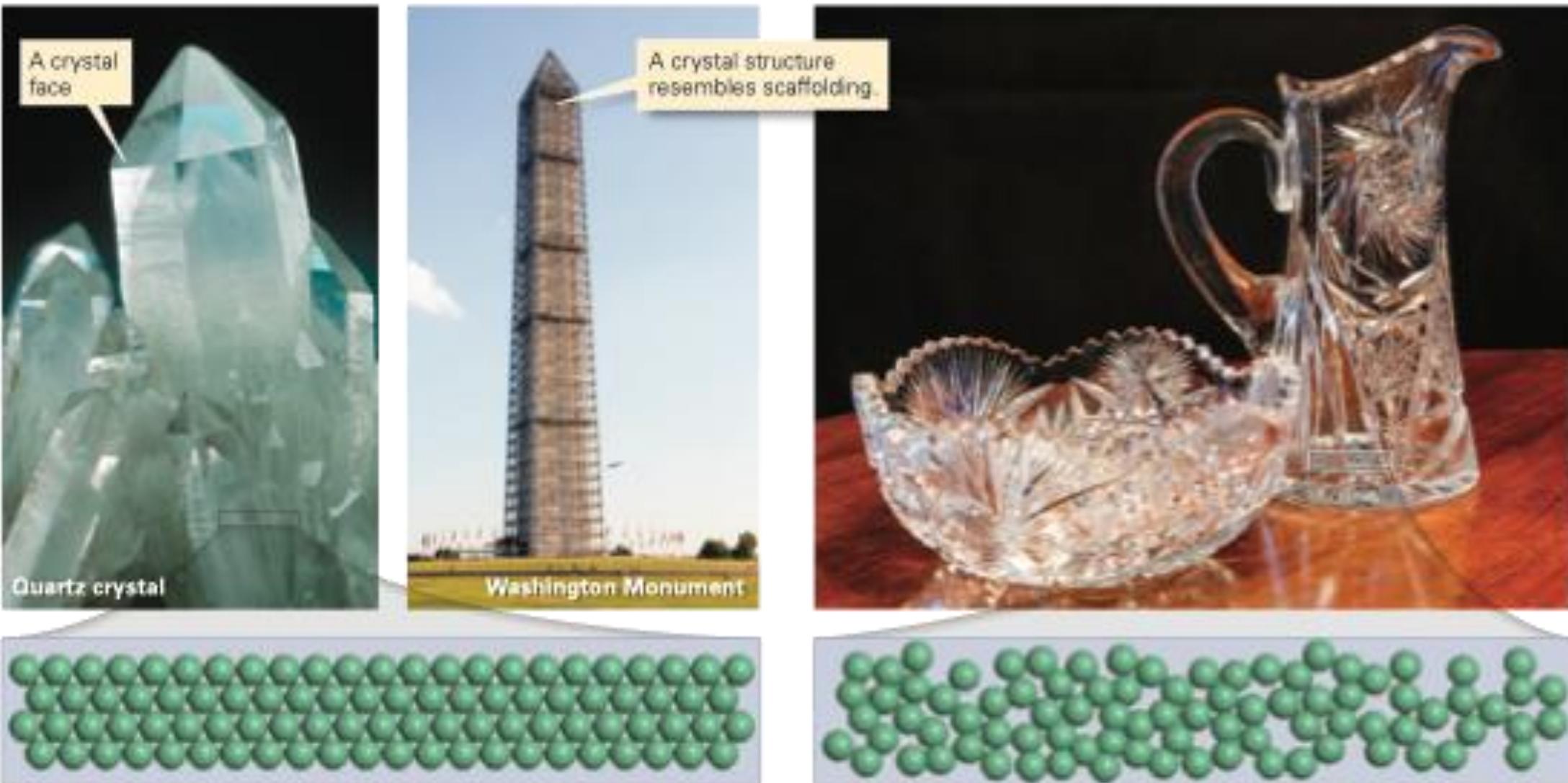


FIGURE 5.3 The nature of crystalline and noncrystalline materials.

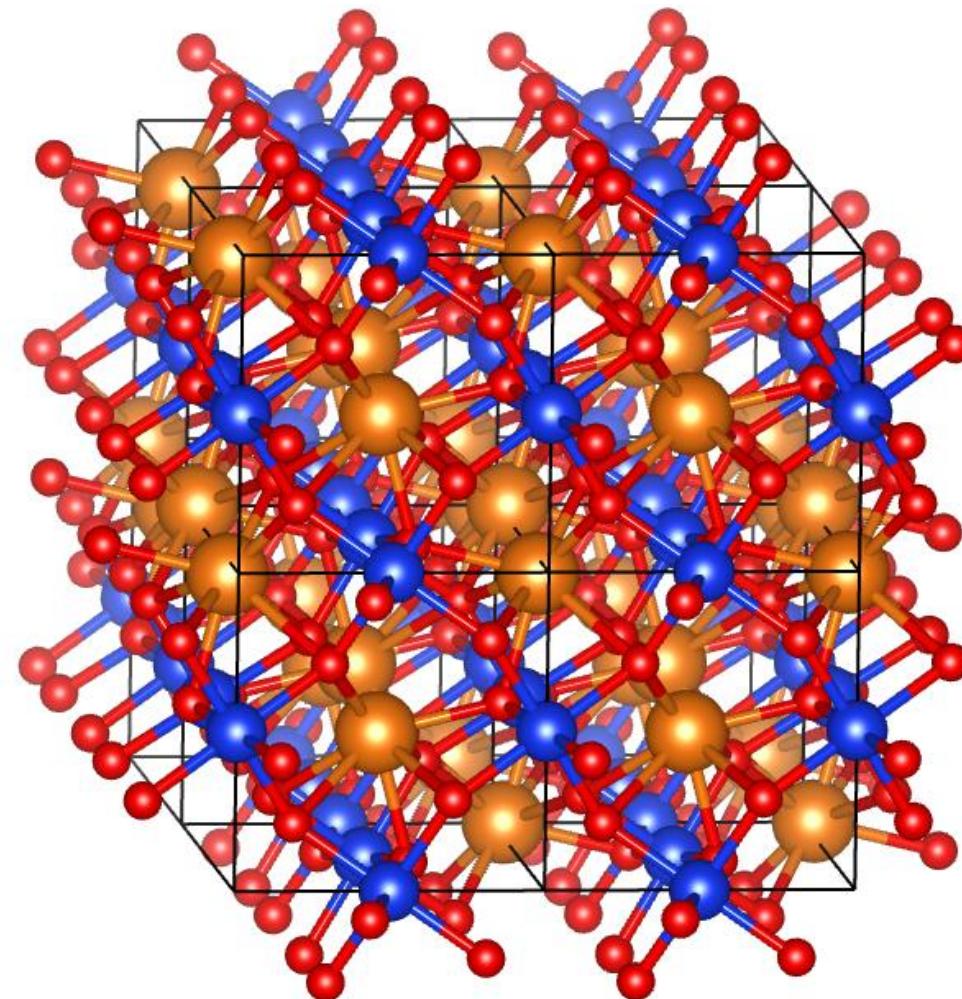
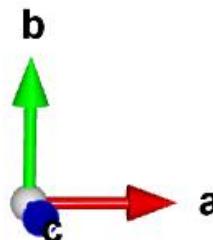


(a) Crystalline substances, like quartz, contain an orderly arrangement of atoms. The geometry of the arrangement defines the crystal structure.

(b) A "cut crystal" bowl is actually made of glass. The atoms within do not have an orderly arrangement.

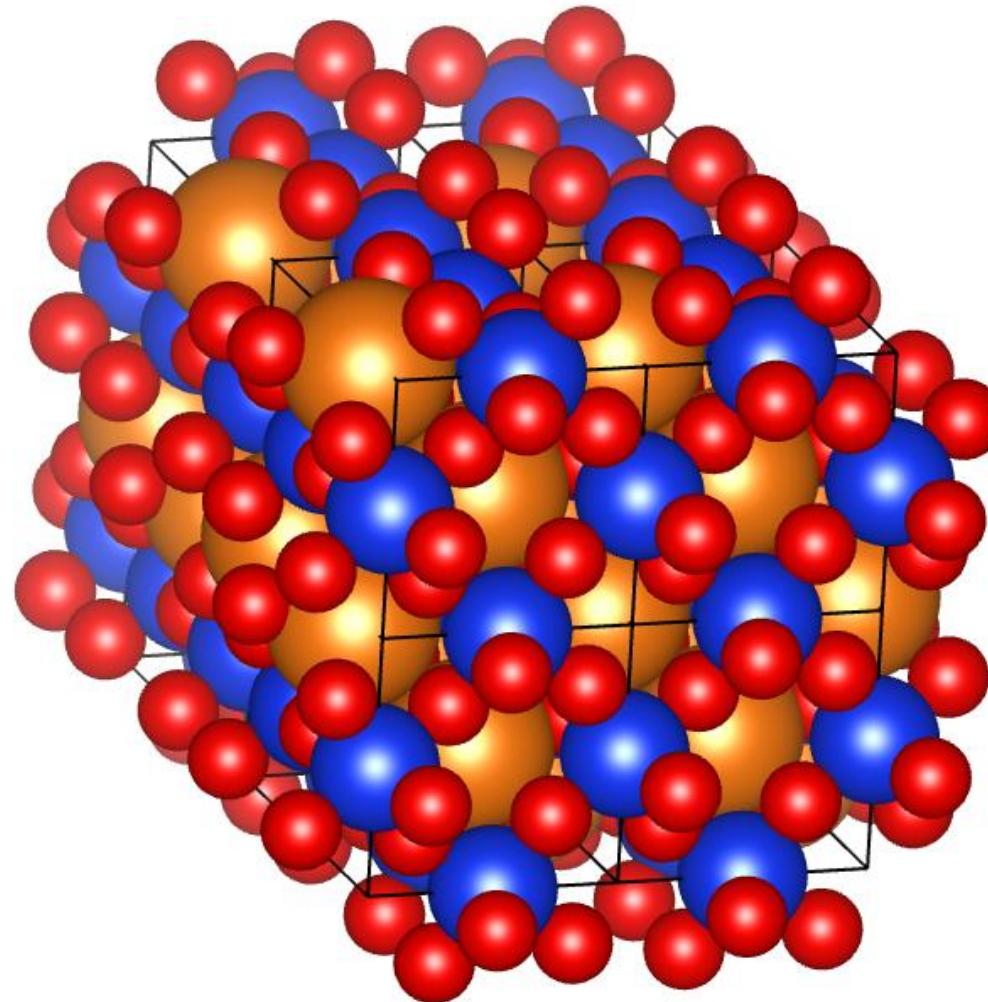
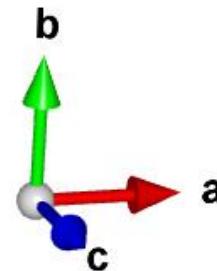
Definition of Minerals:

Crystalline (periodic) solid:

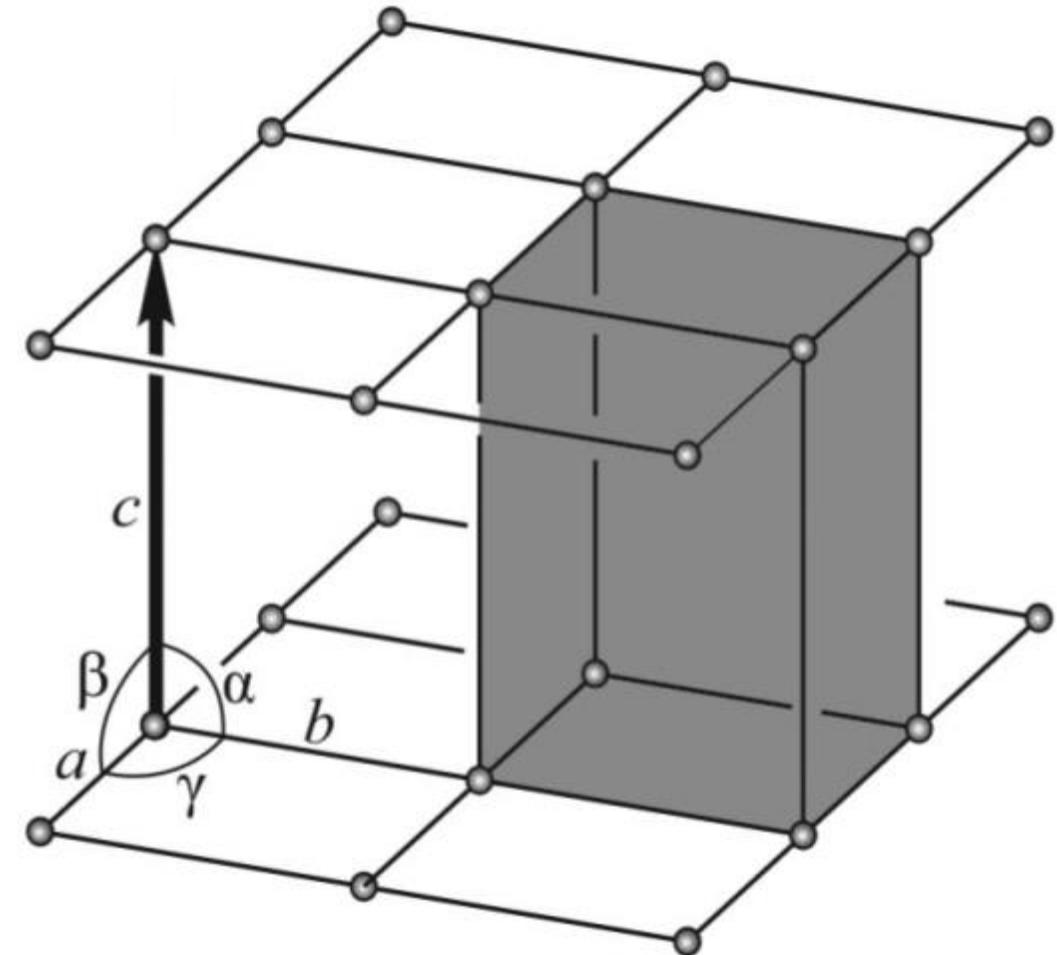
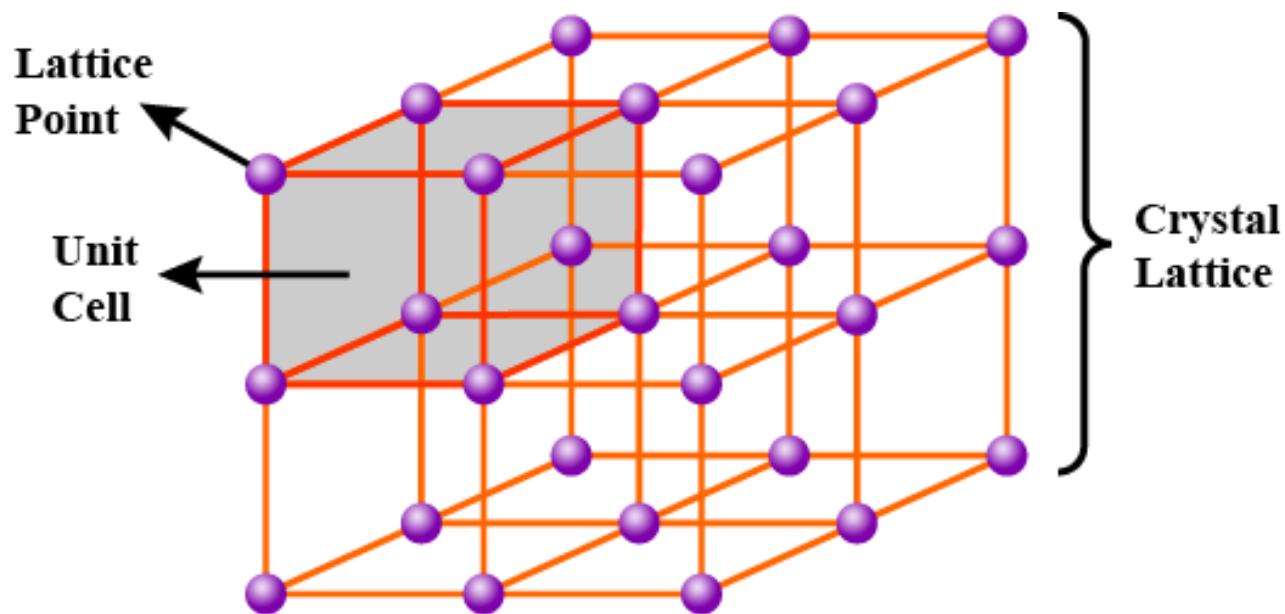


Definition of Minerals:

Crystalline (periodic) solid:



Crystallography of Minerals



Lattice Parameter: a, b, c & α, β, γ

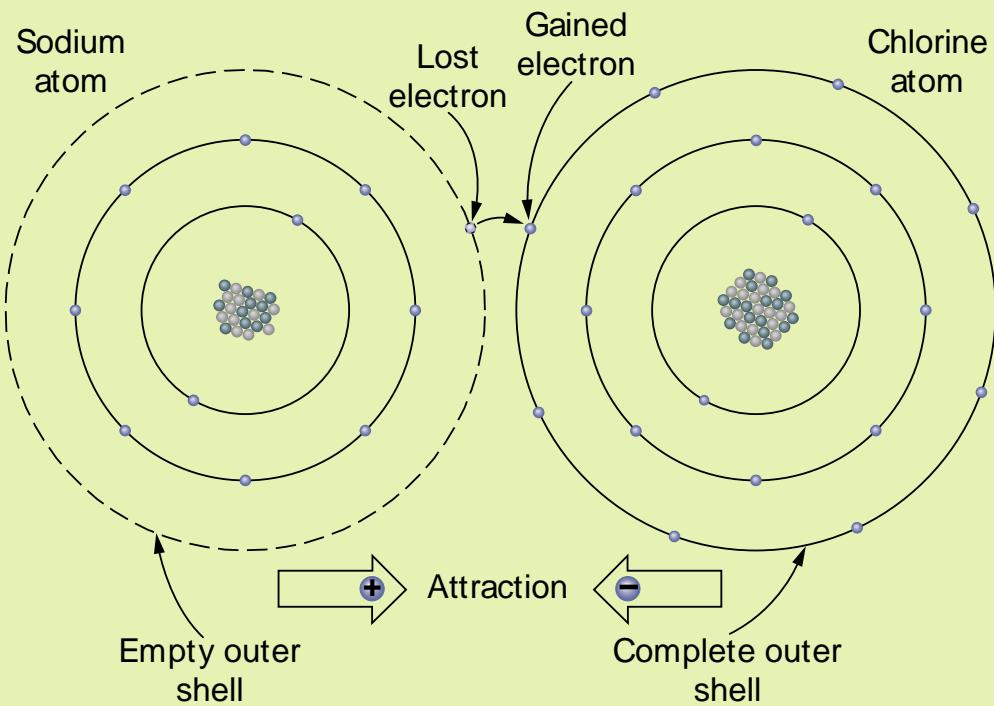


Quartz

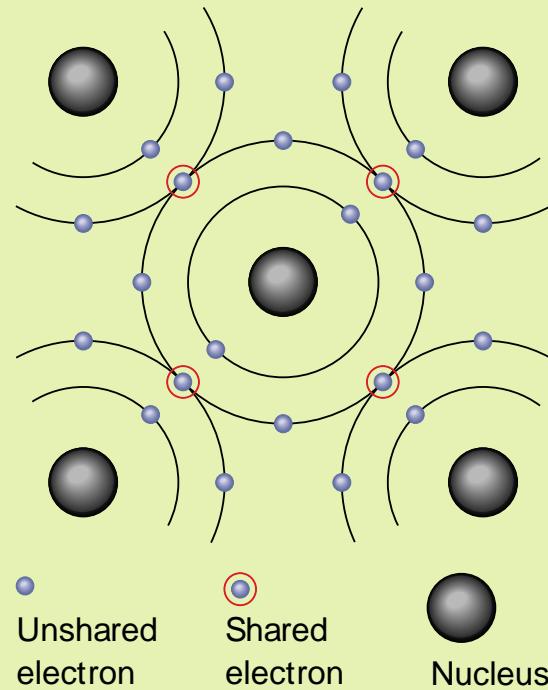


FIGURE 3.21 ■ Trace elements give gems their colors. Sapphire (left) and ruby (center) are formed of the same common mineral, corundum (aluminum oxide). Small amounts of impurities produce the intense colors that we value. Ruby, for example, is red because of small amounts of chromium, the same element that gives emerald (right) its green color. [John Grotzinger/Ramón Rivera-Moret/Harvard Mineralogical Museum.]

