Earth and Planetary Sciences (ES1101)

(Minerals: Building Blocks of Rocks)
(Autumn 2020 by Gaurav Shukla)

Book: **1) Understanding Earth by Grotzinger & Jordan (Text Book)**
2) Earth: An introduction to Physical Geology by Tarbuck & Lutgens
3) The Solid Earth: An introduction to global geophysics by Fowler

What are minerals?

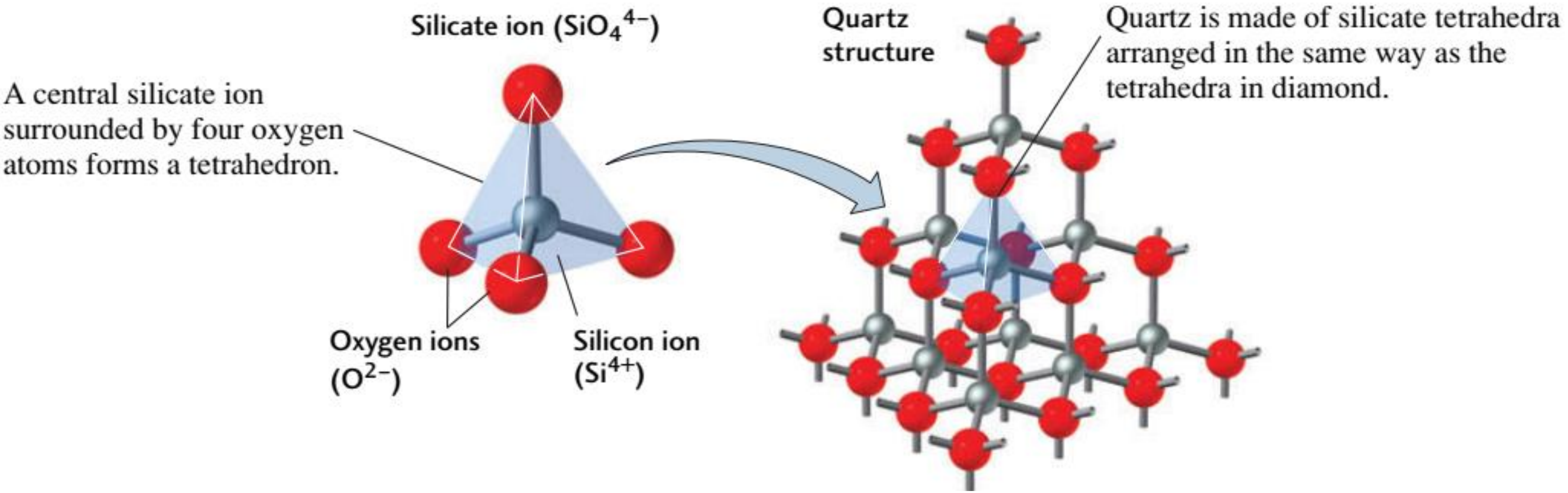
- Minerals are building blocks of rocks.

- 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.

Definition of Minerals:

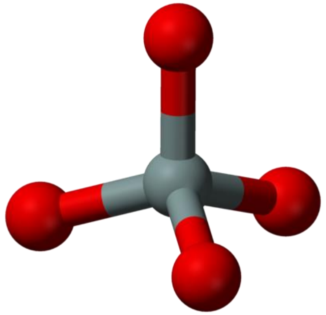
A mineral is a naturally occurring crystalline (inorganic) solid with a definite, but not necessarily a fixed, chemical composition.

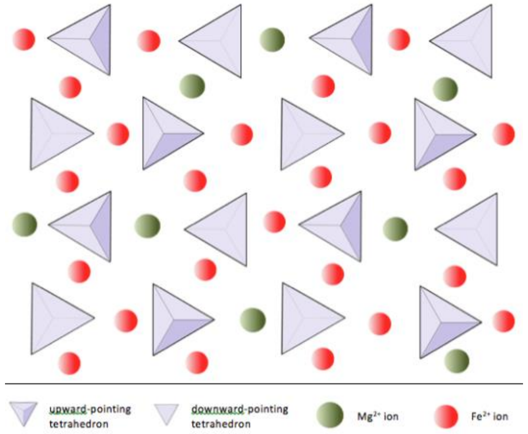


Definition of Minerals:

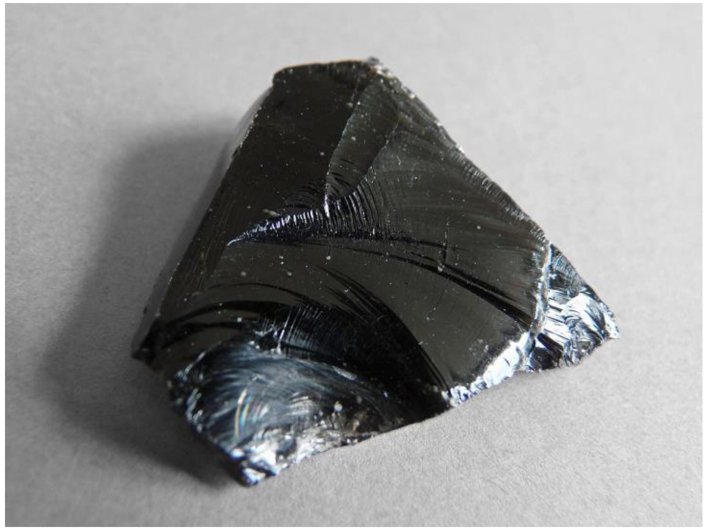
OLIVINE (M_2SiO_4); M : Fe^{2+}, Mg^{2+}
M:Si:O = 2:1:4

Definite BUT NOT NECESSARILY FIXED CHEMICAL COMPOSITION





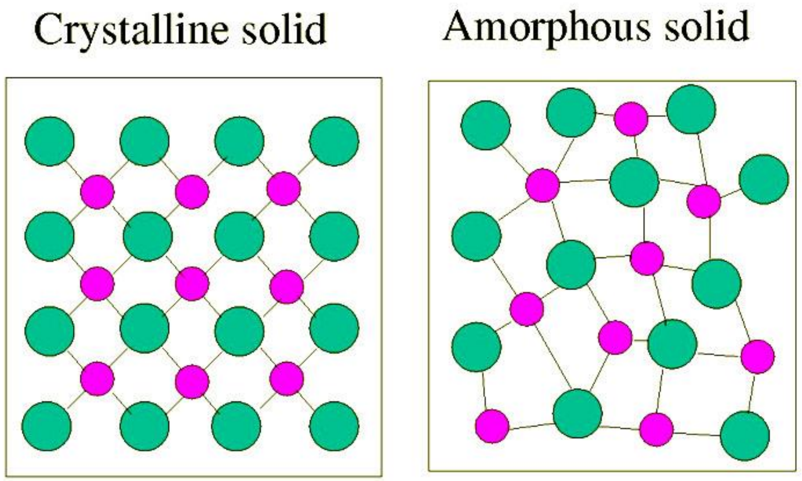
Definition of Minerals:



Volcanic GLASS (obsidian)