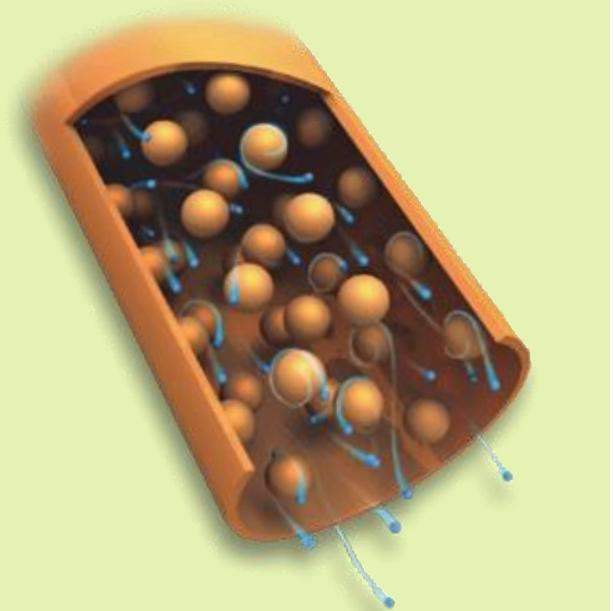
Bonding in Minerals: Ionic, Covalent, and Metallic



(b) An ionic bond forms between a positive ion of sodium (Na^+) and chloride (Cl^-), a negative ion of chlorine. When sodium gives up one electron to chlorine, so that both have filled shells, halite (NaCl) is produced.



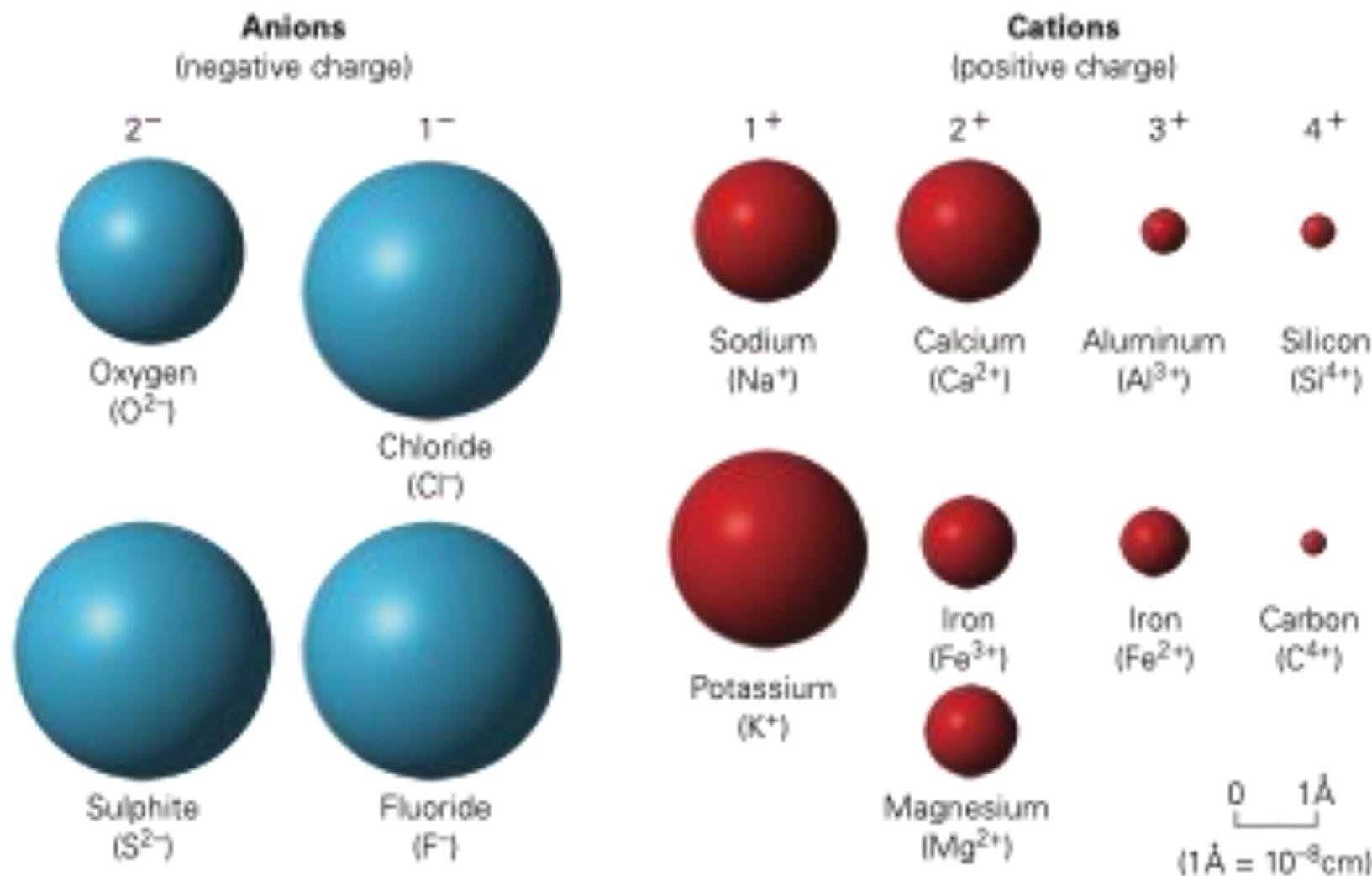
(c) Covalent bonds form when carbon atoms share electrons so that all have filled electron shells.



(d) In metallically bonded material, nuclei and their inner shells of electrons float in a “sea” of free electrons. The electrons stream through the metal if there is an electrical current.

Coordination Number and Cation to Anion Radius Ratio

FIGURE 5.9 The various sizes of ions and the ways they pack together in minerals.



Structure of Minerals

Radii of the most relevant cations and anions

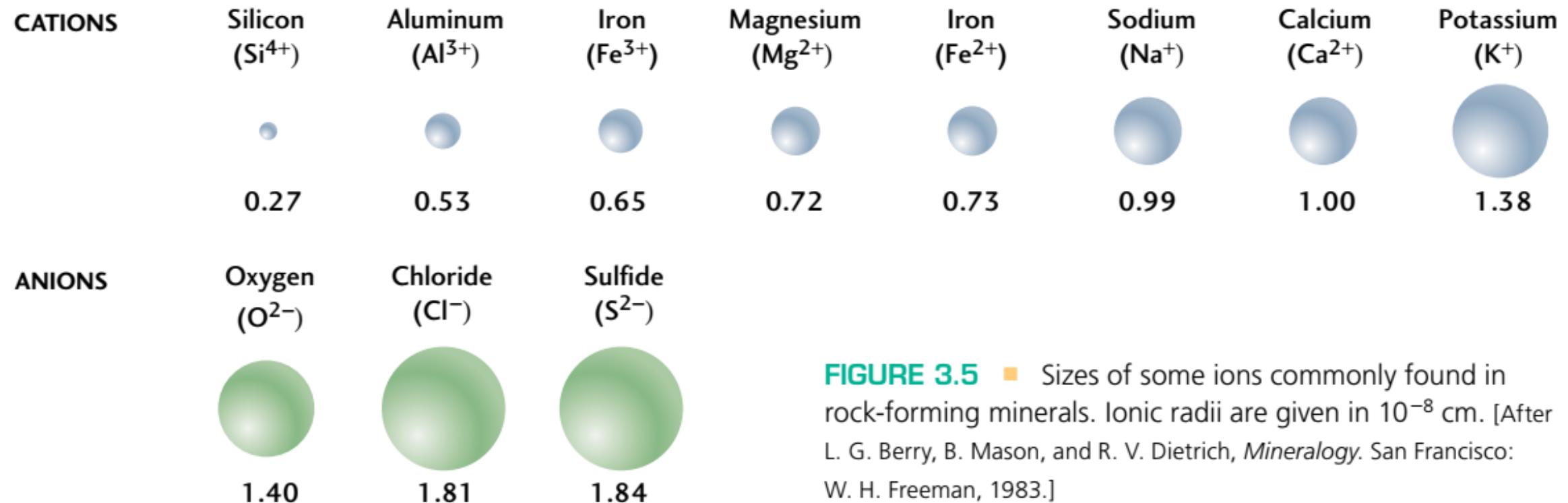
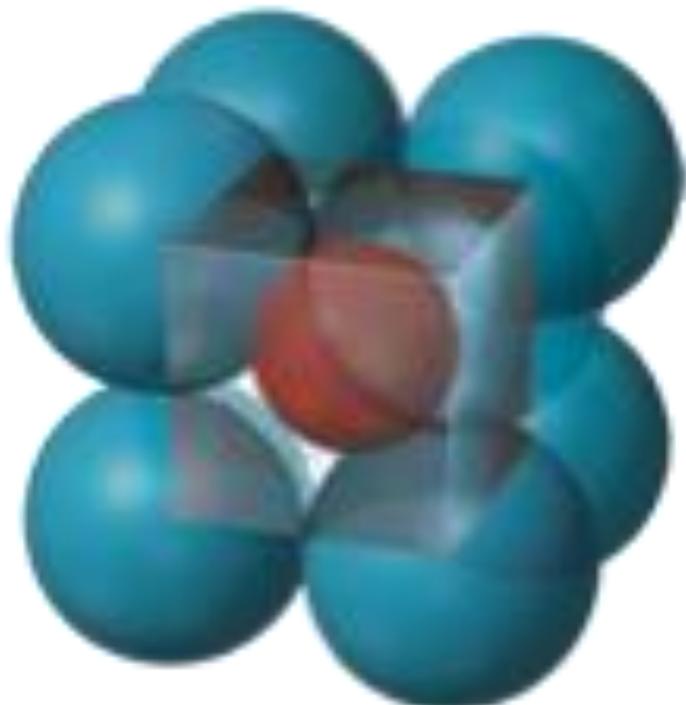


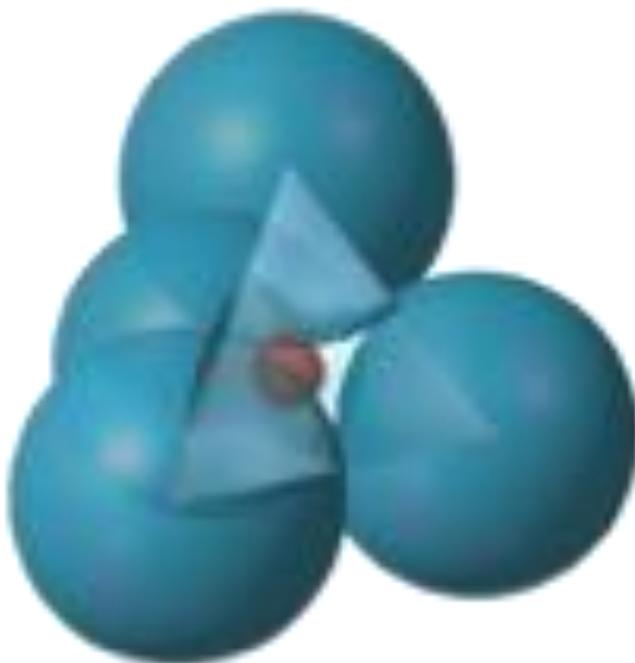
FIGURE 3.5 ■ Sizes of some ions commonly found in rock-forming minerals. Ionic radii are given in 10^{-8} cm. [After L. G. Berry, B. Mason, and R. V. Dietrich, *Mineralogy*. San Francisco: W. H. Freeman, 1983.]

These radii shown here are averaged out rough estimates. You may follow the link for the expected values of radii: <http://abulafia.mt.ic.ac.uk/shannon/ptable.php>

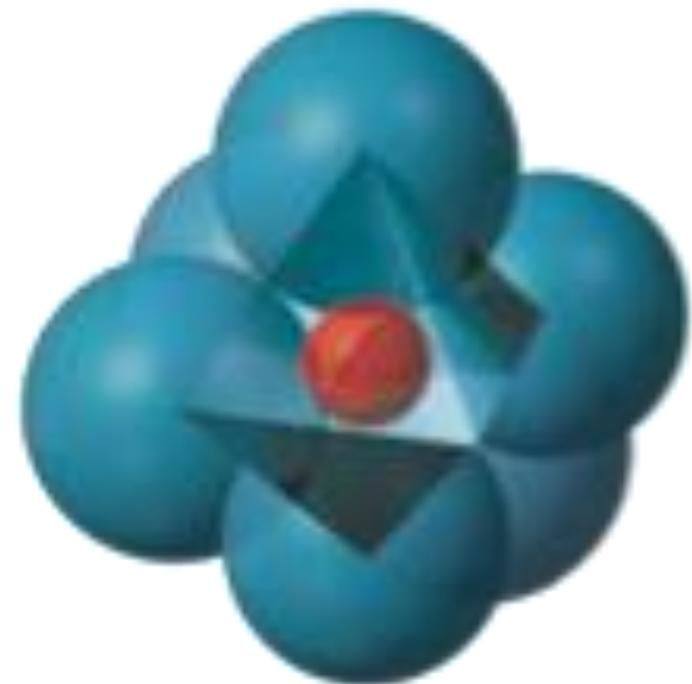
Coordination Number and Cation to Anion Radius Ratio



Cubic



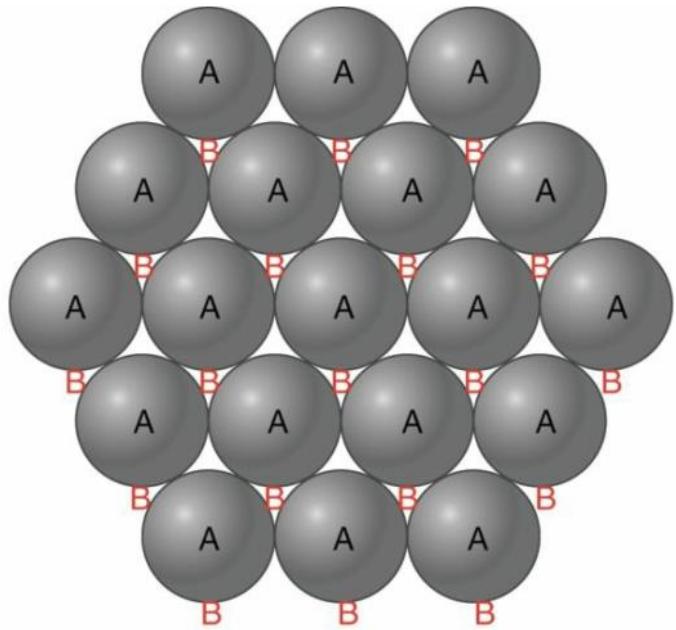
Tetragonal



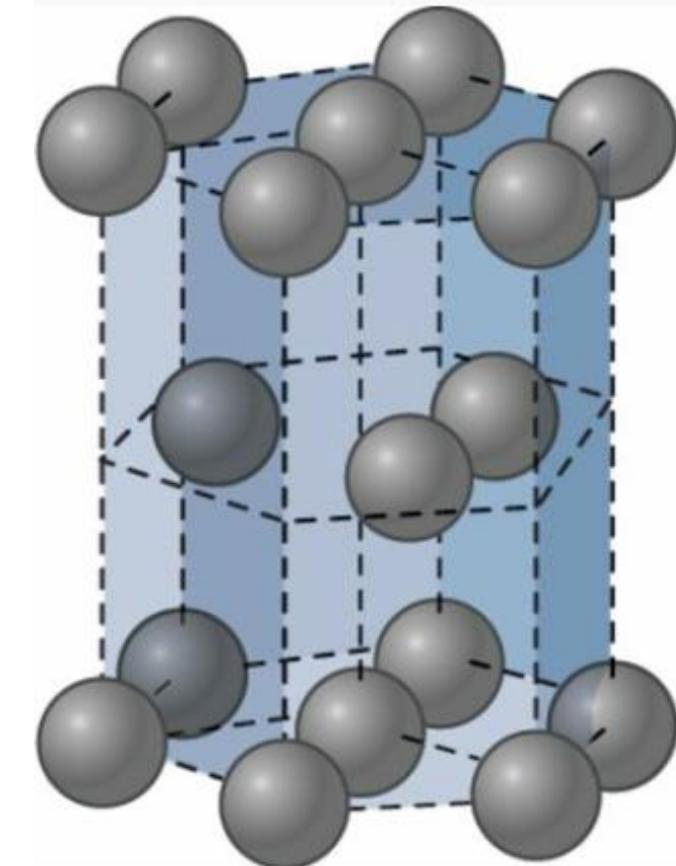
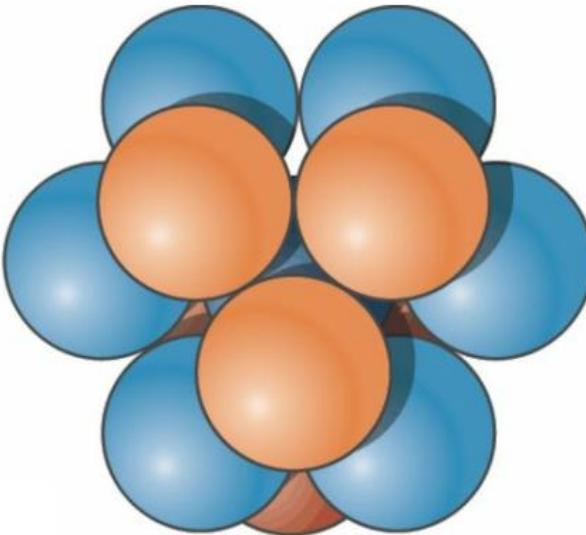
Octahedral

(b) Ions can pack together in different ways. Each configuration can be described by a geometric shape.