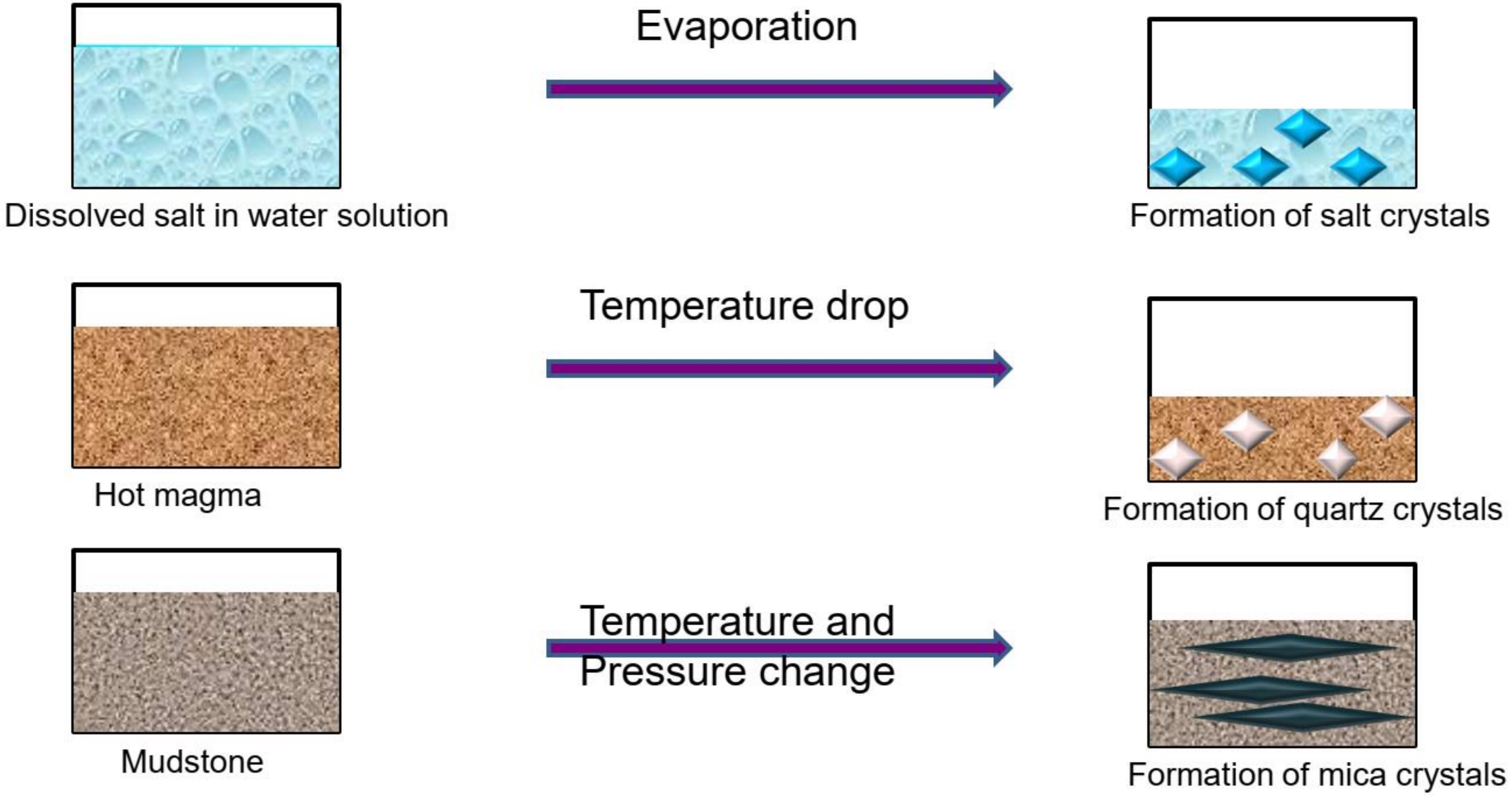
Criteria to be fulfilled

- Naturally occurring
- **Regular arrangement of atoms X**
- Solid
- **Definite chemical composition X**



How do minerals form?

Minerals form through crystallization. The molecules, or ions chemically bond to form an orderly structure.



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.

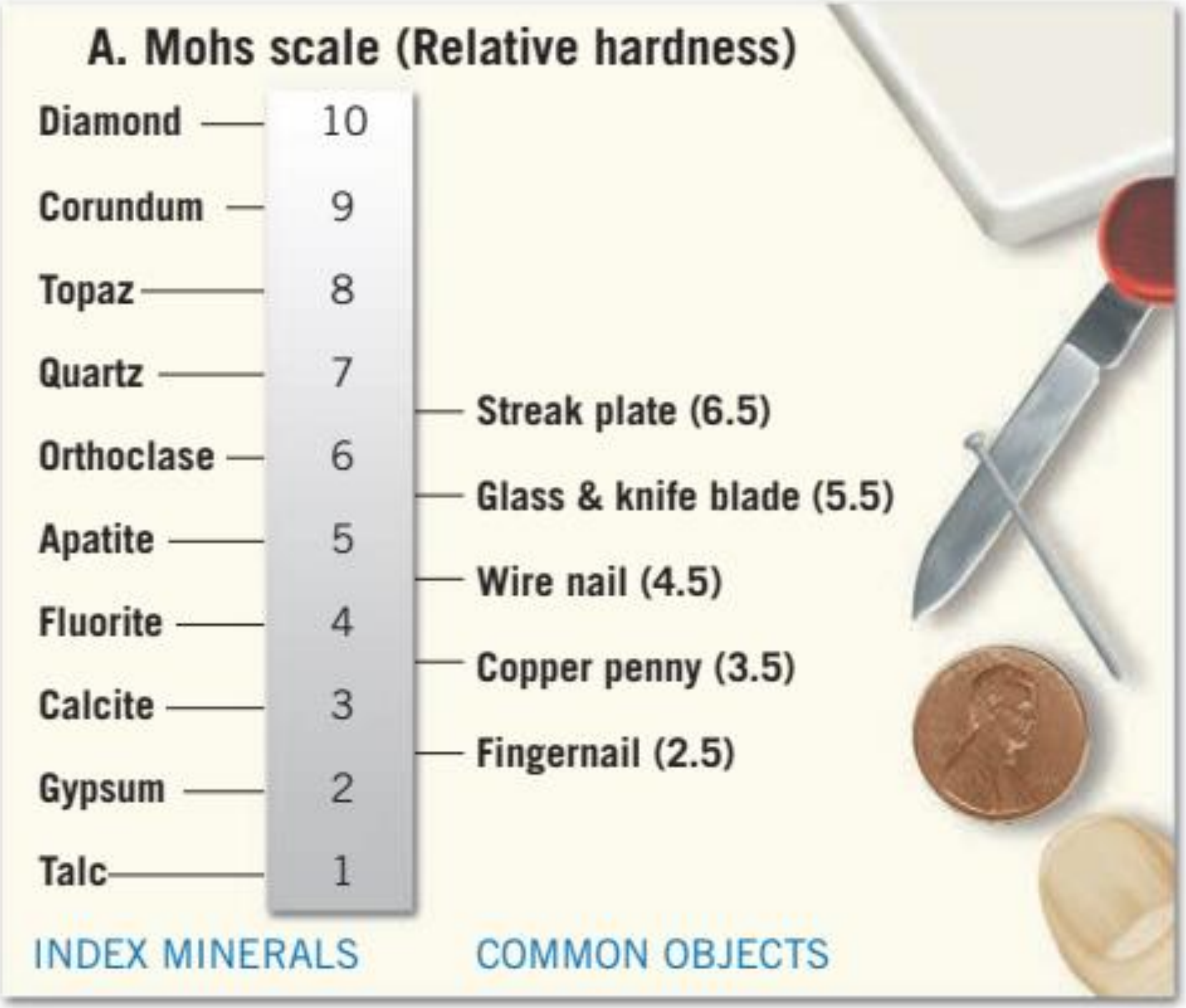
Mineral Properties

Optical Properties:

- **Color**
- **Streak**
- **Luster**

Mineral Properties

Hardness: Mohs scale of hardness



Mineral Properties

Shape

Bladed kyanite

Botryoidal hematite

Prismatic quartz

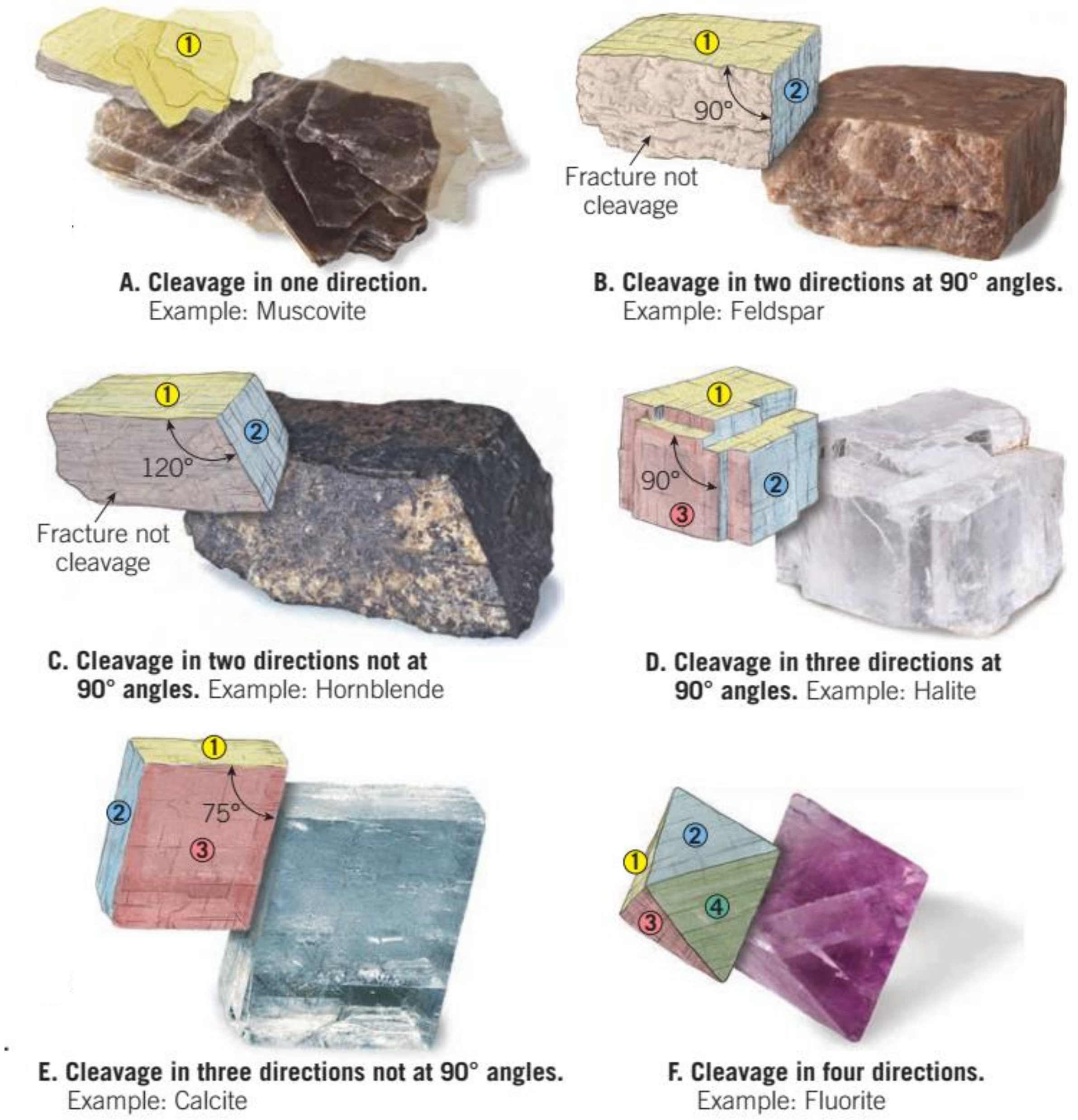
Banded agate

Fibrous okenite

Mineral Properties

Cleavage

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



Mineral Properties (Optical)

Color

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.

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.**

Structure of Minerals

Most abundant elements in the crust

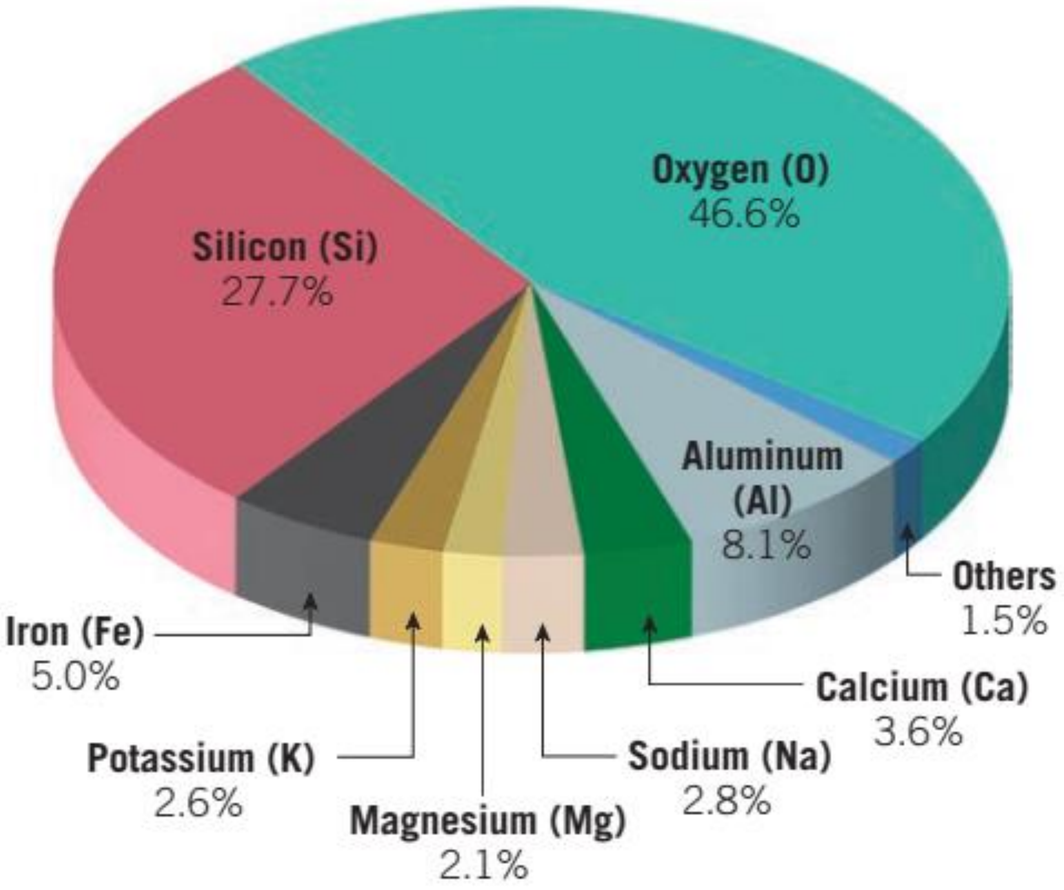


Figure 3.30
The eight most abundant elements in the continental crust

Structure of Minerals

Radii of the most relevant cations and anions

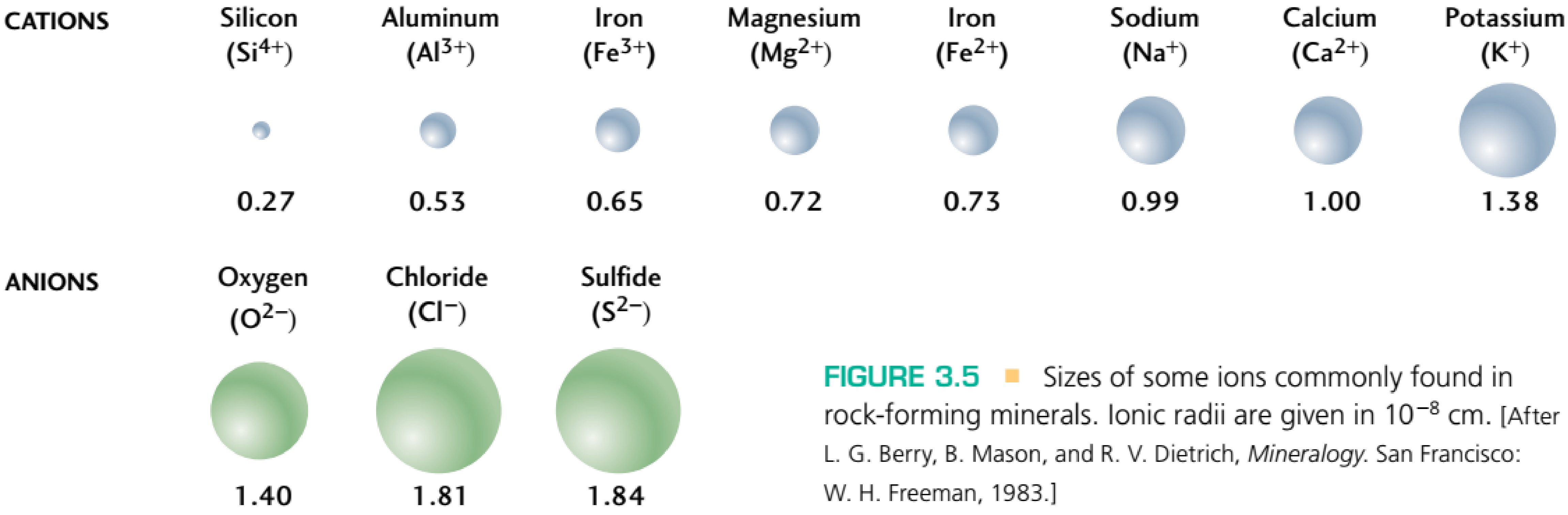


FIGURE 3.5 Sizes of some ions commonly found in rock-forming minerals. Ionic radii are given in 10^{-8} cm. [After L. G. Berry, B. Mason, and R. V. Dietrich, *Mineralogy*. San Francisco: W. H. Freeman, 1983.]

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

Structure of Minerals

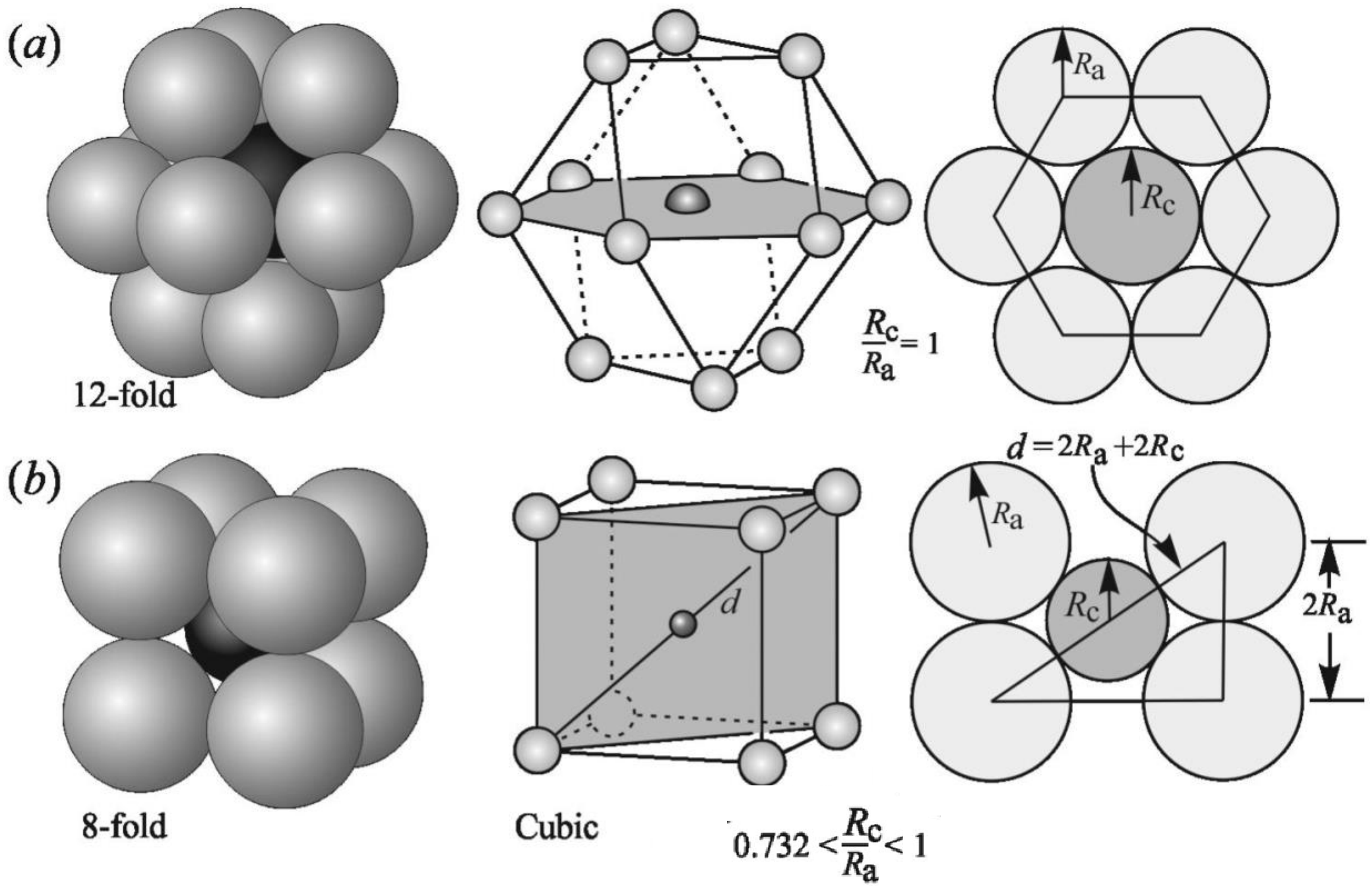
Radii of the most relevant cations and anions