Coordination Number and Cation to Anion Radius Ratio

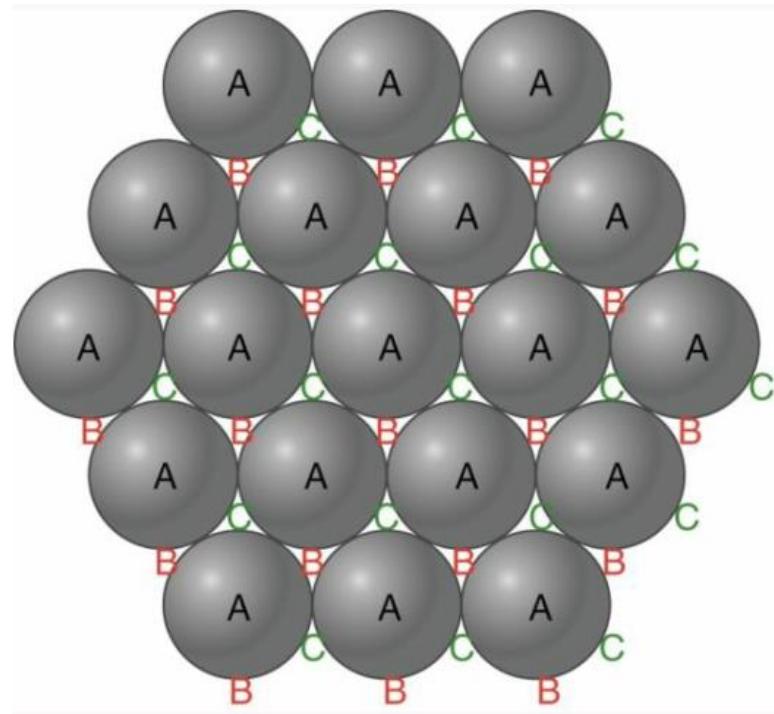


AB AB AB Sequence

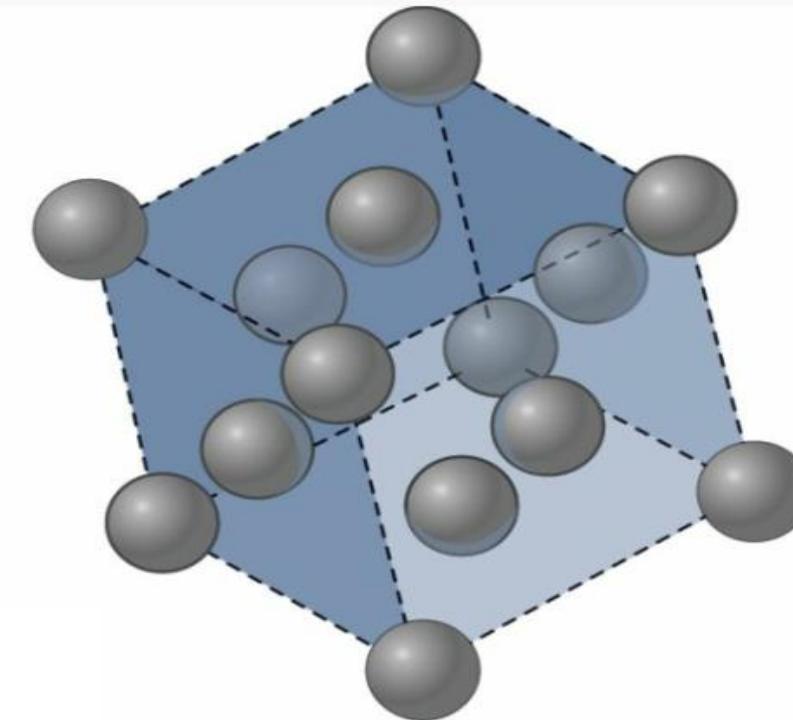


HCP Structure

Coordination Number and Cation to Anion Radius Ratio

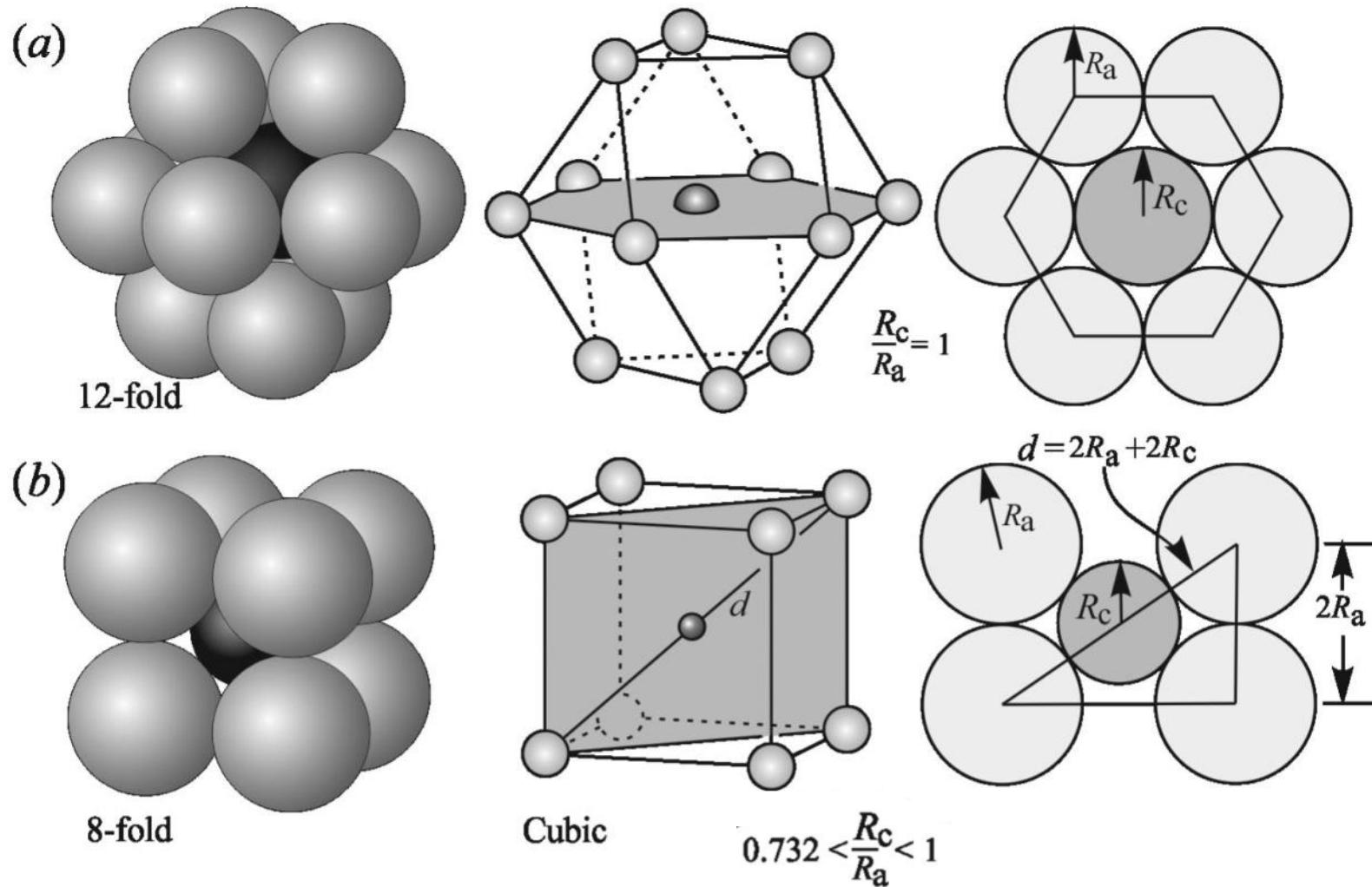


ABC ABC Sequence



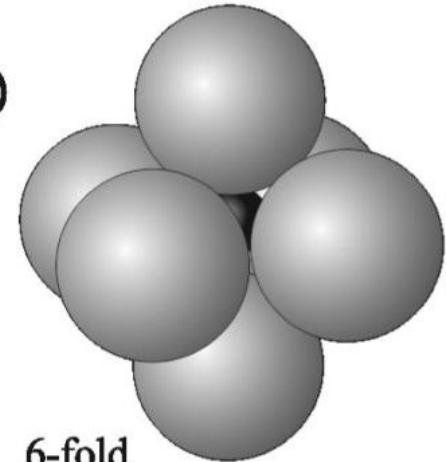
CCP Structure

Coordination Number and Cation to Anion Radius Ratio

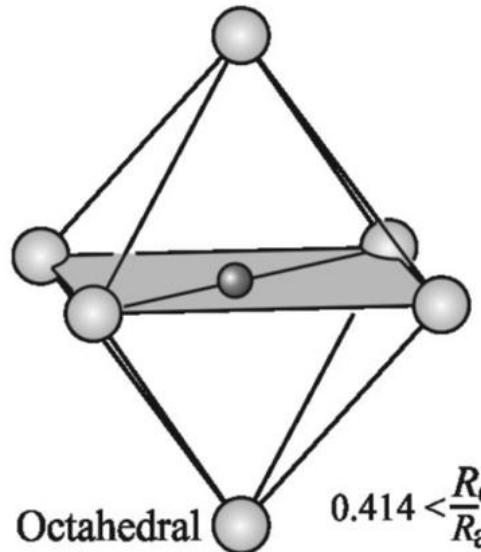


Coordination Number and Cation to Anion Radius Ratio

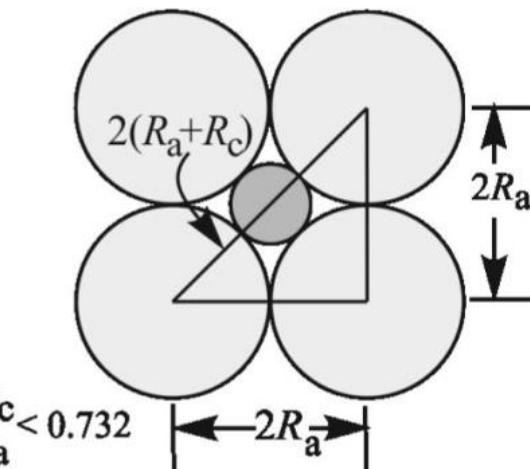
(c)



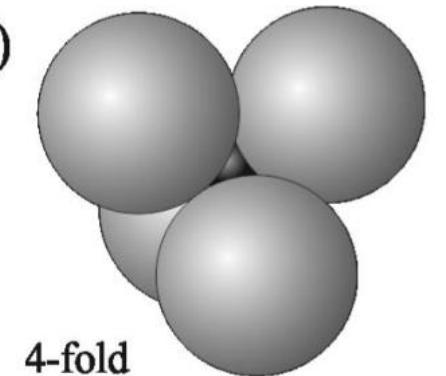
6-fold



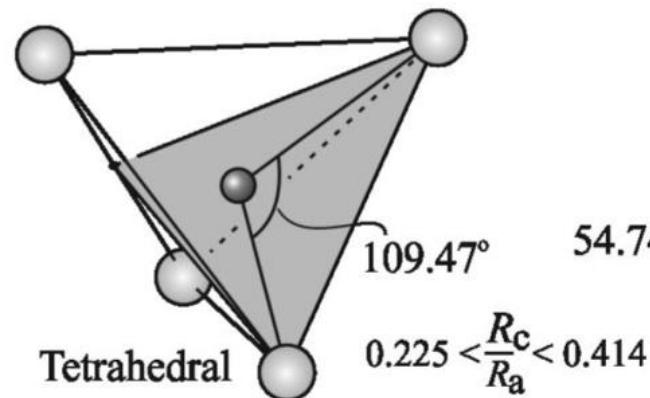
Octahedral



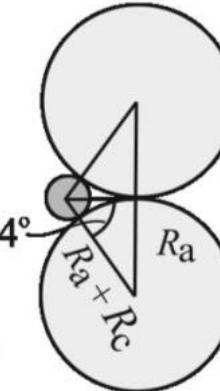
(d)



4-fold



Tetrahedral



Coordination Number and Cation to Anion Radius Ratio

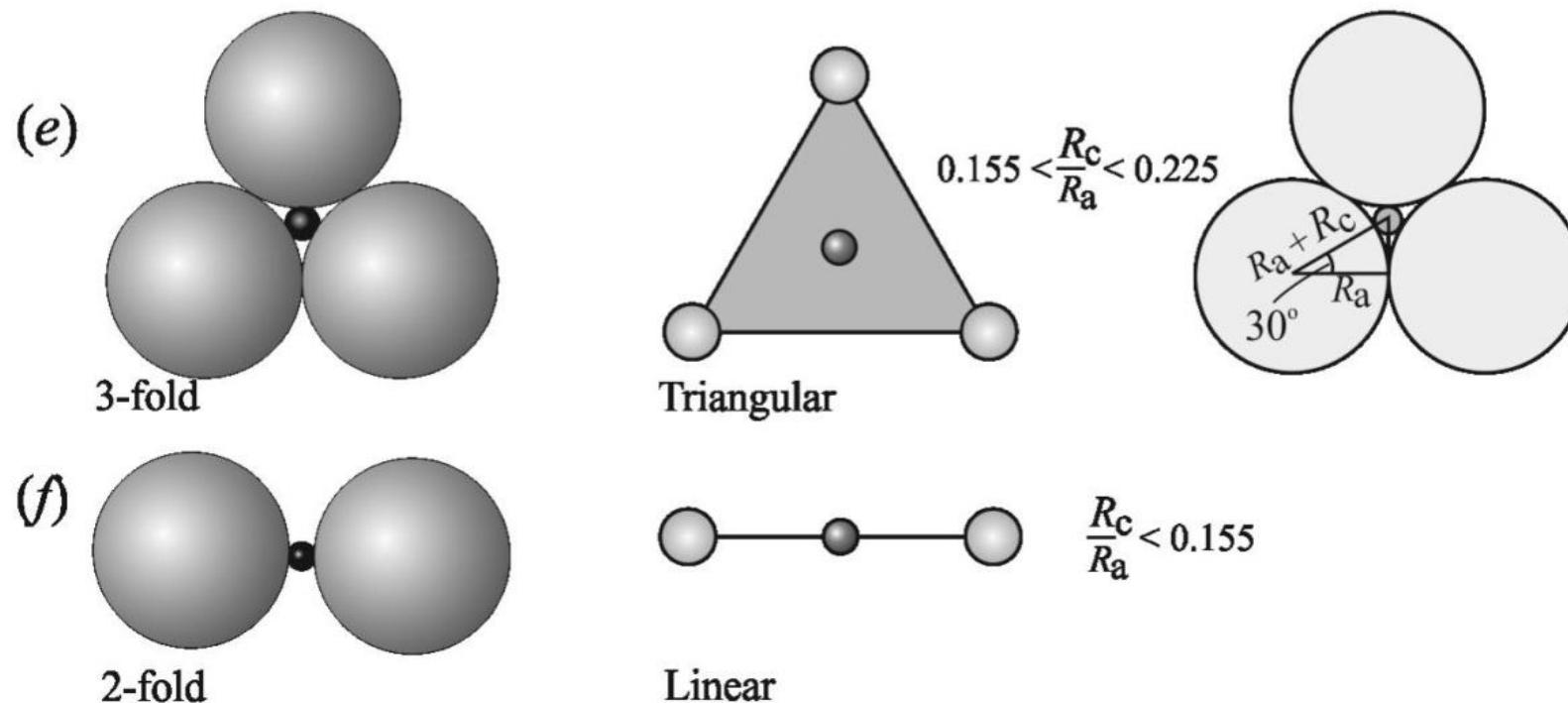


Figure 4.4 Coordination polyhedra. Anions with radius R_a are shown with light shading, cations with radius R_c with dark. Left view shows cation and anions drawn to scale. Center view shows the coordination polyhedra. Right view shows the plane through the polyhedron (shaded in center view) from which the radius ratio is calculated. See text for additional discussion. (a) 12-fold coordination (based on cubic closest packing). The coordination polyhedron is not a regular shape. (b) 8-fold, or cubic, coordination. (c) 6-fold, or octahedral, coordination. (d) 4-fold, or tetrahedral, coordination. (e) 3-fold, or triangular, coordination. (f) 2-fold, or linear, coordination.

Structure of Minerals

Radii of the most relevant cations and anions

Table 4.2 Cation Sizes Appropriate for Regular Coordination Polyhedra When Coordinating with O²⁻ (~1.26 Å)

Coordination	Radius Ratio	Minimum Radius (Å)	~Maximum Radius (Å)	Common Cations
12	~1.00	1.26	N/A	K ⁺ , Ca ²⁺ , Na ⁺
8	0.732–1.00	0.92	1.26	Fe ²⁺ , Ca ²⁺ , Na ⁺ , Mg ²⁺
6	0.414–0.732	0.52	0.92	Al ³⁺ , Fe ²⁺ , Fe ³⁺ , Mg ²⁺
4	0.225–0.414	0.28	0.52	Si ⁴⁺ , Al ³⁺ , S ⁶⁺ , P ⁵⁺
3	0.155–0.225	0.20	0.28	C ^{4+ a}
2	<0.155	N/A	0.20	None

Symmetry in Nature



Symmetry

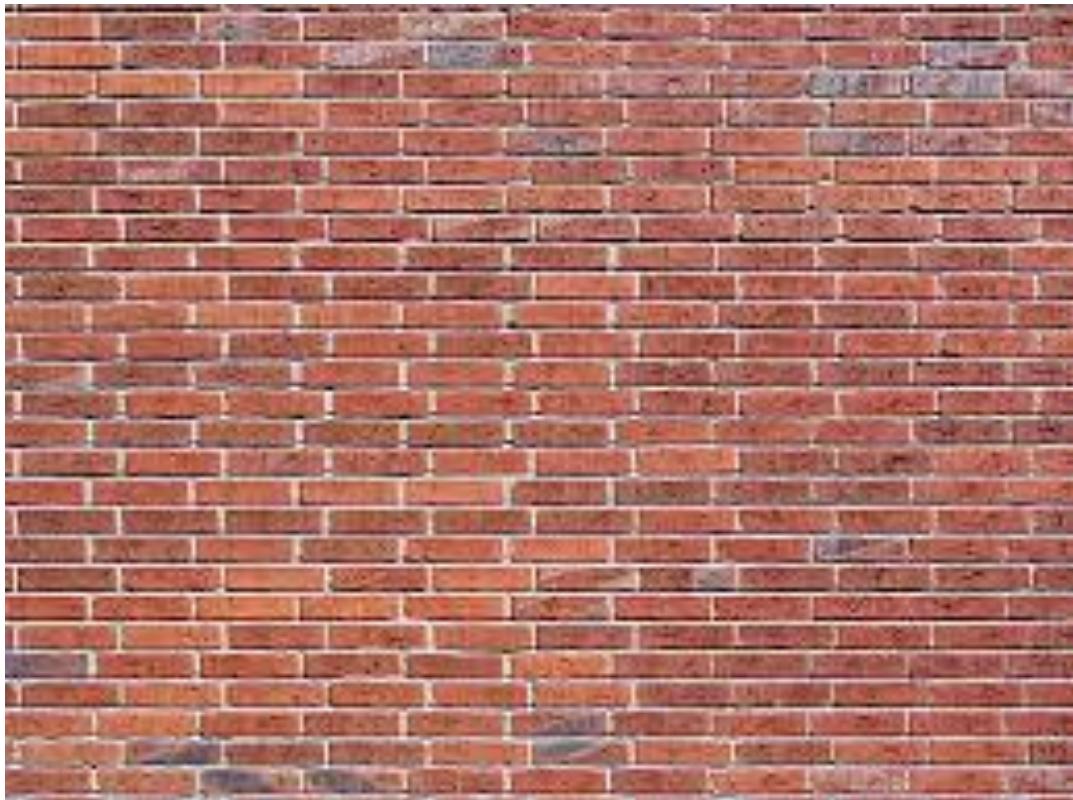
Translational Symmetry

Point group symmetry

**Translational symmetry + Point symmetry =
Space group symmetry**

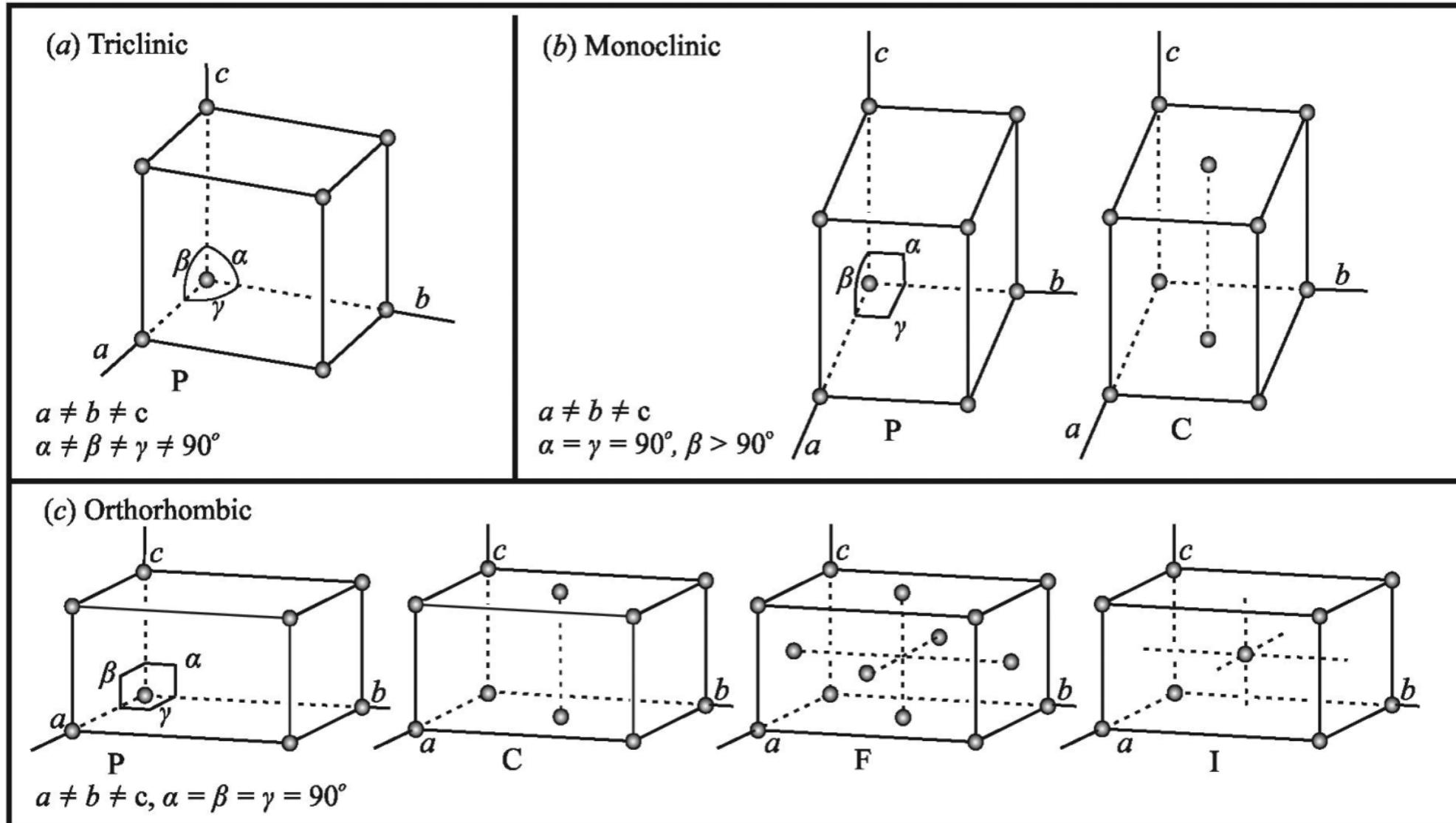
Symmetry

Translational Symmetry



Crystallography of Minerals

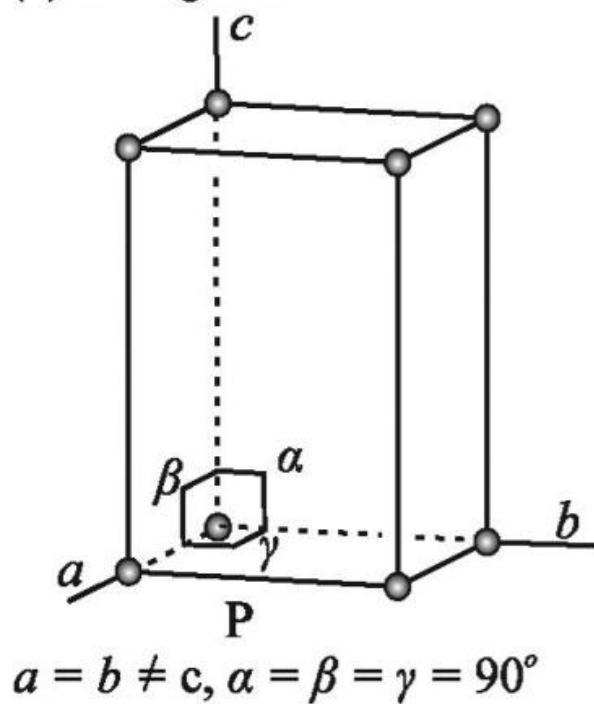
(14 Bravais Lattice from translational Symmetry)



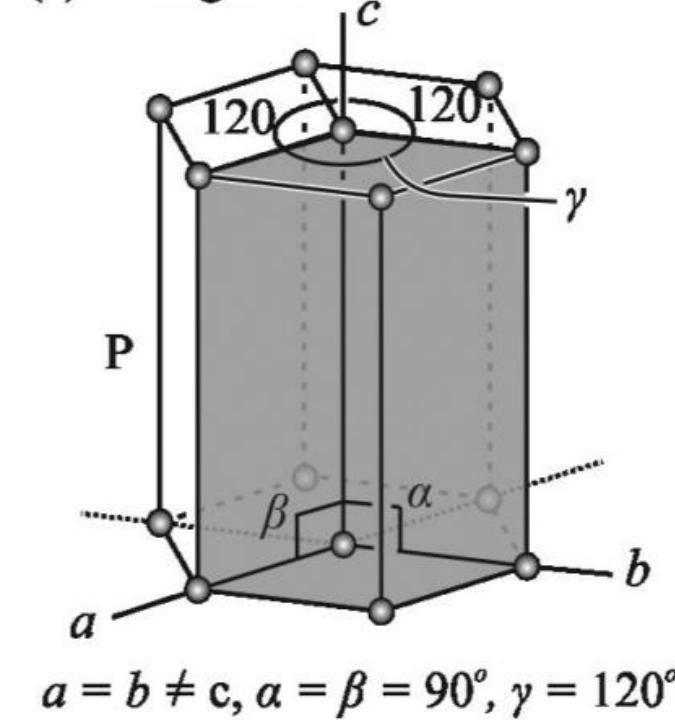
Crystallography of Minerals

(14 Bravais Lattice from translational Symmetry)

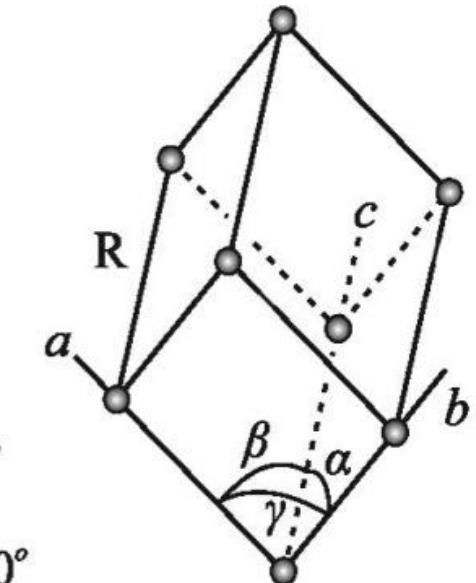
(d) Tetragonal



(e) Hexagonal



$$\begin{aligned}a &= b = c \\ \alpha &= \beta = \gamma \neq 90^\circ\end{aligned}$$



Crystallography of Minerals

(14 Bravais Lattice from translational Symmetry)

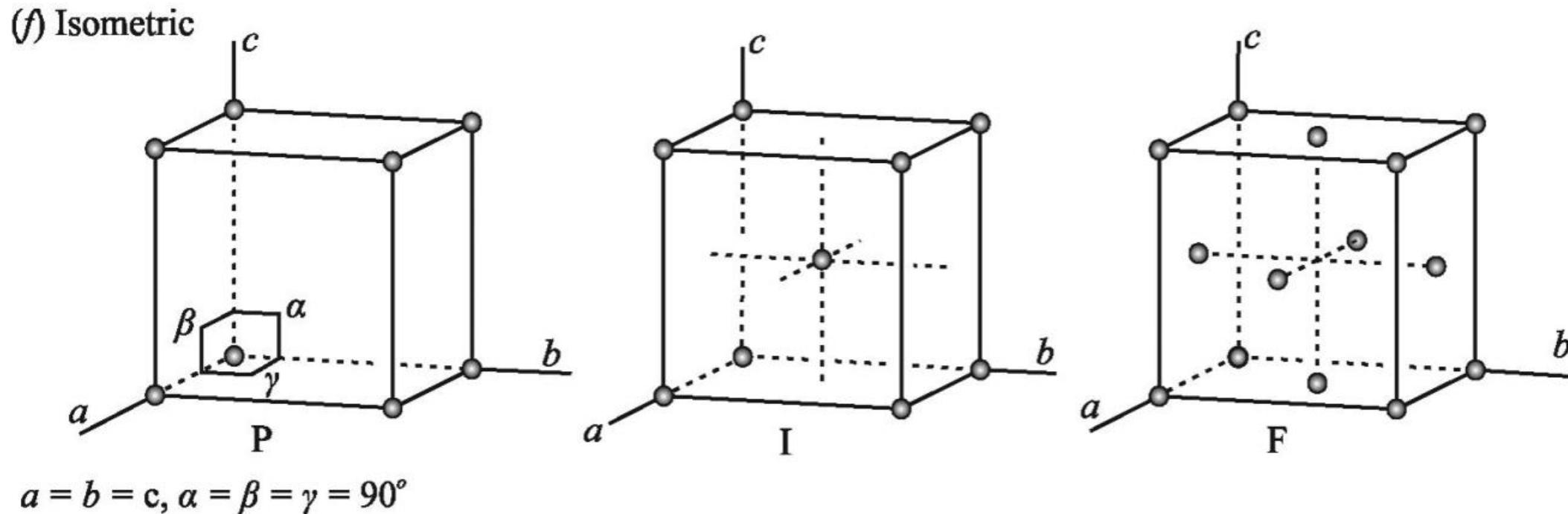


Figure 2.10 The 14 Bravais lattices define six different three-dimensional volumes ($a-f$) that correspond to the unit cells of the six crystal systems. The lengths of the three unit cell axes are a , b , and c , and the angles between them are α , β , and γ . In the notations, the \neq sign indicates that equality of the axis lengths or angles is not required, although occasionally equality may occur by chance. The hexagonal (R) lattice shown in (e) is based on the rhombohedral axes shown in Figure 2.8c. A unit cell with the same geometry as the hexagonal (P) lattice shown in Figure 2.8a is far more commonly used.

Point Symmetry



Point Symmetry

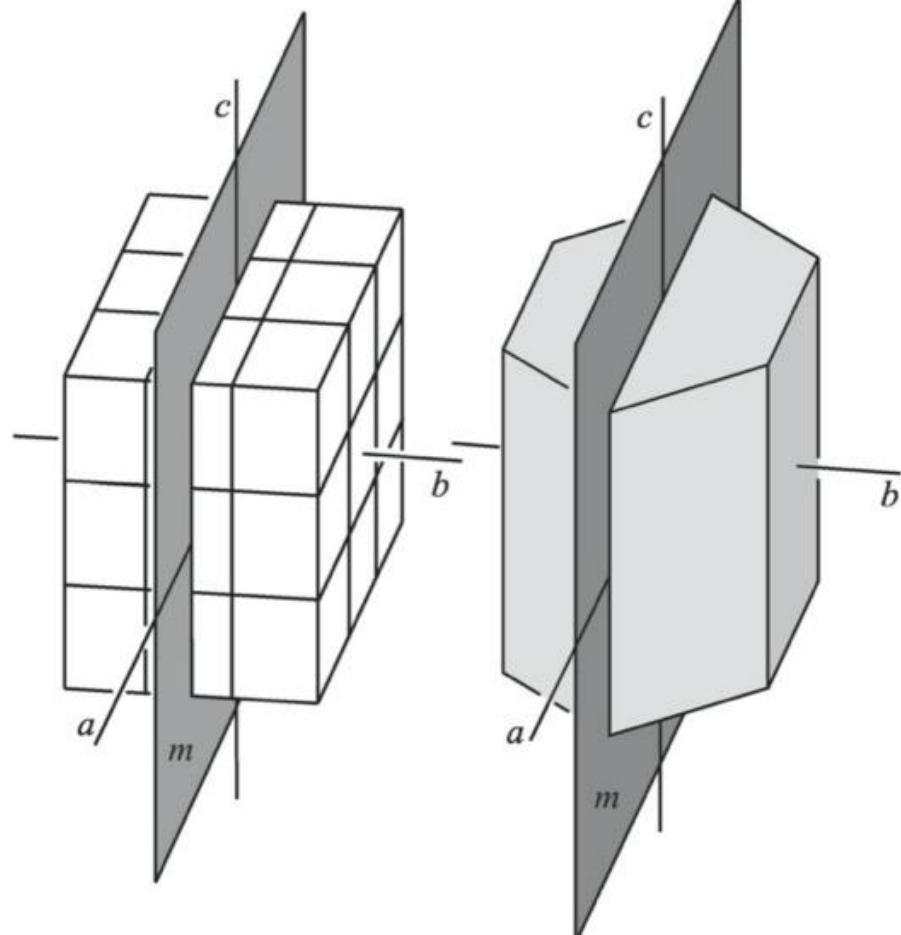
- An object that consists of a systematic repetition of identical features is said to have “symmetry”.
- Three main external symmetry are recognized:
 - I. Symmetry with respect to a plane
 - II. Symmetry with respect to a line
 - III. Symmetry with respect to a point
- It is possible for an object to possess more than one type of symmetry.

Point Symmetry

- **Mirror (reflection) Symmetry with respect to a plane.**
- **Rotational symmetry with respect to an axis.**
- **Inversion symmetry with respect to a point.**
- **Roto-inversion (A combination of rotation with a center of inversion) Symmetry**

Point Symmetry

Mirror Symmetry



- Symmetry by a mirror “m” plane of reflection.
- Monoclinic minerals will have only one mirror plane.
- Triclinic minerals will have no mirror plane.
- A cubic mineral may have as many as 9 mirror planes.

Point Symmetry

Rotational Symmetry

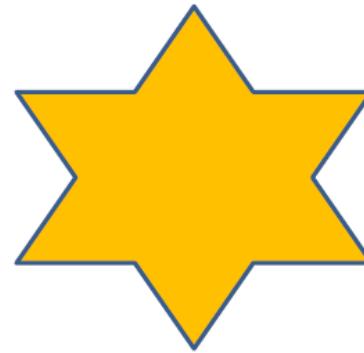
Vertically oriented symmetry axis



4 ($\alpha = 90 \text{ deg}$)



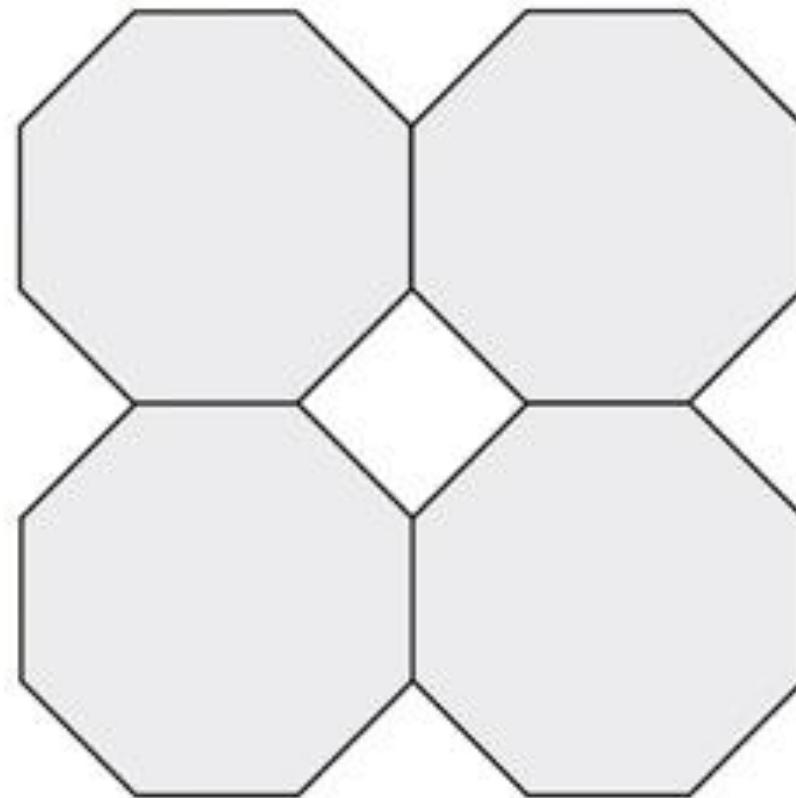
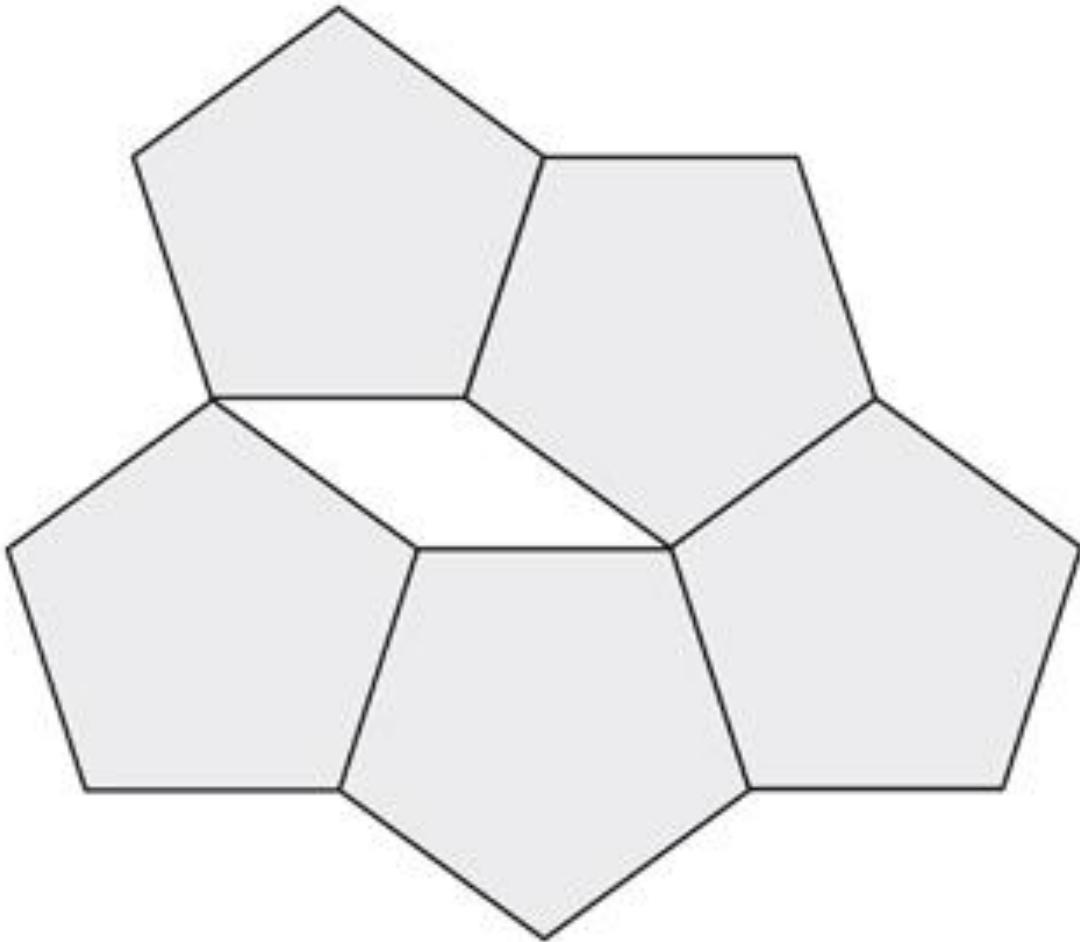
5 ($\alpha = 72 \text{ deg}$)



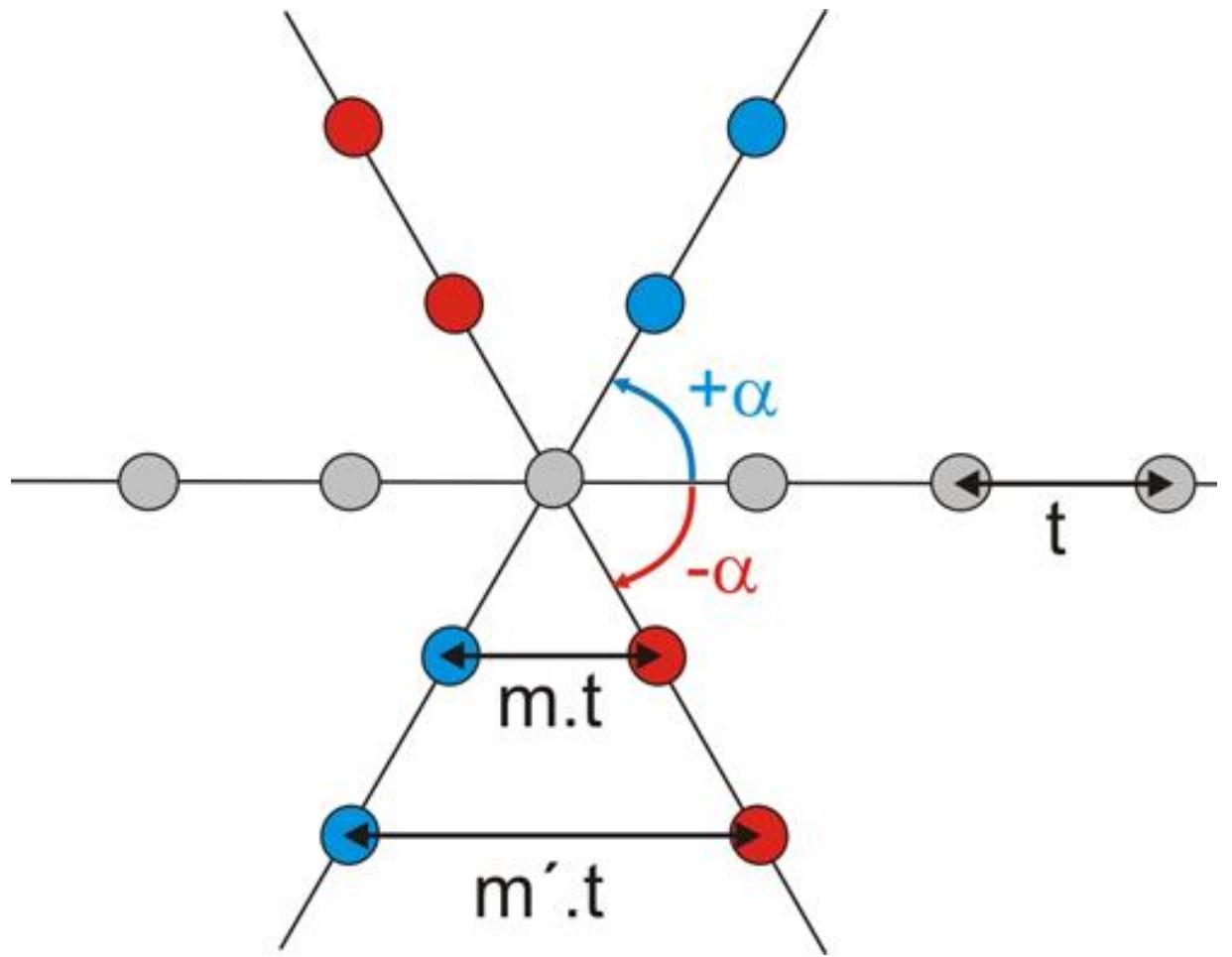
6 ($\alpha = 60 \text{ deg}$)

If “ α ” symbolizes the repeat angle for an “X”-fold axis of symmetry – that is, the angle of rotation about this axis necessary to ”repeat the scene”– then,

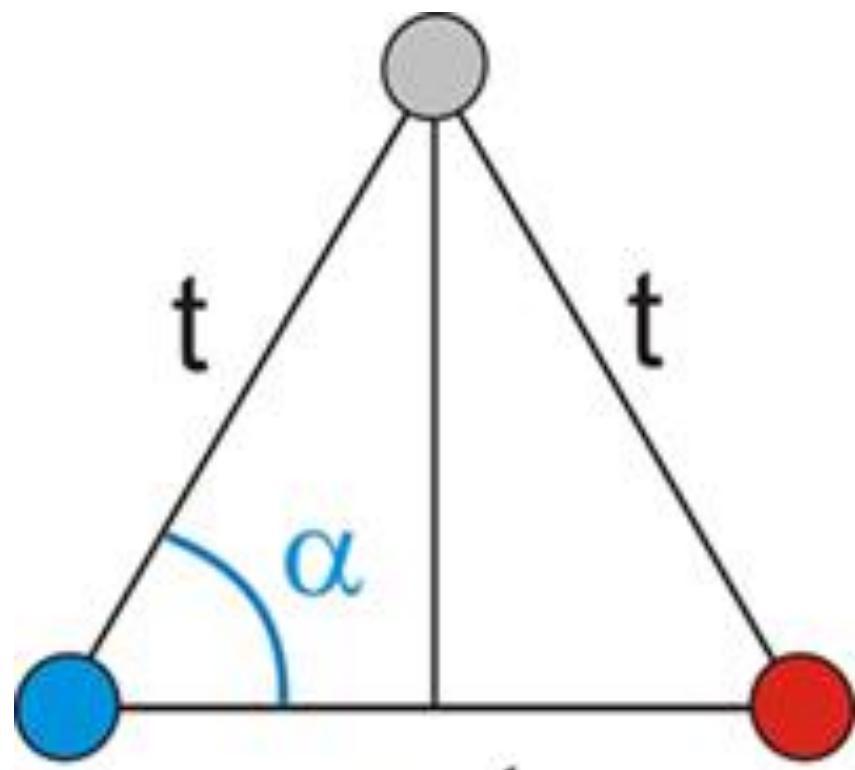
$$\alpha = \frac{360}{X}$$



Objects having five- and eight-fold rotational symmetries do not fill the space completely



- ‘ t ’ is a translational vector along (let say) x-axis
- If α is angle of rotation symmetry operation (repeat angle) with respect to axis perpendicular to plane, so any distance between blue and red points (shown in figure) must be integer multiple of translational lattice length ‘ t ’.