Table 4.2 Cation Sizes Appropriate for Regular Coordination Polyhedra When Coordinating with O^{2-} (~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

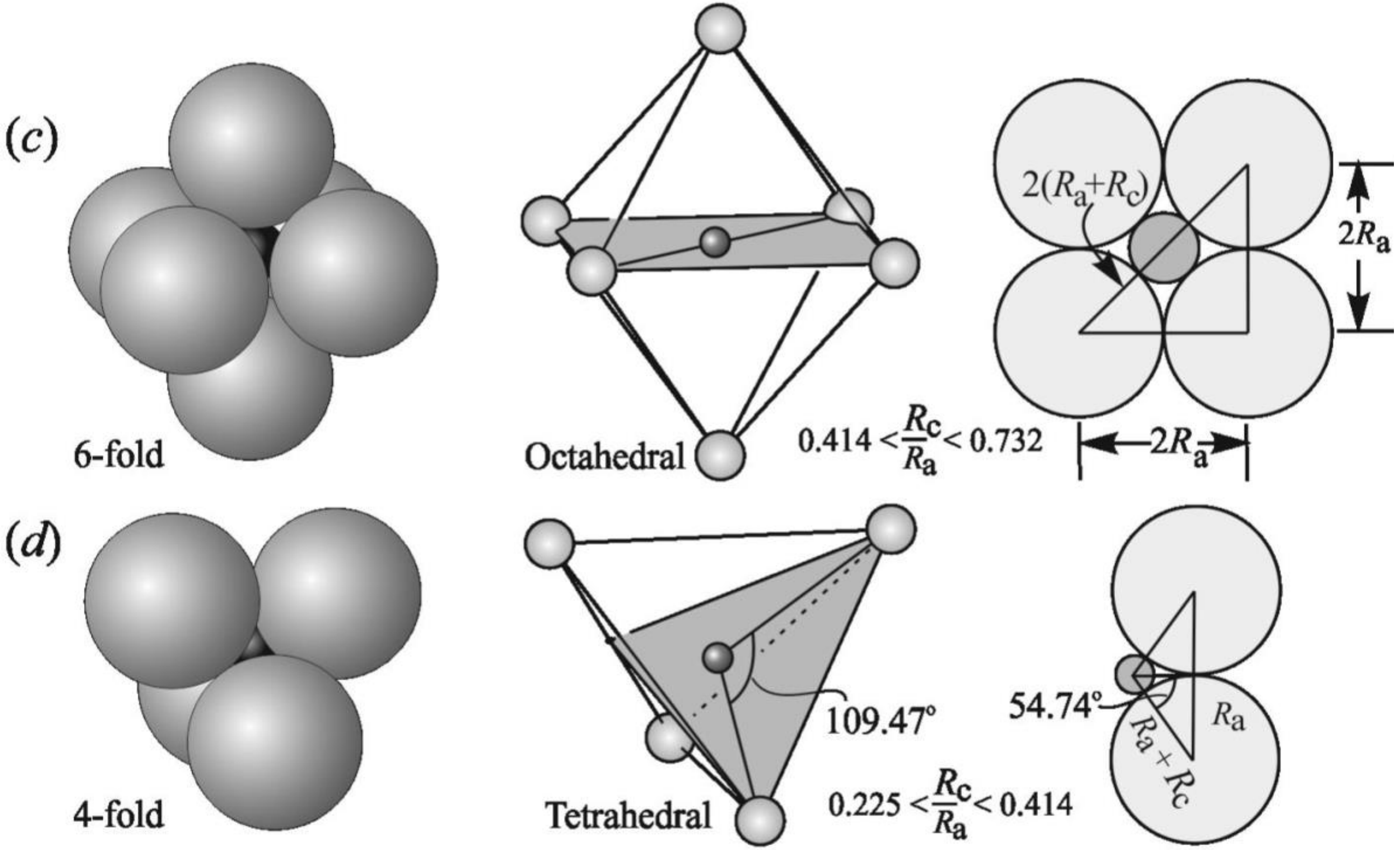
Structure of Minerals

Radius ratio and coordination number (contd)



Structure of Minerals

Radius ratio and coordination number (contd)