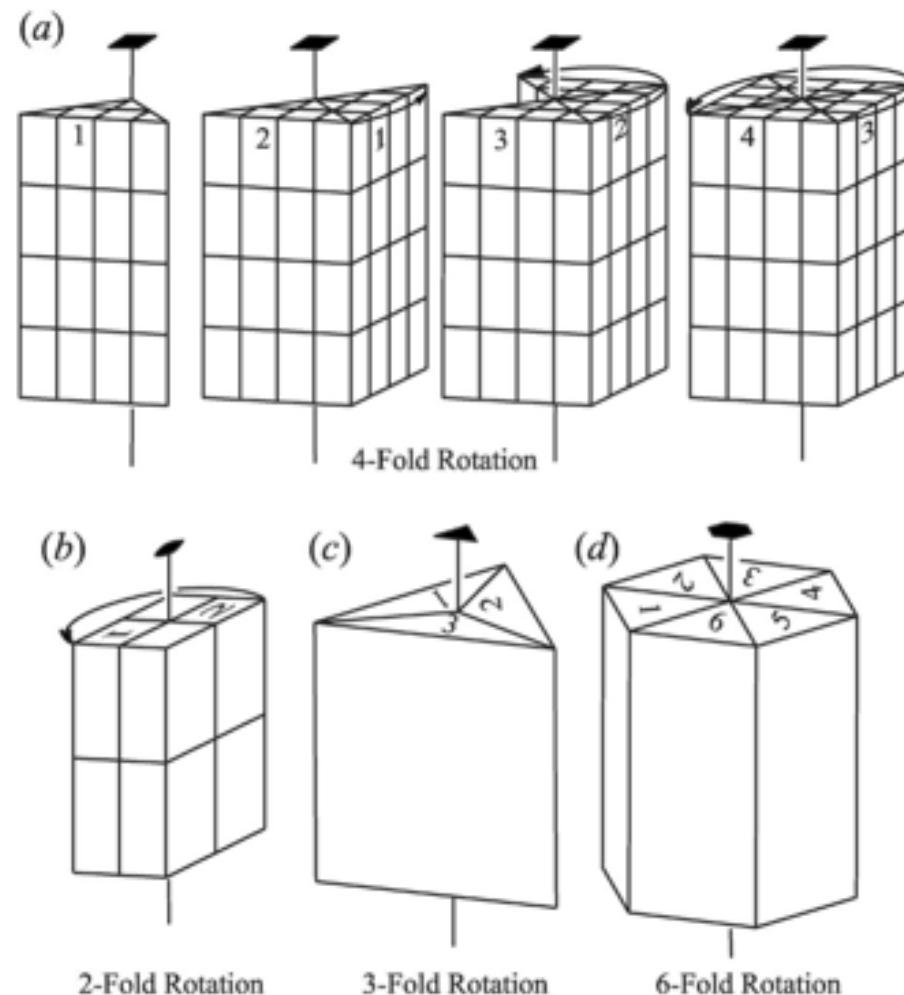


$$\cos(\alpha) = \frac{\left(\frac{1}{2}\right)mt}{\sqrt{m^2+t^2}} = \frac{m}{\sqrt{m^2+t^2}}$$

m	-2	-1	0	1	2
$\cos \alpha$	-1	-1/2	0	1/2	1
α	180	120	90	60	0
n	2	3	4	6	1

Point Symmetry

Rotational Symmetry

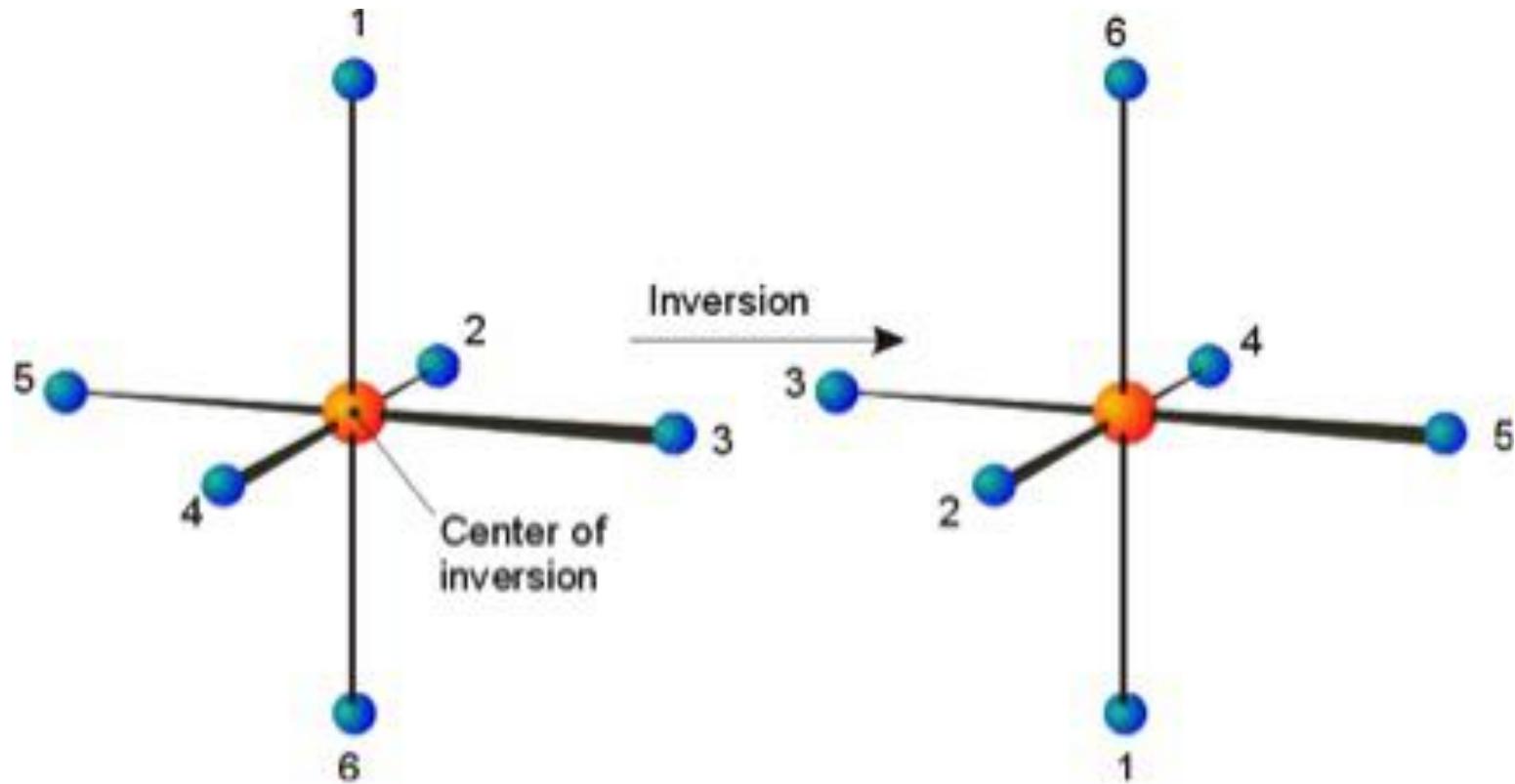


Point Symmetry

Inversion Symmetry:

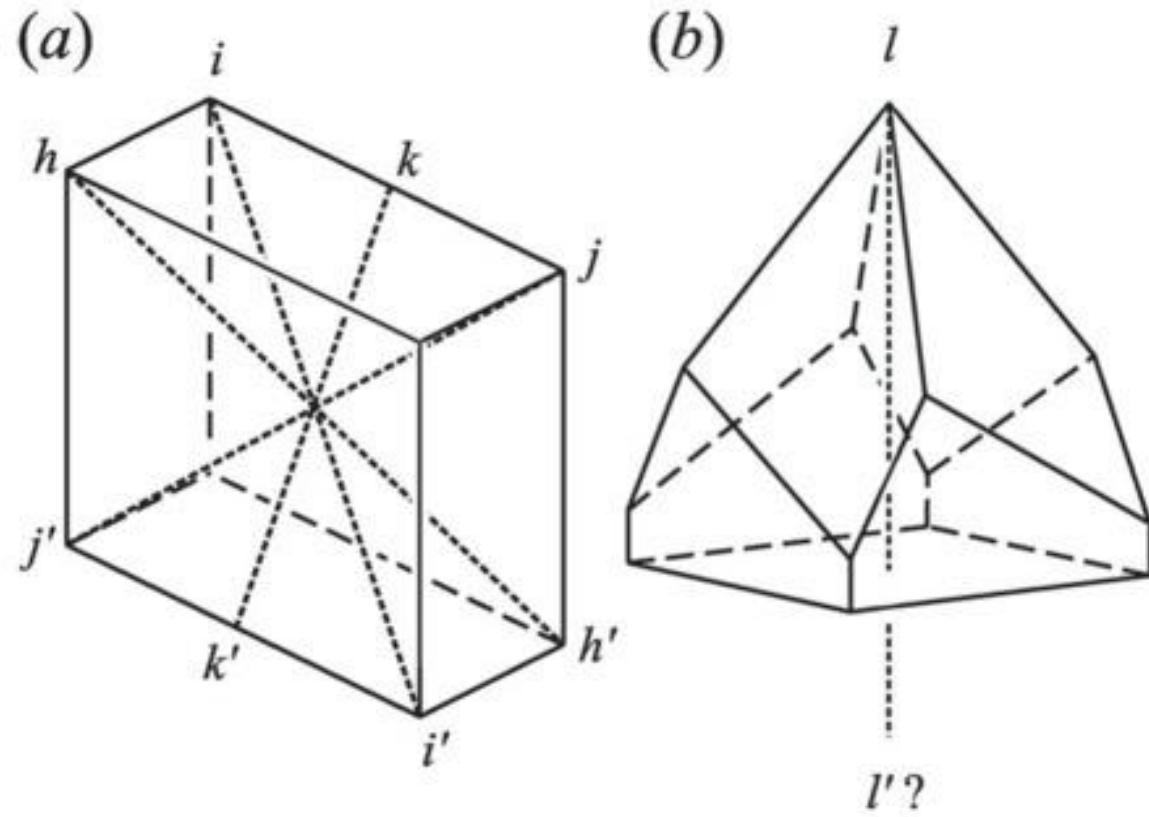
➤ Inversion relative to the origin (centre of inversion):

$$X, Y, Z \leftrightarrow -X, -Y, -Z$$



Point Symmetry

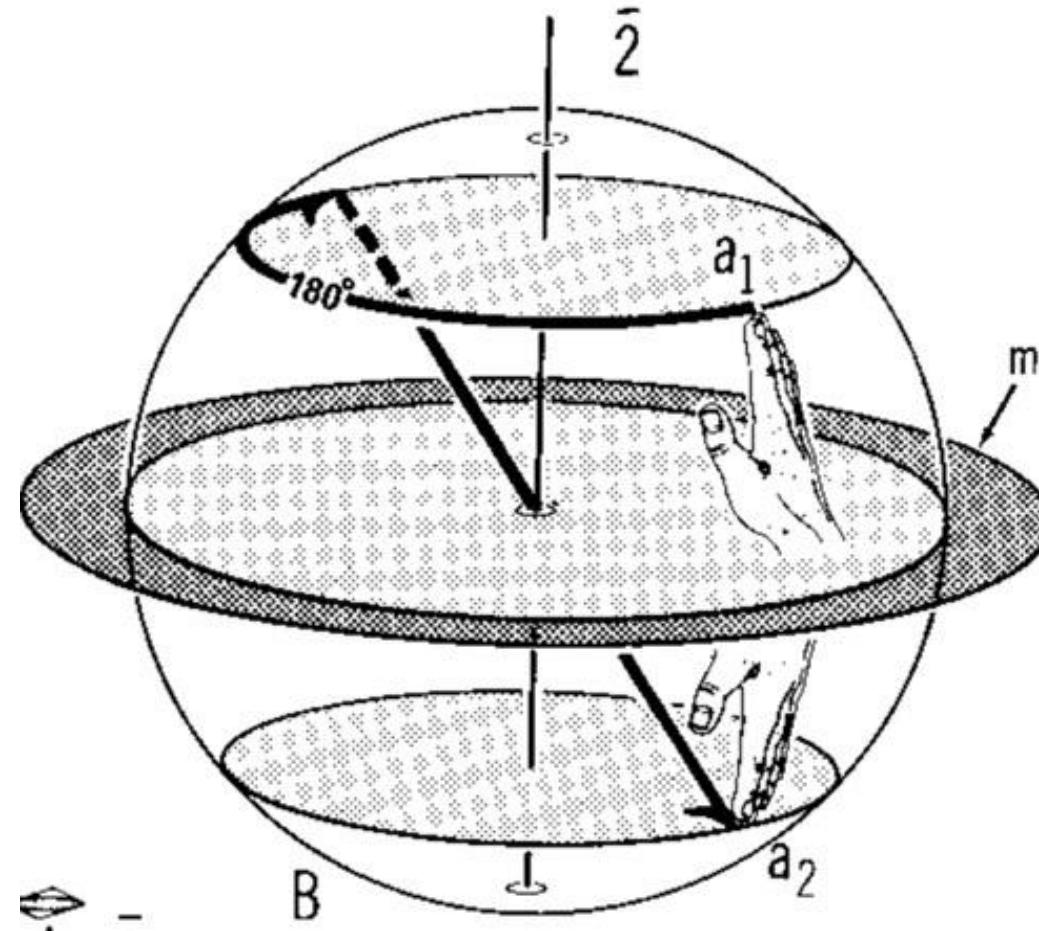
Inversion Symmetry



- If a crystal has inversion or center of symmetry, any line drawn through the origin will find identical features equidistant from the origin on opposite sides of the crystal.
- Inversion symmetry is identified with the letter "i".

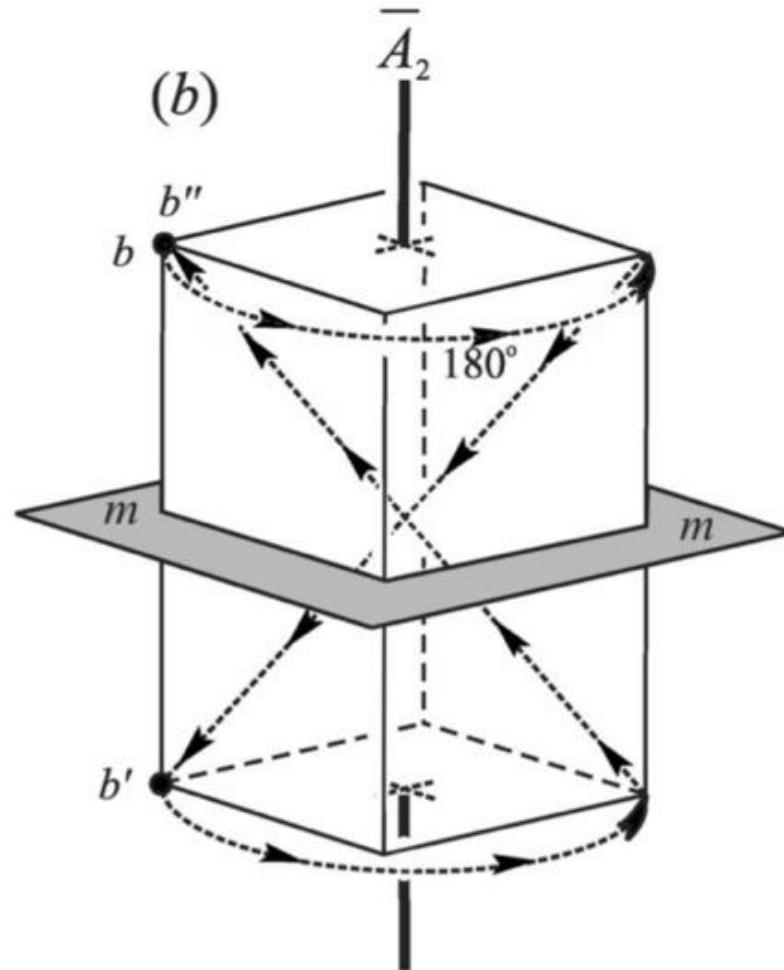
Point Symmetry

Roto-inversion Symmetry: A combination of rotation with respect to an axis and inversion with respect to a point.



Point Symmetry

Roto-inversion Symmetry: A combination of rotation with respect to an axis and inversion with respect to a point.



Point “ b ” upon rotation by 180 degree followed by inversion through the centre produces b' .

Mineral Properties

Hardness:

- Hardness of a mineral primarily depends on the crystal structure.
- It is classified based on the Mohs scale of relative hardness.

Habit/Shape

- Determined by crystal structure
- Depends on the speed and direction of crystal growth
- Types:
 - I. Bladed
 - II. Platy
 - III. Prismatic
 - IV. Banded
 - V. Fibrous
 - VI. Botryoidal

Cleavage: These are weak planes in the crystal structures of the minerals.

Specific gravity: Ratio of the weight of mineral with the equal volume of pure water at 4°C.

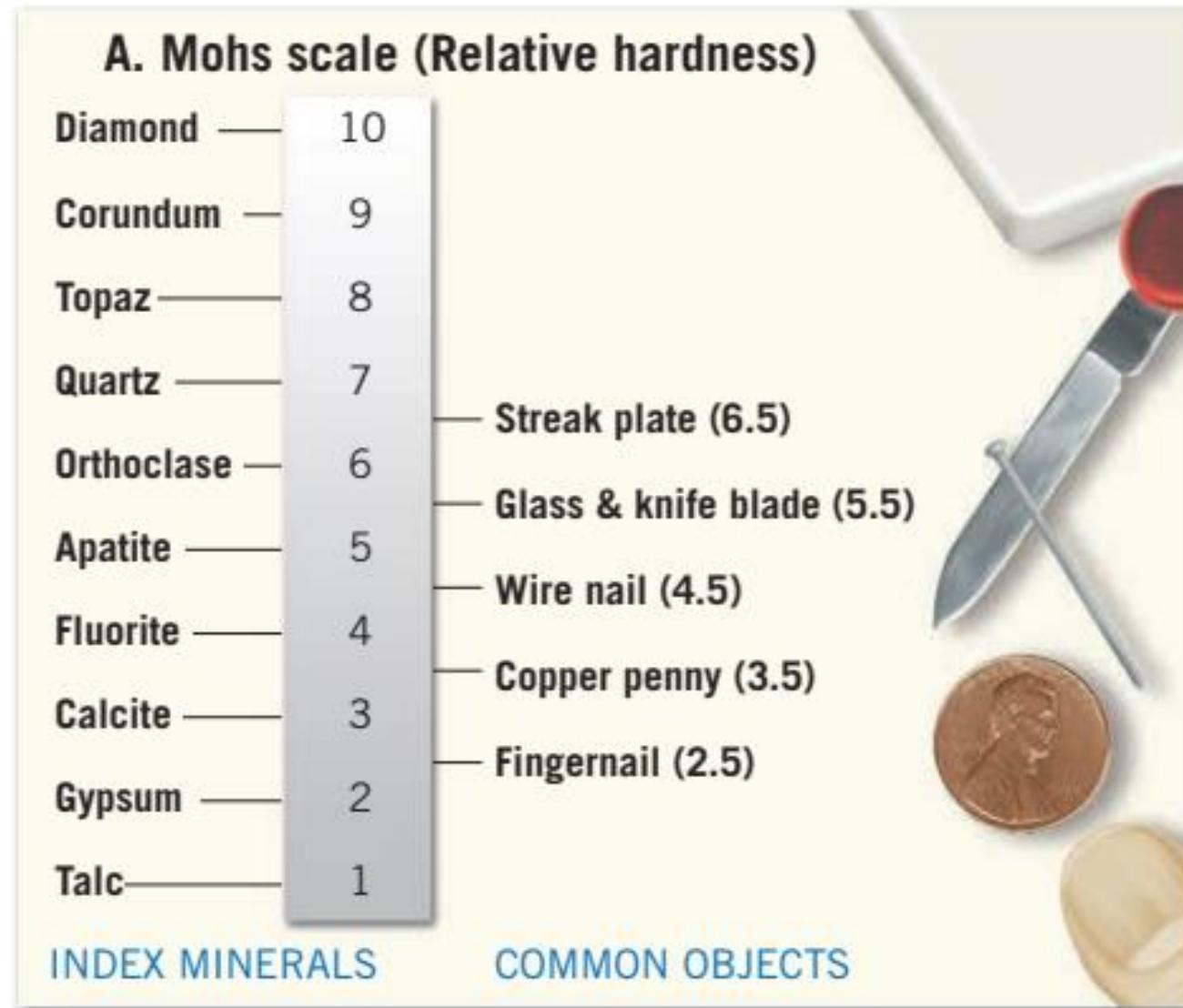
Mineral Properties

Optical Properties:

- Color
- Streak
- Luster
- Identification of Minerals using polarizing optical microscope.