Structure of Minerals

Radius ratio and coordination number

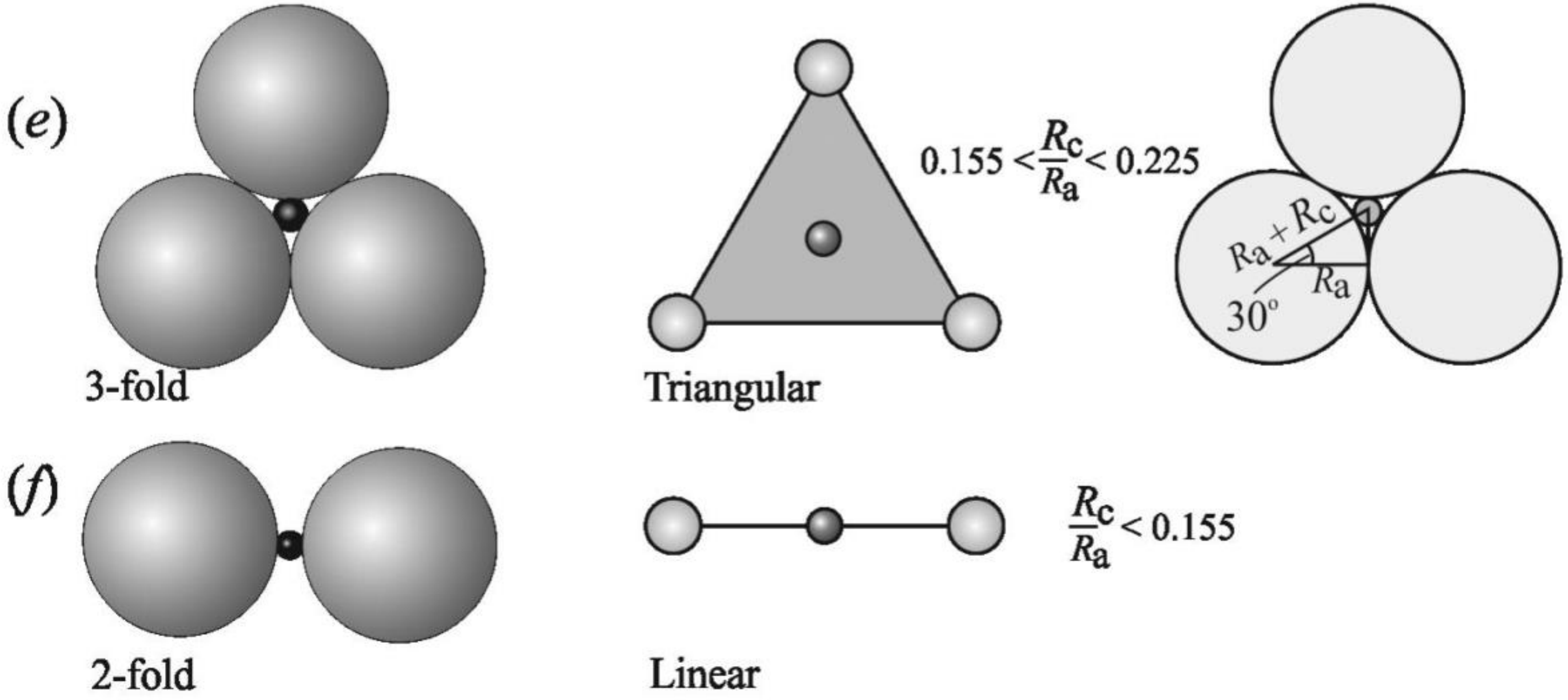
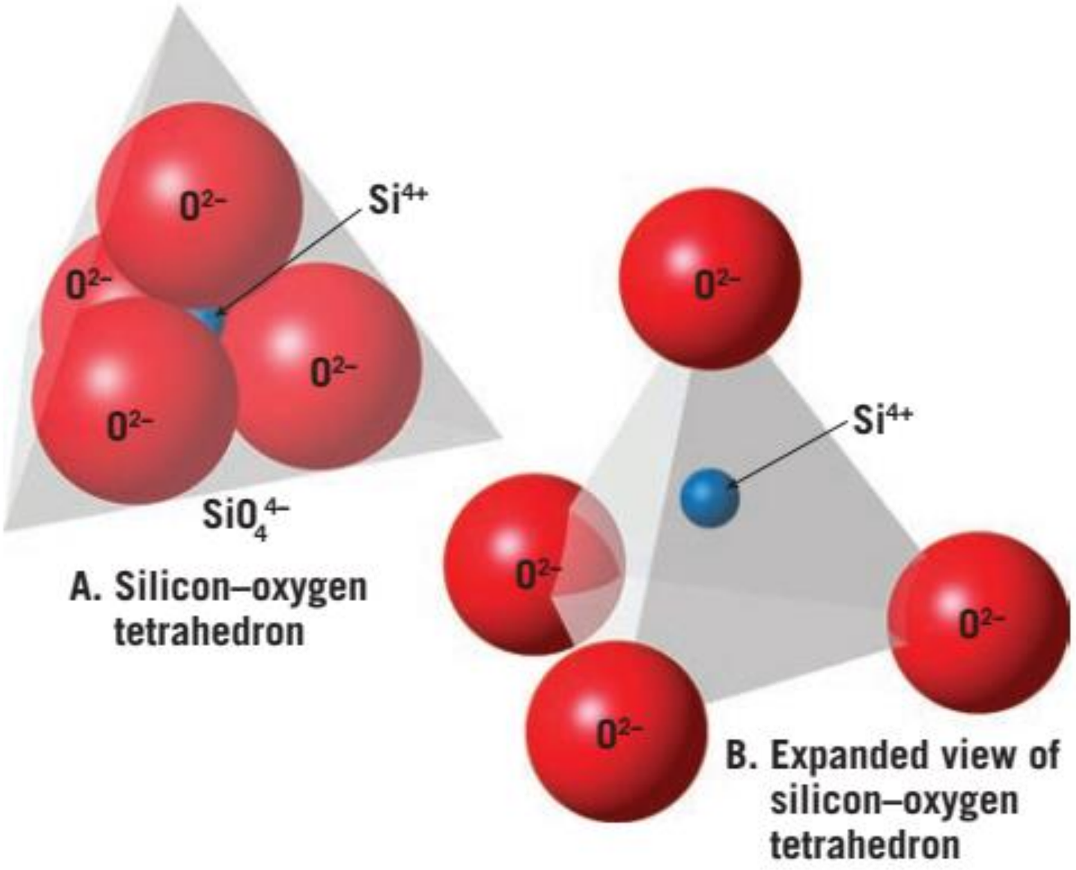
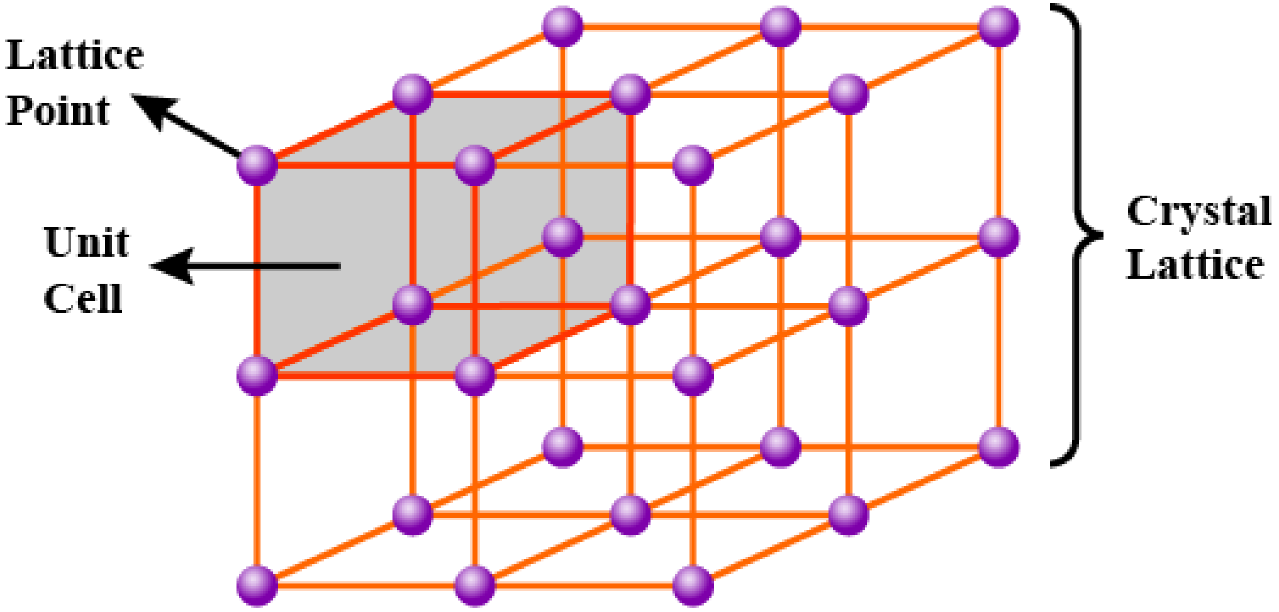


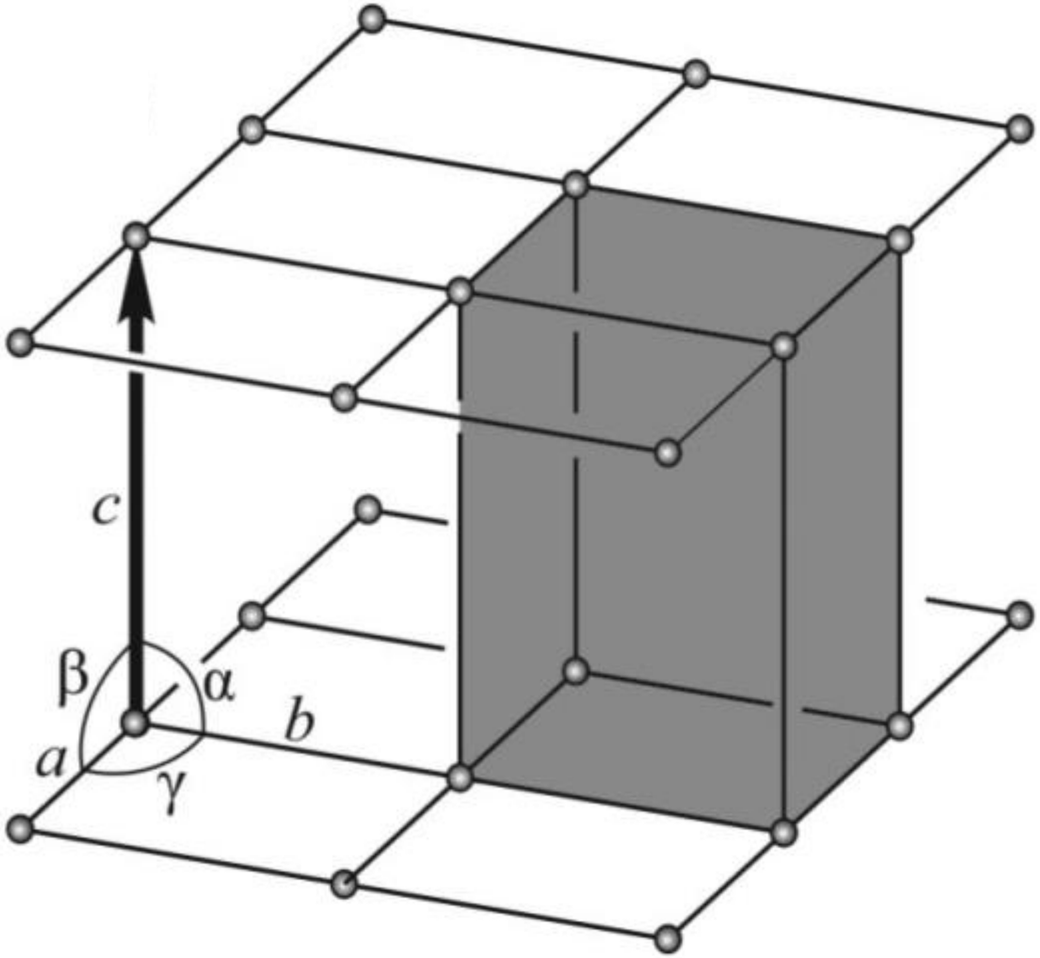
Figure 4.4 Coordination polyhedra. Anions with radius R_a are shown with light shading, cations with radius R_c with dark. Left view shows cation and anions drawn to scale. Center view shows the coordination polyhedra. Right view shows the plane through the polyhedron (shaded in center view) from which 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.

Silicon-Oxygen Tetrahedra

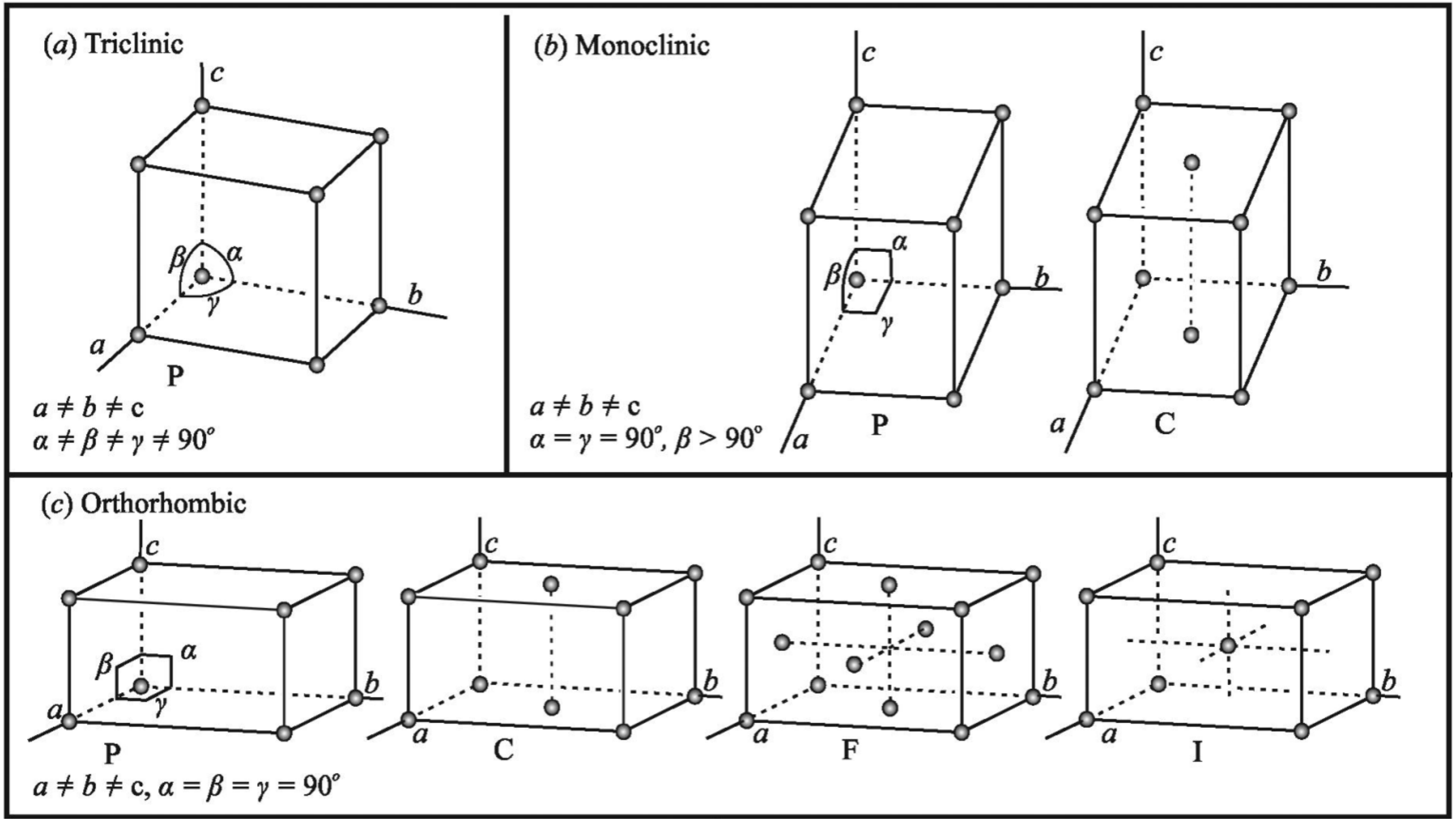


Crystallography of Minerals

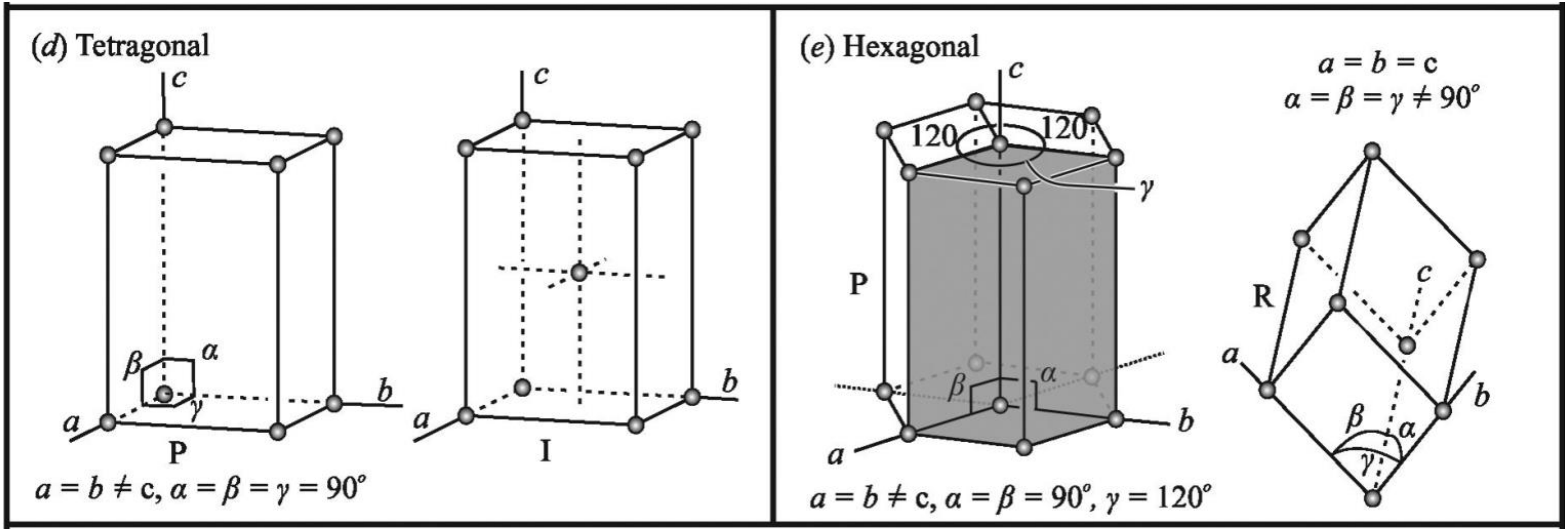




Crystallography of Minerals



Crystallography of Minerals



Crystallography of Minerals

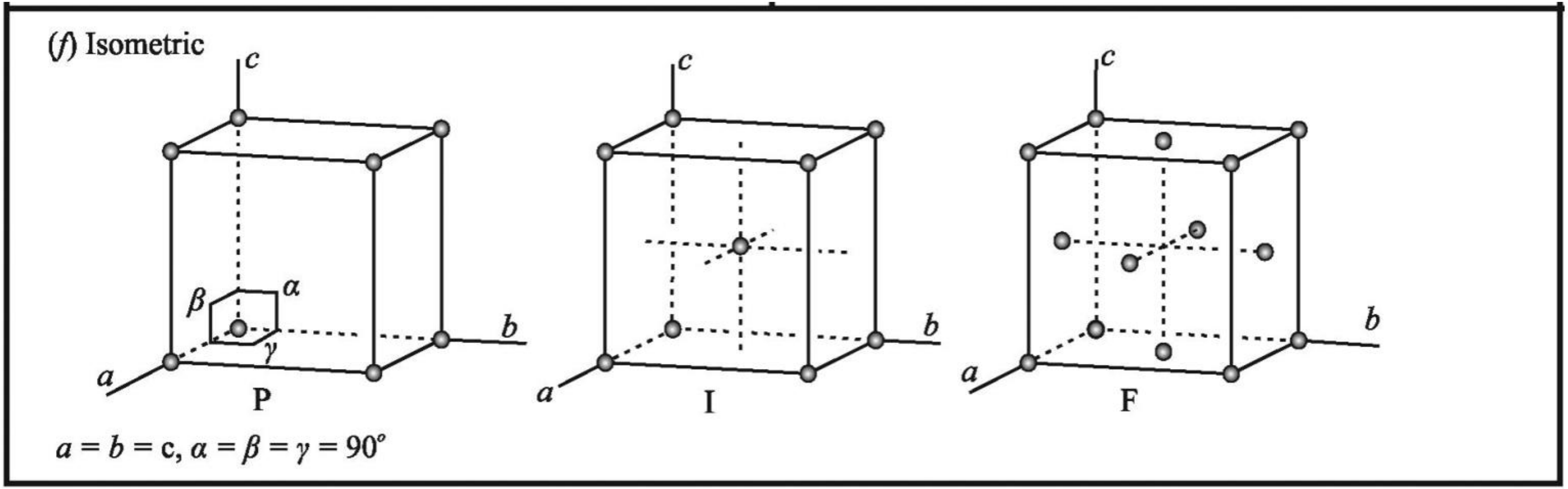


Figure 2.10 The 14 Bravais lattices define six different three-dimensional volumes (*a–f*) that correspond to the unit cells of the six crystal systems. The lengths of the three unit cell axes are *a*, *b*, and *c*, and the angles between them are *α*, *β*, and *γ*. In the notations, the ≠ sign indicates 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.