Mineral Properties

Hardness: Mohs scale of hardness



Mineral Properties

Shape



Bladed kyanite



Botryoidal hematite



Prismatic quartz



Banded agate



Fibrous okenite

Mineral Properties

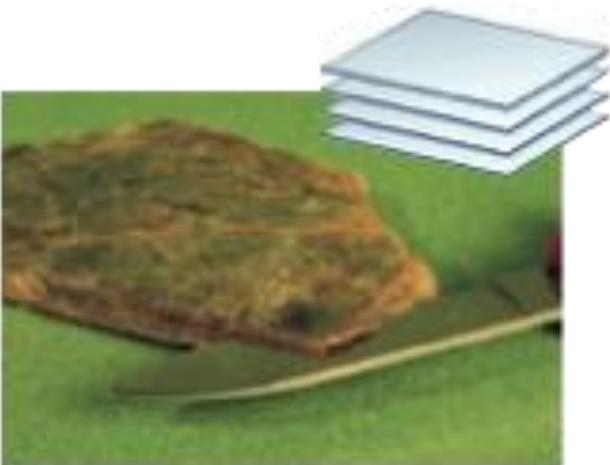
Cleavage

- Preferred plane of breakage.
- Creates a smooth plane
- Generated by crystal arrangements.

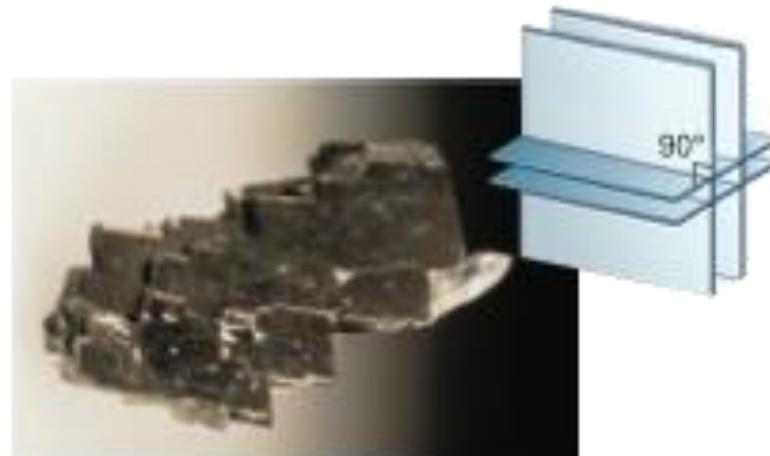
Mineral Properties

Cleavage

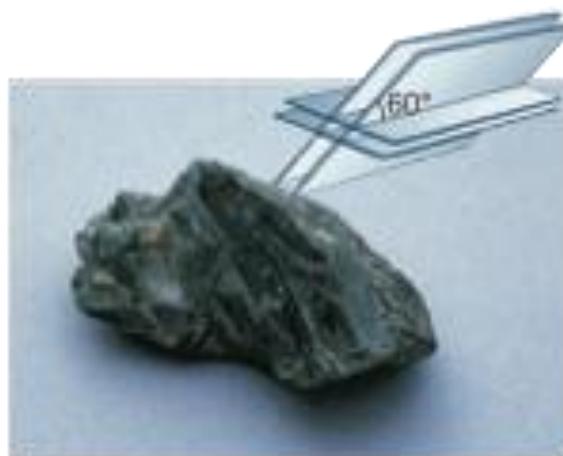
FIGURE 5.13 The nature of mineral cleavage and fracture.



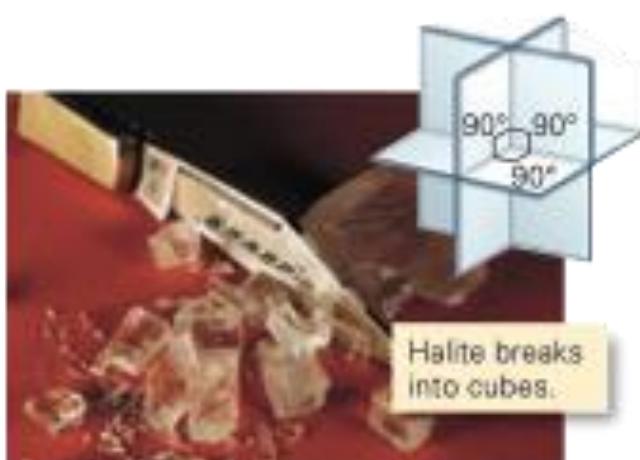
(a) Mica has one strong plane of cleavage and splits into sheets.



(b) Pyroxene has two planes of cleavage that intersect at 90°.



(c) Amphibole has two planes of cleavage that intersect at 60°.



(d) Halite has three mutually perpendicular planes of cleavage.



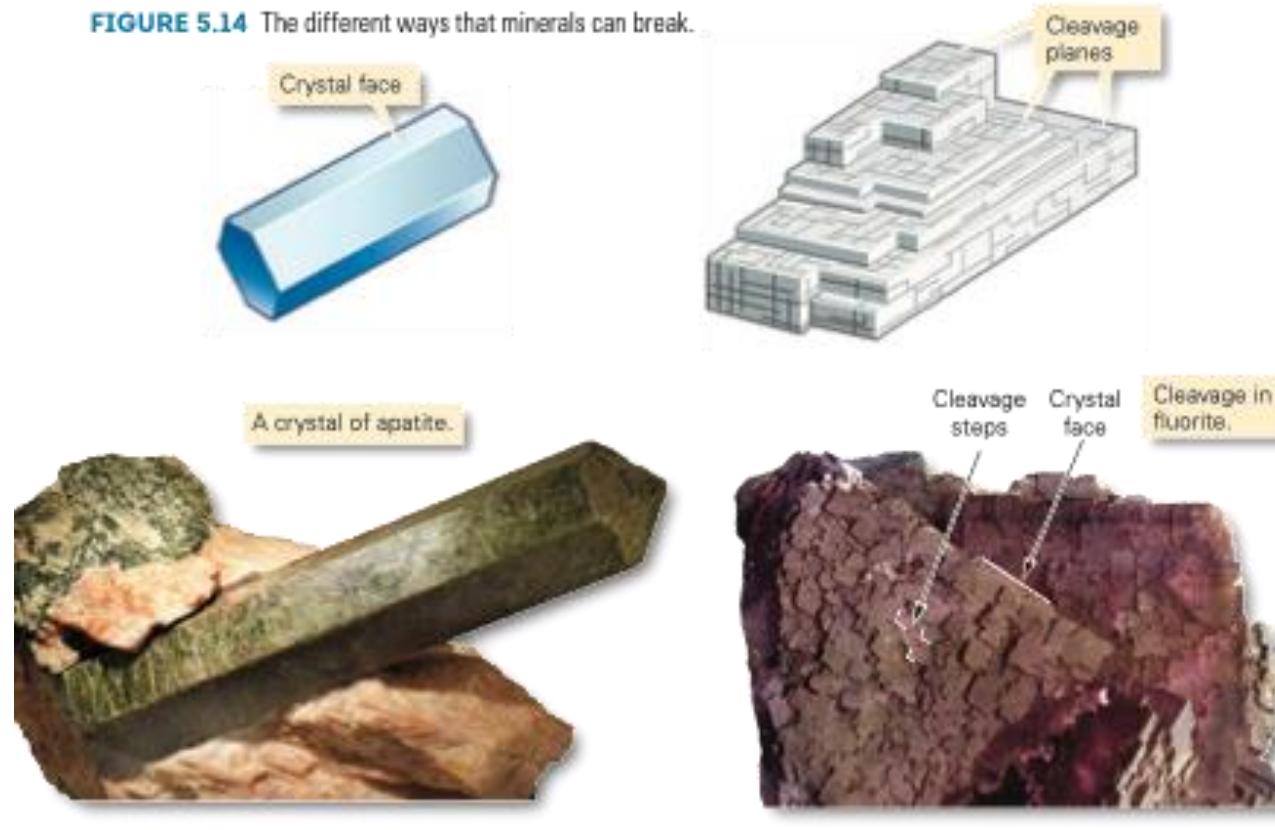
(e) Calcite has three planes of cleavage, one of which is inclined.



(f) Diamond has four planes of cleavage, each inclined to the others.

Mineral Properties

FIGURE 5.14 The different ways that minerals can break.



(a) How do you distinguish between crystal faces and cleavage planes? A crystal face is a single surface, whereas cleavage planes can be repeated.



(b) Minerals without cleavage can develop irregular or conchoidal fractures.

Mineral Properties (Optical)

Color



Quartz

Mineral Properties (Optical)

Streak: The color of powdered mineral



FIGURE 3.20 ■ Hematite may be black, red, or brown, but it always leaves a reddish brown streak when scraped along a ceramic streak plate. [Breck P. Kent.]

Mineral Properties (Optical)

Luster: The appearance of light reflected from mineral surface.

Type:

- Metallic
- Non-metallic: Earthy/Dull, Glassy, Pearly, Silky



Metallic luster of pyrite



Glassy luster of quartz



Earthy luster of limonite



Pearly luster of talc



Silky luster of siderite

Mineral Properties

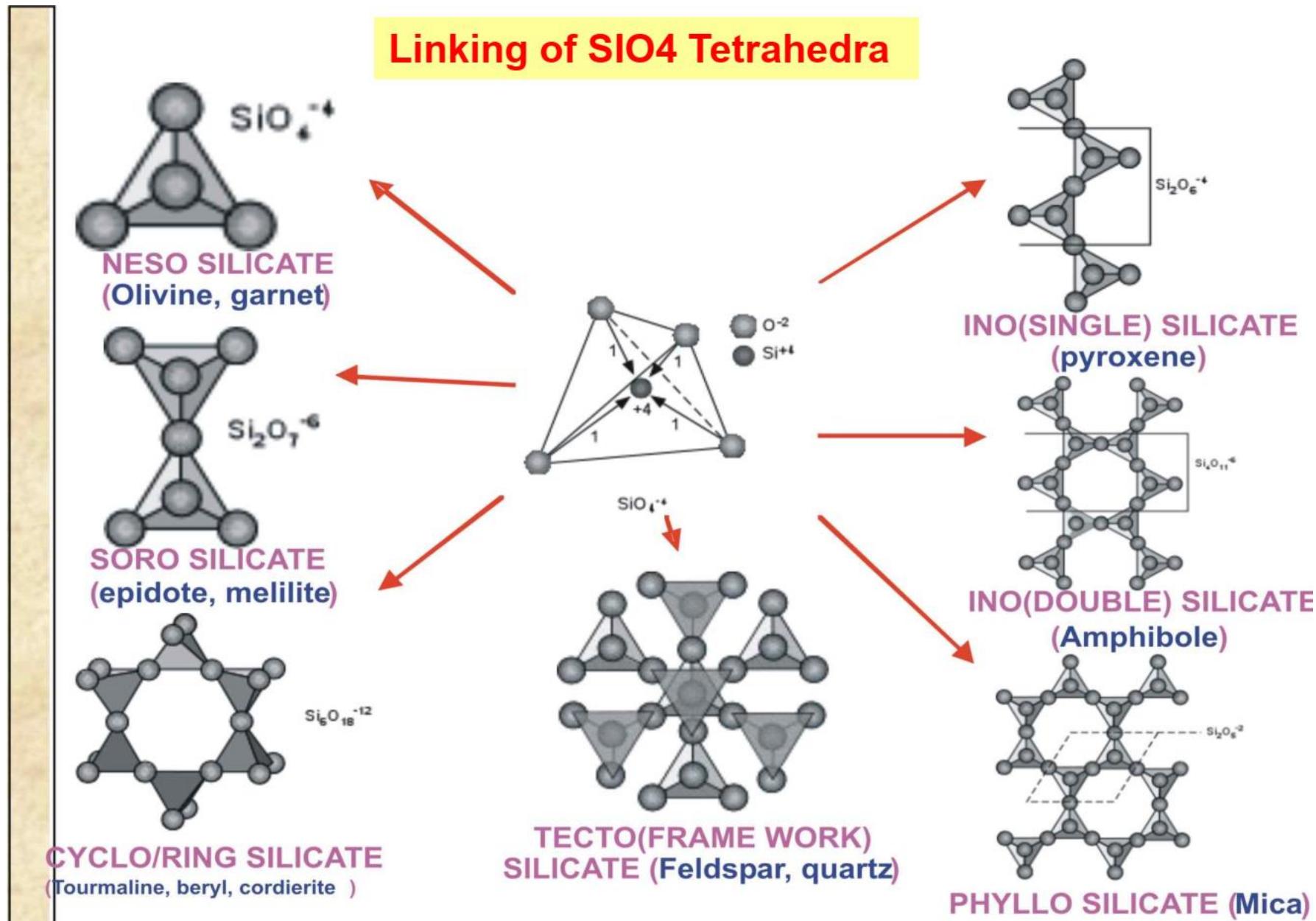
TABLE 3-4 Physical Properties of Minerals

Property	Relation to Composition and Crystal Structure
Hardness	Strong chemical bonds result in hard minerals. Covalently bonded minerals are generally harder than ionically bonded minerals.
Cleavage	Cleavage is poor if bonds in crystal structure are strong, good if bonds are weak. Covalent bonds generally give poor or no cleavage; ionic bonds are weaker and so give good cleavage.
Fracture	Related to distribution of bond strengths across irregular surfaces other than cleavage planes.
Luster	Tends to be glassy for ionically bonded crystals, more variable for covalently bonded crystals.
Color	Determined by ions and trace elements. Many ionically bonded crystals are colorless. Iron tends to color strongly.
Streak	Color of fine mineral powder is more characteristic than that of massive mineral because of uniformly small size of grains.
Density	Depends on atomic weight of atoms or ions and their closeness of packing in crystal structure.
Crystal habit	Depends on the planes of a mineral's crystal structure and the typical speed and direction of crystal growth.

TAKE-HOME MESSAGE

The properties of minerals (such as color, streak, luster, crystal habit, hardness, specific gravity, cleavage, magnetism, and reaction with acid) are a manifestation of the crystal structure and chemical composition of minerals and can be used for mineral identification.

Minerals Classification: Silicate Minerals



Minerals Classification: Silicate Minerals

Table 11.1 Silicate Classification^a

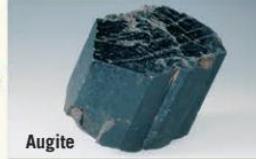
Orthosilicates = Nesosilicates
Disilicates = Sorosilicates
Ring silicates = Cyclosilicates
Chain silicates = Inosilicates
Sheet silicates = Phyllosilicates
Framework silicates = Tectosilicates

Silicate Class	Number of O ²⁻ Shared per Tetrahedron	Z:O Ratio	Structural Configuration
Orthosilicates	0	1:4	Isolated tetrahedra
Disilicates	1	2:7	Double tetrahedra
Ring silicates	2	1:3	Rings of tetrahedra
Chain silicates			Chains of tetrahedra
Single chain	2	1:3	
Double chain	2 or 3	4:11	
Sheet silicates	3	2:5	Sheets of tetrahedra
Framework silicates	4	1:2	Framework of tetrahedra

^aZ refers to the cation(s), usually Si⁴⁺, and also Al³⁺, that occupy the tetrahedral sites.

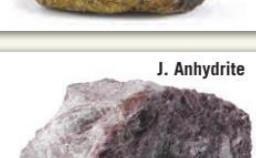
Minerals Classification:

Silicate Minerals

Common Silicate Minerals and Mineral Groups			
Mineral/Formula	Cleavage	Silicate Structure	Example
Olivine group $(\text{Mg},\text{Fe})_2\text{SiO}_4$	None	Single tetrahedra	 Olivine
Pyroxene group (Augite) $(\text{Mg},\text{Fe},\text{Ca},\text{Na})\text{AlSiO}_3$	Two planes at 90°	Single chains	 Augite
Amphibole group (Hornblende) $\text{Ca}_2(\text{Fe},\text{Mg})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	Two planes at 60° and 120°	Double chains	 Hornblende
Micas	Biotite $\text{K}(\text{Mg},\text{Fe})_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2$	One plane	 Biotite
	Muscovite $\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$		 Muscovite
Feldspars	Potassium feldspar (Orthoclase) KAlSi_3O_8	Two planes at 90°	 Potassium feldspar
	Plagioclase $(\text{Ca},\text{Na})\text{AlSi}_3\text{O}_8$		
	Quartz SiO_2	None	 Quartz

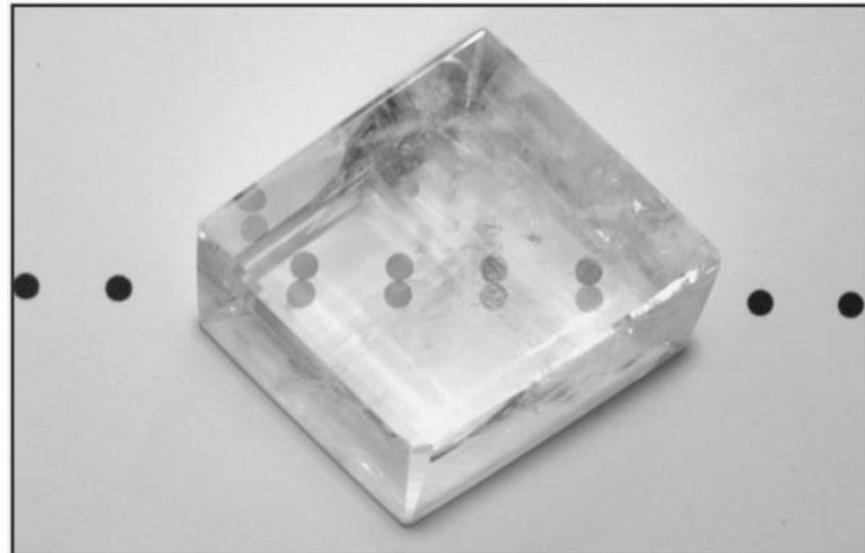
Minerals Classification

Nonsilicate Minerals

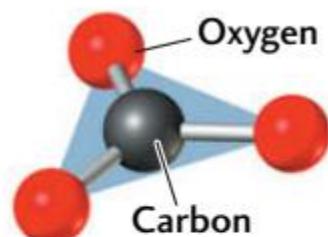
Common Nonsilicate Mineral Groups				
Mineral Group (key ion(s) or element(s))	Mineral Name	Chemical Formula	Economic Use	Examples
Carbonates (CO ₃ ²⁻)	Calcite Dolomite	CaCO ₃ CaMg(CO ₃) ₂	Portland cement, lime Portland cement, lime	 
Halides (Cl ¹⁻ , F ¹⁻ , Br ¹⁻)	Halite Fluorite Sylvite	NaCl CaF ₂ KCl	Common salt Used in steelmaking Used as fertilizer	 
Oxides (O ²⁻)	Hematite Magnetite Corundum Ice	Fe ₂ O ₃ Fe ₃ O ₄ Al ₂ O ₃ H ₂ O	Ore of iron, pigment Ore of iron Gemstone, abrasive Solid form of water	 
Sulfides (S ²⁻)	Galena Sphalerite Pyrite Chalcopyrite Cinnabar	PbS ZnS FeS ₂ CuFeS ₂ HgS	Ore of lead Ore of zinc Sulfuric acid production Ore of copper Ore of mercury	 
Sulfates (SO ₄ ²⁻)	Gypsum Anhydrite Barite	CaSO ₄ •2H ₂ O CaSO ₄ BaSO ₄	Plaster Plaster Drilling mud	 
Native elements (single elements)	Gold Copper Diamond Graphite Sulfur Silver	Au Cu C C S Ag	Trade, jewelry Electrical conductor Gemstone, abrasive Pencil lead Sulfadugs, chemicals Jewelry, photography	 