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.**

Minerals Classification

TABLE 3-1 Some Chemical Classes of Minerals

Class	Defining Anions	Example
Native elements	None: no charged ions	Copper metal (Cu)
Oxides	Oxygen ion (O^{2-})	Hematite (Fe_2O_3)
Halides	Chloride (Cl^-), fluoride (F^-), bromide (Br^-), iodide (I^-)	Halite (NaCl)
Carbonates	Carbonate ion ($CO_3{}^{2-}$)	Calcite ($CaCO_3$)
Sulfates	Sulfate ion ($SO_4{}^{2-}$)	Anhydrite ($CaSO_4$)
Silicates	Silicate ion ($SiO_4{}^{4-}$)	Olivine $(Mg,Fe)_2SiO_4$
Sulfides	Sulfide ion (S^{2-})	Pyrite (FeS^2)

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	 A. Calcite, B. Dolomite
Halides (Cl^{1-}, F^{1-}, Br^{1-})	Halite Fluorite Sylvite	$NaCl$ CaF_2 KCl	Common salt Used in steelmaking Used as fertilizer	 C. Halite, D. Fluorite
Oxides (O^{2-})	Hematite Magnetite Corundum Ice	Fe_2O_3 Fe_3O_4 Al_2O_3 H_2O	Ore of iron, pigment Ore of iron Gemstone, abrasive Solid form of water	 E. Hematite, F. Magnetite
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	 G. Galena, H. Chalcopyrite
Sulfates (SO_4^{2-})	Gypsum Anhydrite Barite	$CaSO_4 \cdot 2H_2O$ $CaSO_4$ $BaSO_4$	Plaster Plaster Drilling mud	 I. Gypsum, J. Anhydrite
Native elements (single elements)	Gold Copper Diamond Graphite Sulfur Silver	Au Cu C C S Ag	Trade, jewelry Electrical conductor Gemstone, abrasive Pencil lead Sulfadrugs,chemicals Jewelry, photography	 K. Copper, L. Sulfur

Minerals Classification

Nonsilicate Minerals: Calcite

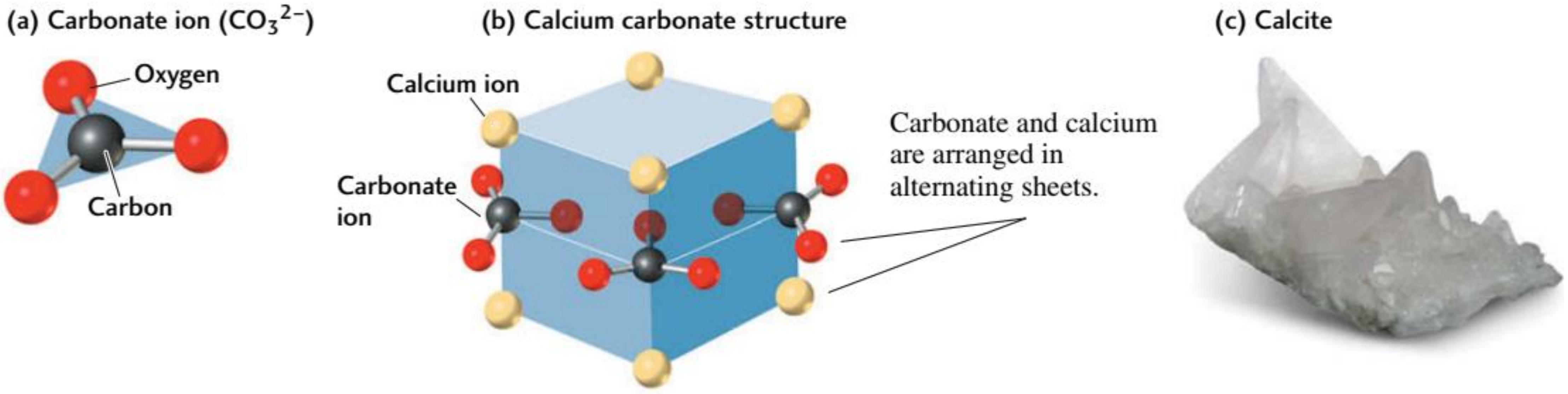


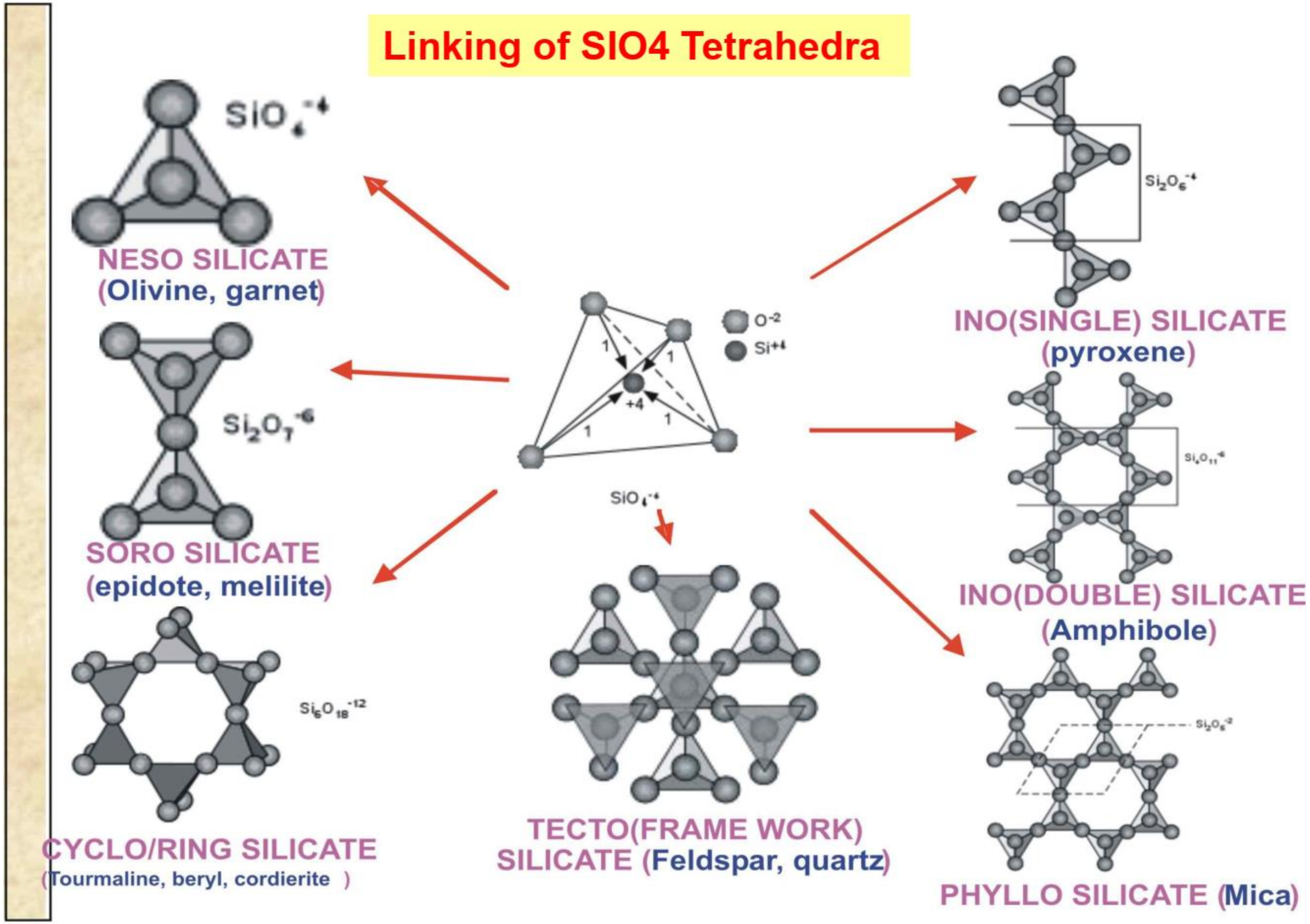
FIGURE 3.12 ■ Carbonate minerals, such as calcite (calcium carbonate, $CaCO_3$), have a layered structure. (a) Top view of the carbonate ion, composed of a carbon ion surrounded by three oxygen ions in a triangle. (b) View of the alternating layers of calcium and carbonate ions in calcite. (c) Calcite.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

Minerals Classification

Nonsilicate Minerals: Pyrite

FIGURE 3.14 ■ Pyrite, a sulfide mineral, is also known as "fool's gold." [John Grotzinger/Ramón Rivera-Moret/Harvard Mineralogical Museum.]