Minerals Classification

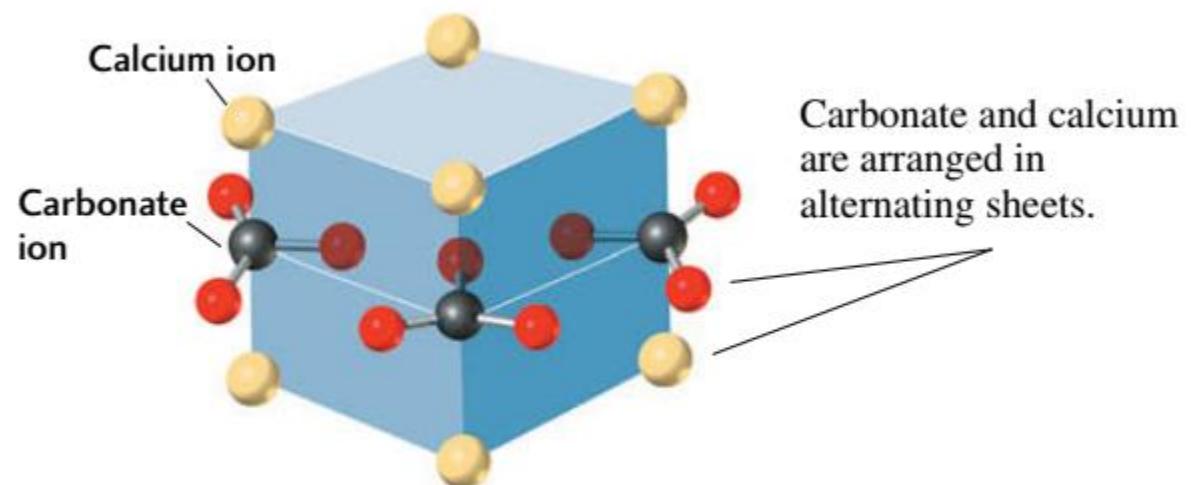
Nonsilicate Minerals: Calcite



(a) Carbonate ion (CO_3^{2-})



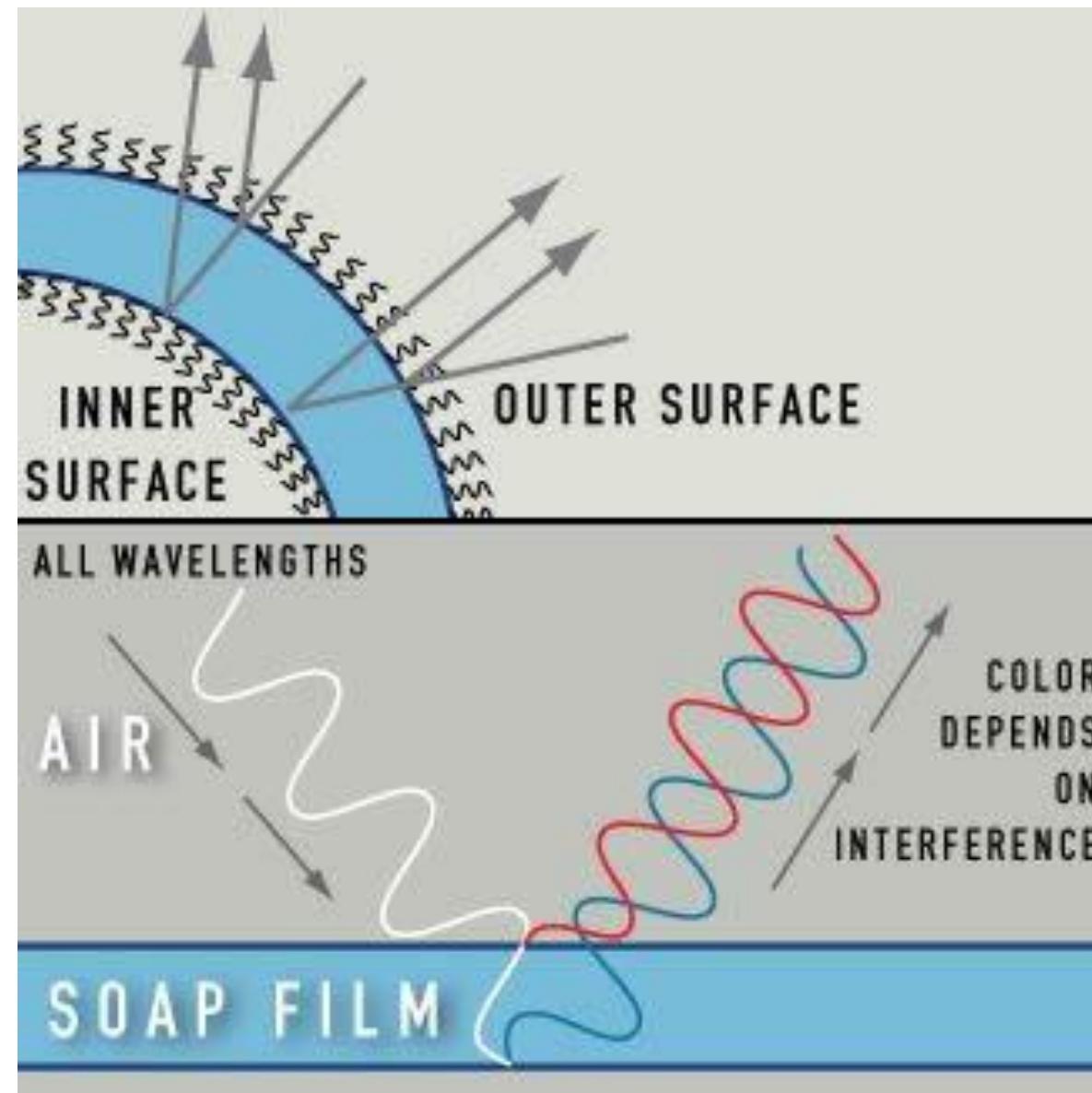
(b) Calcium carbonate structure



(c) Calcite



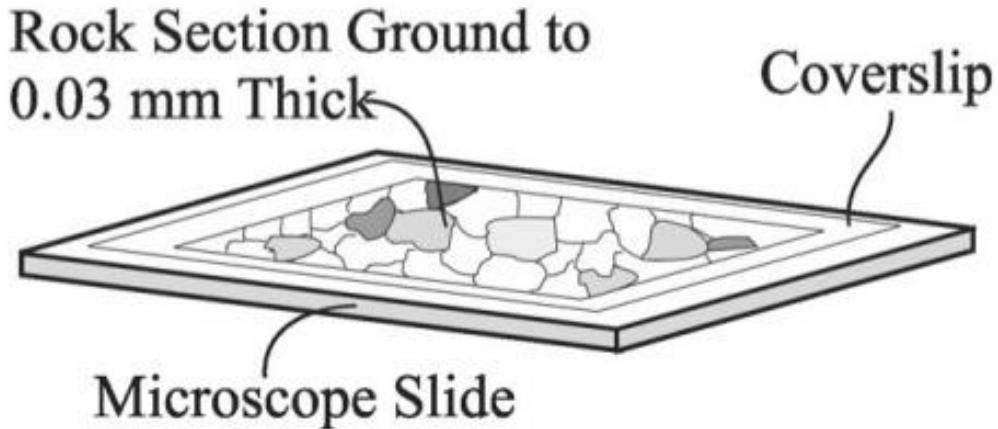
FIGURE 3.12 ■ Carbonate minerals, such as calcite (calcium carbonate, CaCO_3), have a layered structure. (a) Top view of the carbonate ion, composed of a carbon ion surrounded by three oxygen ions in a triangle. (b) View of the alternating layers of calcium and carbonate ions in calcite. (c) Calcite. [Photo by John Grotzinger/Ramón Rivera-Moret/Harvard Mineralogical Museum.]



Optical Mineralogy

Petrographic microscope utilizes *polarized light* to allow measurement of a variety of optical properties to identify unknown minerals.

Thin sections are thin slices of rock or mineral mounted on a microscopic slide.

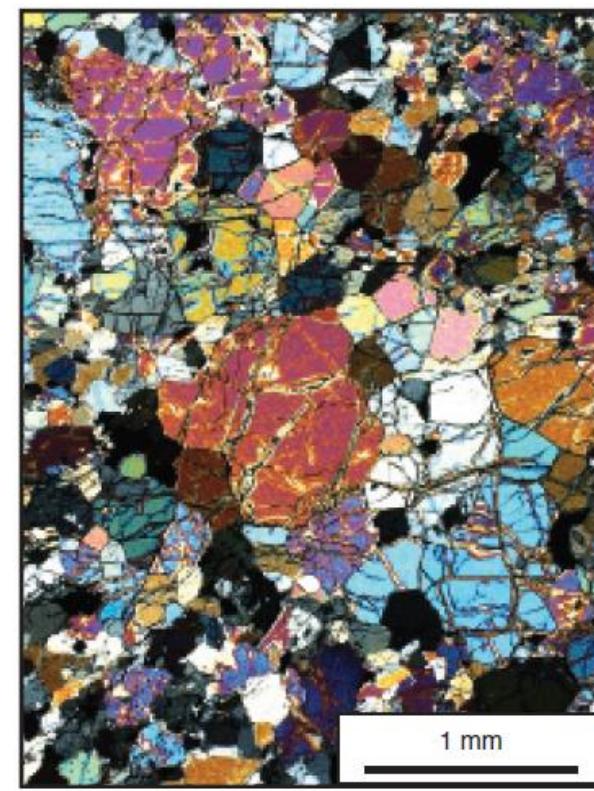


80



80 Peridotite (lherzolite) in plane-polarized light.

81

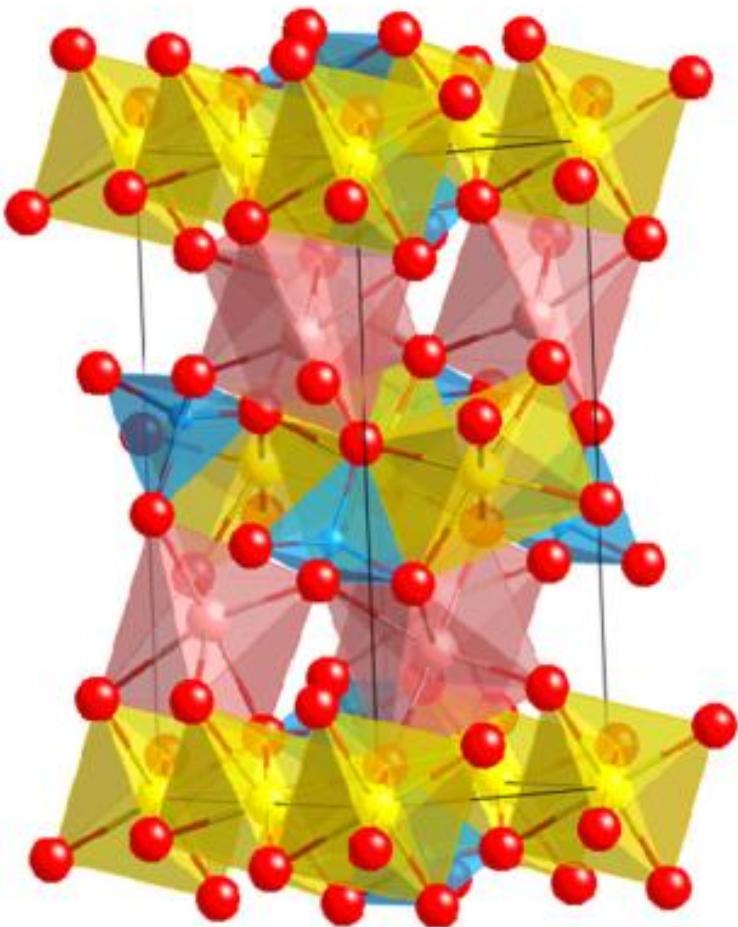


81 Peridotite (lherzolite) with crossed polars.

Some interesting facts about Olivine

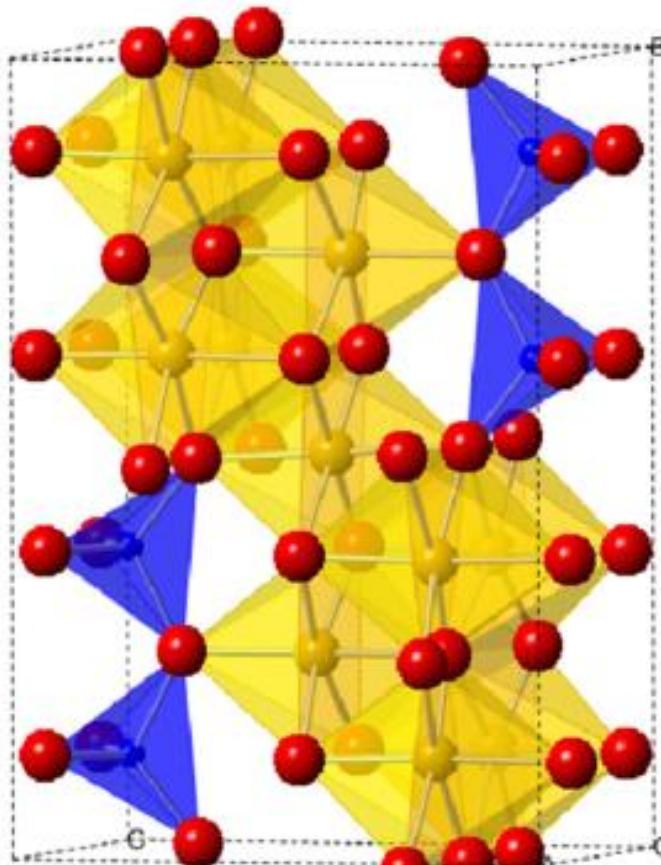
- **Nesosilicate:** Isolated SiO_4 tetrahedra
- **Most common mineral in the Earth's upper mantle.**
- **Chemical Formula:** $(\text{Mg}, \text{Fe})_2\text{SiO}_4$
- **Mg, and Fe forms MO_6 octahedra that link SiO_4 tetrahedra**
- **Olivine is orthorhombic near surface conditions and usually called α –olivine.**
- **At higher P-T, olivine changes to β –olivine which is also called wadsleyite.**
 β –olivine contains sites having OH.
- **The wadsleyite structure is currently of great interest because it is being invoked as a reservoir of water (as chemically bound OH) in the Earth's mantle.**
- **At more higher pressure P-T conditions, β –olivine changes to γ –olivine which also contains OH.**
- **At even more higher P-T conditions, γ –olivine changes to bridgmanite (perovskite structure).**

Phase Transitions in Olivine



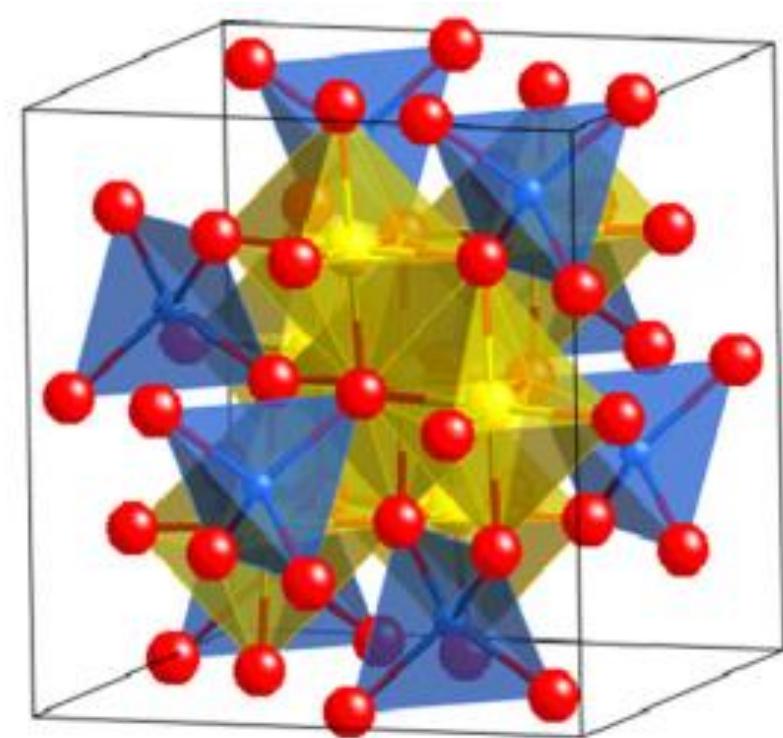
olivine

α –Olivine



wadsleyite

β –Olivine



ringwoodite

γ –Olivine

Phase Transitions in Olivine

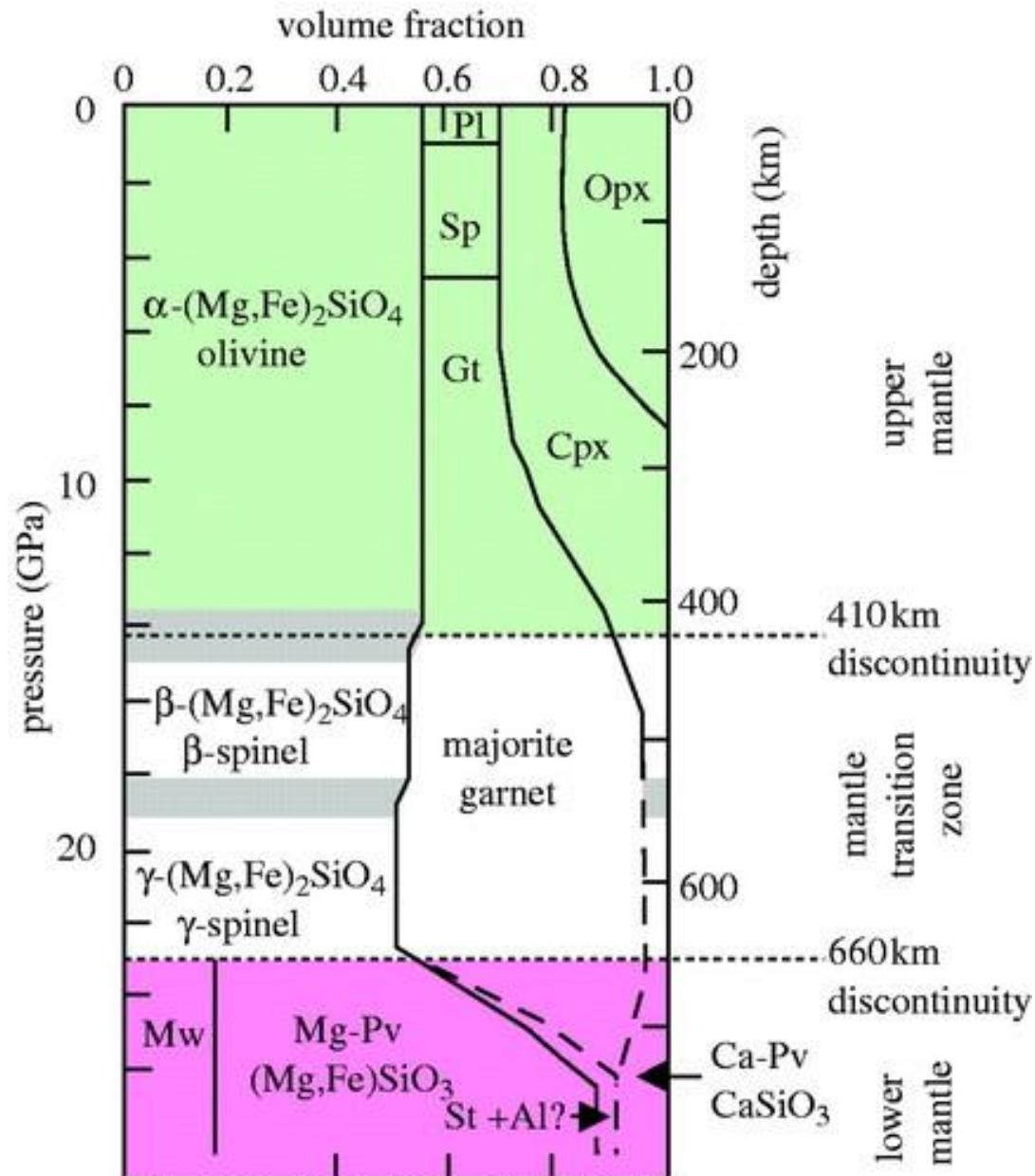


Figure 1. Schematic of the volumetric mineral constitution of a peridotite mantle down to the lower mantle (modified after Ito & Takahashi 1987). Peridotite is a dense coarse-grained igneous rock consisting mainly of olivine and pyroxene. It is high in Fe and Mg and contains less than 45% Si. Peridotite can be found in xenoliths (rock fragments) brought to the surface by magma deriving from the upper mantle. Pl = plagioclase- $\text{CaAl}_2\text{Si}_2\text{O}_8$; Sp = spinel- MgAl_2O_4 ; Gt = garnet- $(\text{Mg},\text{Fe},\text{Ca})_3\text{Al}_2\text{Si}_3\text{O}_{12}$; majorite garnet- $\text{Mg}_3(\text{Mg},\text{Si})_2\text{Si}_3\text{O}_{12}$; Cpx = clinopyroxene- $(\text{Ca},\text{Fe},\text{Mg})\text{SiO}_3$; Opx = orthopyroxene- $(\text{Mg},\text{Fe})\text{SiO}_3$; Mg-Pv = Mg-perovskite- $(\text{Mg},\text{Fe})\text{SiO}_3$; olivine- $(\text{Mg},\text{Fe})_2\text{SiO}_4$; Mw = magnesiowüstite- $(\text{Mg},\text{Fe})\text{O}$; Ca-Pv = Ca-perovskite- CaSiO_3 ; St = stishovite- SiO_2 .

Phase Transitions in Olivine

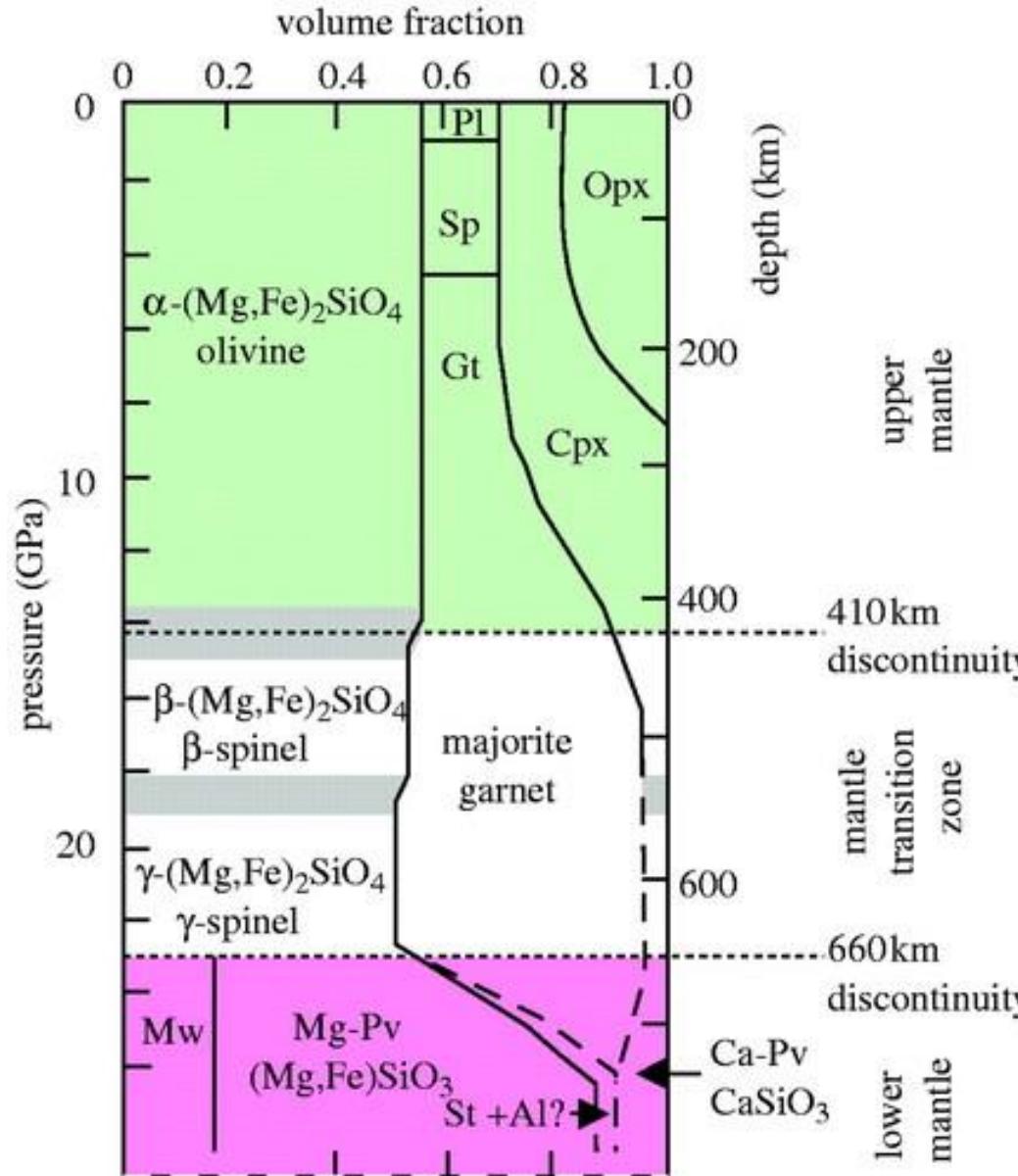


TABLE 4.2 Summary of Mantle Mineral Assemblages for Average Garnet Lherzolite from High-Pressure Studies

Depth (km)	Mineral assemblage (minerals in vol%)	Density contrast (%)	Slope of reaction (MPa/°C)
<410	Olivine 58 Opx 11 Cpx 18 Garnet 13		
350-450	Opx-Cpx → Majorite	6	+1.5
410-km discontinuity			
410	Olivine (α phase) → Wadsleyite (β phase)	6	+5.5
410-550	Wadsleyite 58 Majorite 30 Cpx 9 Opx 3		
520-km discontinuity			
520	Wadsleyite → Ringwoodite (γ phase) Ca-garnet → Ca-perovskite	1	+3.0
550-660	Ringwoodite 58 Majorite 37 Ca-Perovskite 5		
660-km discontinuity			
660	Ringwoodite → Bridgmanite + Magnesiowustite	7-9	-0.5 to -3.5 (dry); ≤-2 (wet)
650-680	Majorite → Perovskite		+1.5 to +2.5
650-680	Ilmenite → Perovskite		
650-680	Pyroxene → Akimotoite		
680-2900	Bridgmanite 77 Magnesiowustite 15 Ca-Perovskite 8 Silica (?)		
D'' discontinuity			
2600-2750	Bridgmanite → post-perovskite	1	7-10

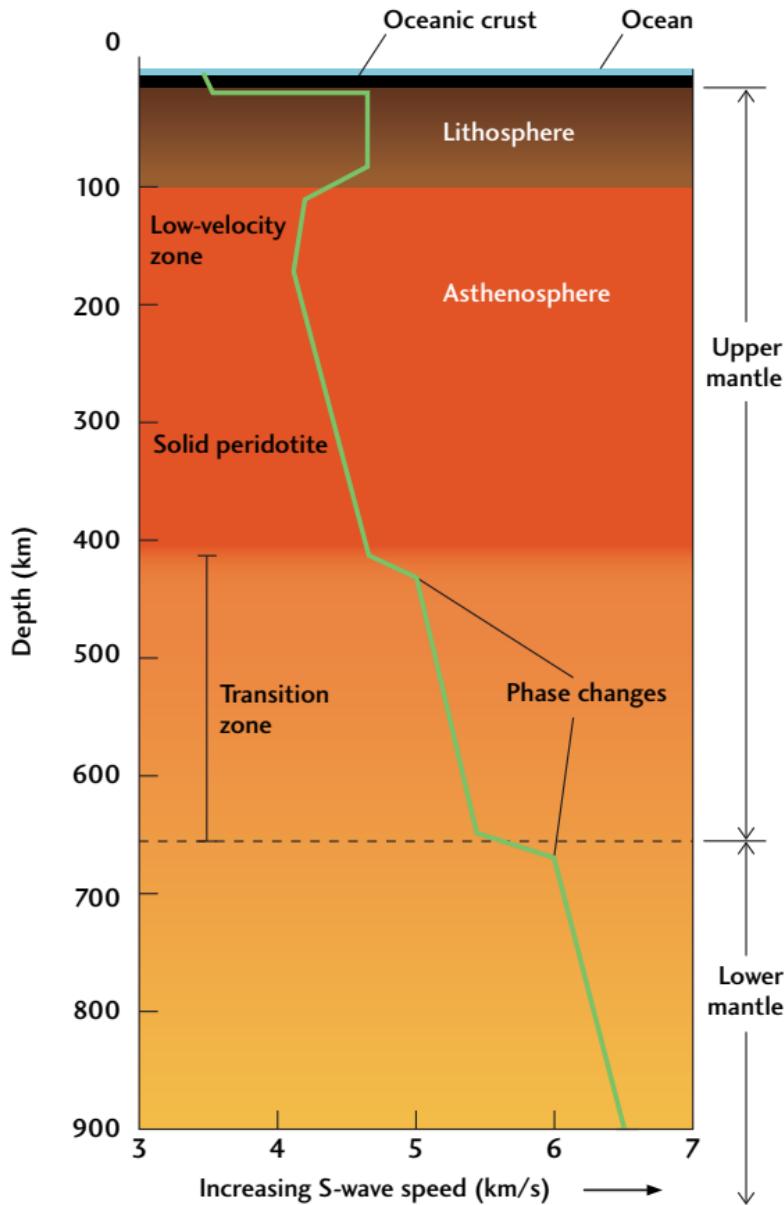
Opx, orthopyroxene; Cpx, clinopyroxene.

Data from [Ita and Stixrude \(1992\)](#), [Christensen \(1995\)](#), [Mambole and Fleitout \(2002\)](#), [Hirose \(2002\)](#), [Katsura et al. \(2003\)](#), [Fei et al. \(2004\)](#), [Litsov et al. \(2005\)](#), [Wolstencroft and Davies \(2011\)](#).

Exploring Earth's Interior using Seismic Waves

Alpha to Beta at 410 Km, Beta to Gamma at 520 Km, Gamma to Perovskite at 660 Km

FIGURE 14.8 □ The structure of the mantle beneath old oceanic lithosphere, showing S-wave velocities to a depth of 900 km. Changes in S-wave velocity mark the strong, brittle lithosphere, the weak, ductile asthenosphere, and a transition zone, in which increasing pressure forces rearrangements of atoms into denser and more compact crystal structures (phase changes).



Compositional Variation in Minerals

- During chemical analysis of different samples of *a mineral*, it is routinely found that these samples do not have same chemical composition (Definite but not a fixed chemical composition).
- Composition variation is possible because different cations can interchangeably occupy the various sites. The term applied to this compositional variation is **solid solution**.
- Practically all naturally occurring minerals containing Fe-Mg-Mn-Ca or Na-K etc. are solid solutions.
- Quartz (SiO_2) is not a solid solution.

Compositional Variation in Minerals

Substitution Solid Solution: Substitution of one cation for another.

- Requirement for substitution solid solution:
 - Ion sizes must be similar
 - Charge neutrality must be maintained
 - Similar electronegativity
- ✓ If the difference in ion size is less than 15%, extensive substitution is possible.
- ✓ If the size difference is ~15-30%, limited substitution possible.
- ✓ If the size difference is greater than 30%, substitution is very unlikely.
- *Temperature* has a substantial influence on the degree to which ions of different sizes may substitute for each other.

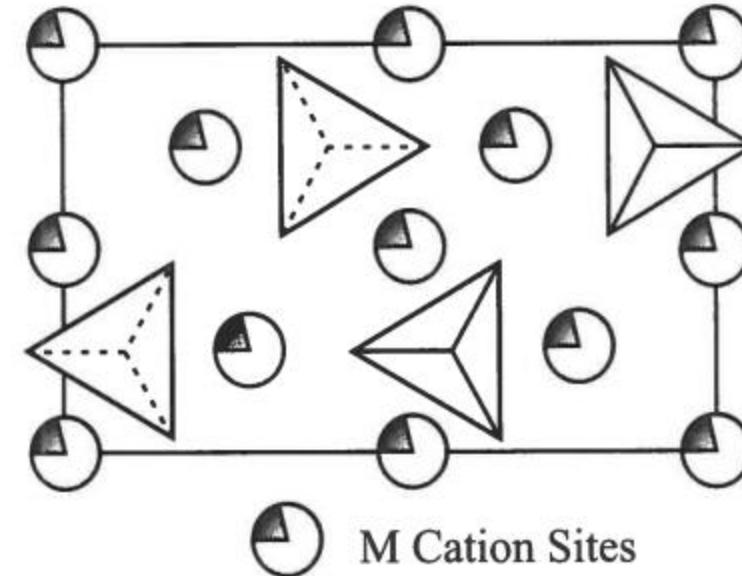
Compositional Variation in Minerals

Substitution Solid Solution: Substitution of one cation for another.

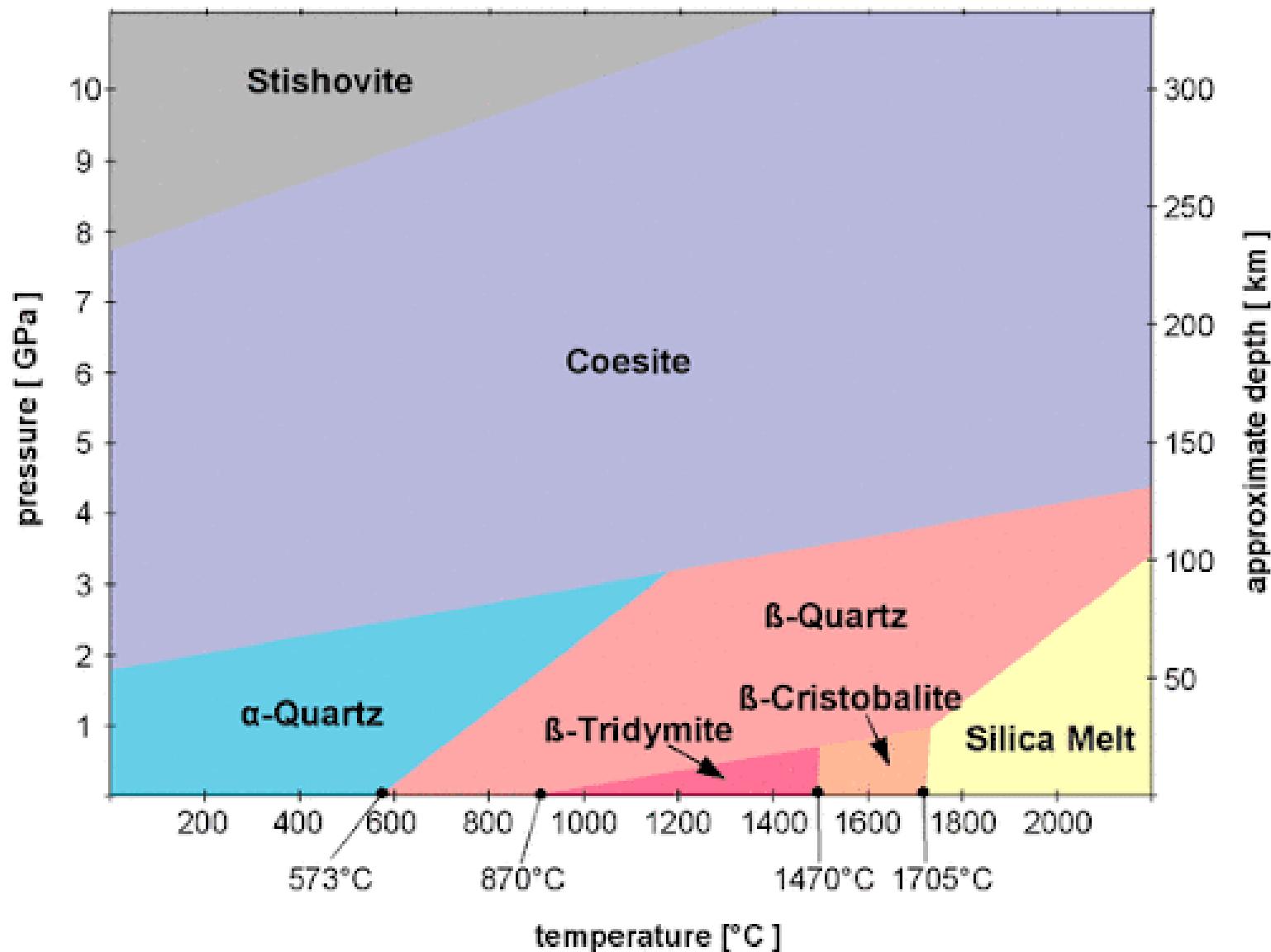
➤ **Simple substitution:**

Olivine $(\text{Mg}, \text{Fe})\text{SiO}_4$: Forsterite (Mg_2SiO_4)-Fayalite (Fe_2SiO_4) end members

- The structure is viewed down the a-axis
- Octahedral M-sites or occupied by Mg^{2+} or Fe^{2+}
- The shaded wedge shown on M-sites represents the occupation of Fe^{2+} . In this case 22%.



Polymorphism: SiO_2



Polymorphism: SiO₂

Meteor Crater, also known as Barringer Crater (Arizona, USA)

https://en.wikipedia.org/wiki/Meteor_Crater



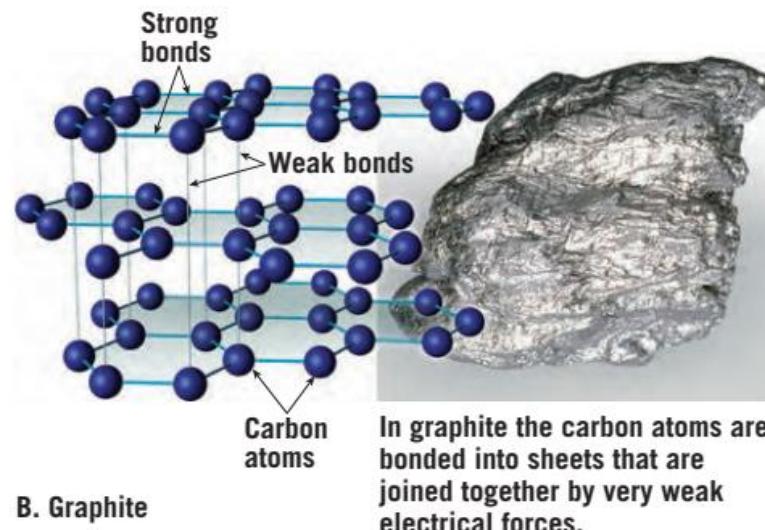
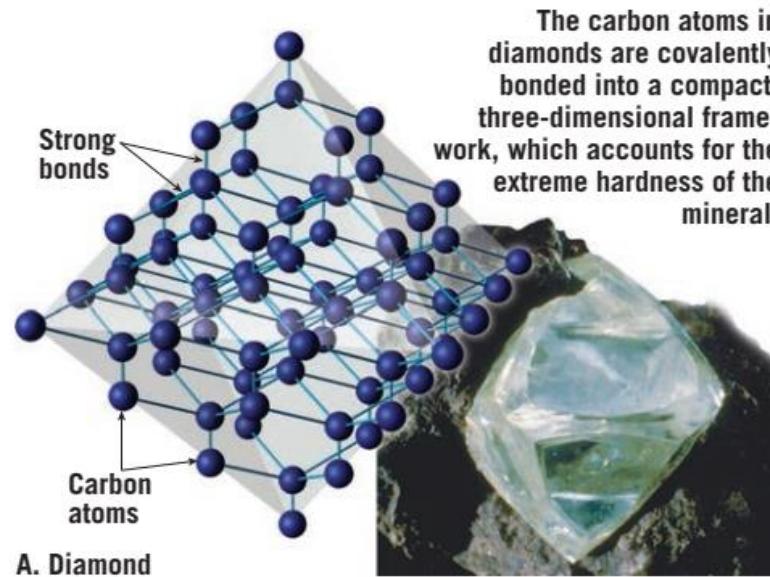
Impact crater/structure	
Confidence	Confirmed <small>[1]</small>
Diameter	0.737 miles (1.186 km)
Depth	560 feet (170 m)
Rise	148 feet (45 m)
Impactor diameter	160 feet (50 m)
<u>Age</u>	50,000 years

Polymorphism: Carbon

Figure 3.29

Diamond versus graphite

Both diamond and graphite are natural substances with the same chemical composition: carbon atoms. Nevertheless, their internal structures and physical properties reflect the fact that each formed in a very different environment. (Photo A Marcel Clemens/Shutterstock; photo B by E. J. Tarbuck)



Polymerism

Table 4.4 Common Polymorphic Mineral Groups

Chemical Composition	Mineral Name
SiO_2	α -Quartz
	β -Quartz
	α -Tridymite
	β -Tridymite
	Cristobalite
	Coesite
	Stishovite
FeS_2	Pyrite
	Marcasite
C	Graphite
	Diamond
AlAlOSiO_4	Andalusite
	Sillimanite
	Kyanite
KAlSi_3O_8	Sanidine
	Orthoclase
	Microcline