Minerals Classification: Silicate Minerals



Minerals Classification: Silicate Minerals

Table 11.1 Silicate Classification[a]

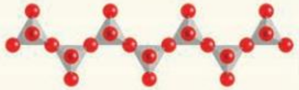
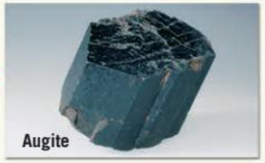
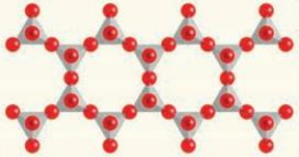
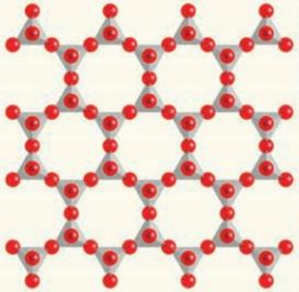
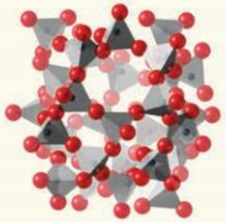
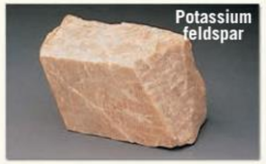
Silicate Class	Number of O^{2-} Shared per Tetrahedron	Z:O Ratio	Structural Configuration
Orthosilicates	0	1:4	Isolated tetrahedra
Disilicates	1	2:7	Double tetrahedra
Ring silicates	2	1:3	Rings of tetrahedra
Chain silicates			Chains of tetrahedra
Single chain	2	1:3	
Double chain	2 or 3	4:11	
Sheet silicates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

[a] Z refers to the cation(s), usually Si^{4+}, and also Al^{3+}, that occupy the tetrahedral sites.

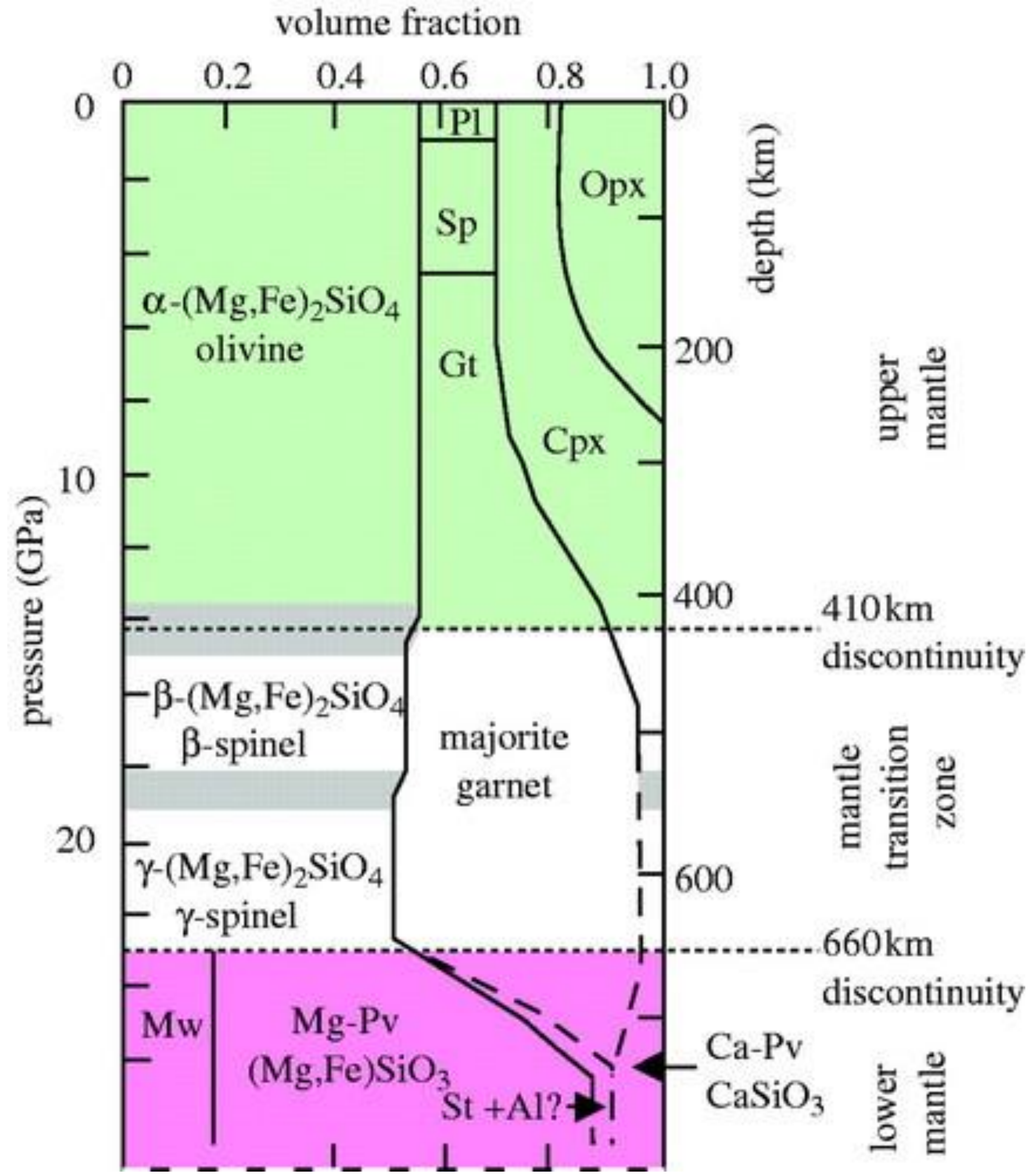
Minerals Classification:

Silicate Minerals

Common Silicate Minerals and Mineral Groups

	Mineral/Formula	Cleavage	Silicate Structure	Example
	Olivine group $(Mg,Fe)_2SiO_4$	None	**Single tetrahedra** 	
	Pyroxene group (Augite) $(Mg,Fe,Ca,Na)AlSiO_3$	Two planes at 90°	**Single chains** 	
	Amphibole group (Hornblende) $Ca_2(Fe,Mg)_5Si_8O_{22}(OH)_2$	Two planes at 60° and 120°	**Double chains** 	
Micas	**Biotite** $K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	One plane	**Sheets** 	
Micas	**Muscovite** $KAl_2(AlSi_3O_{10})(OH)_2$	One plane		
Feldspars	**Potassium feldspar (Orthoclase)** $KAlSi_3O_8$	Two planes at 90°	**Three-dimensional networks** 	
Feldspars	**Plagioclase** $(Ca,Na)AlSi_3O_8$	Two planes at 90°		
	Quartz SiO_2	None		

Phase Transitions in Olivine



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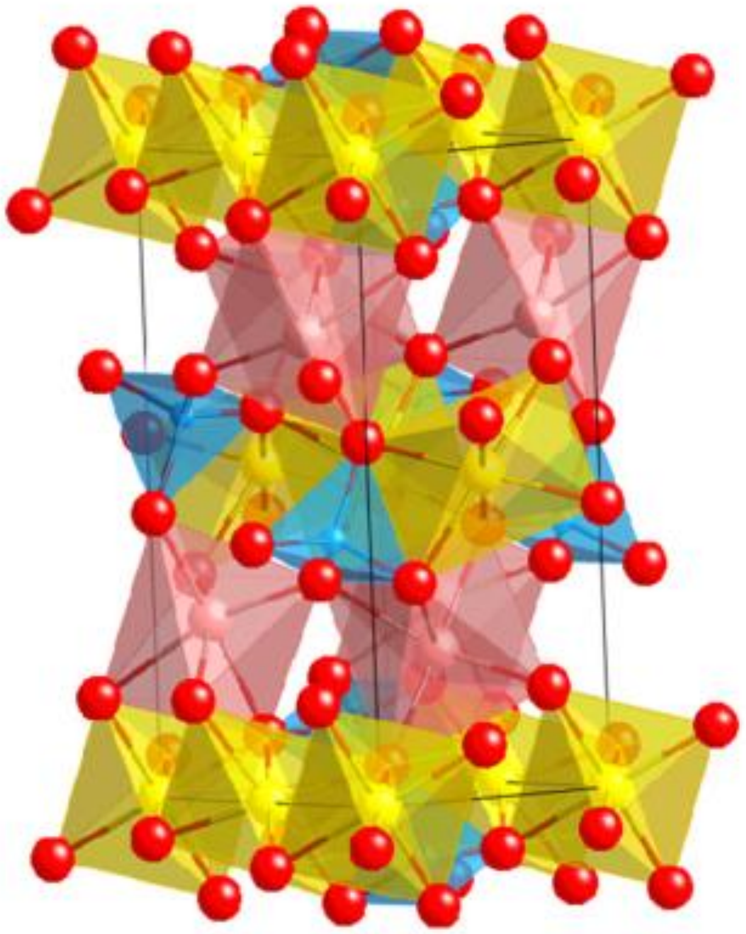
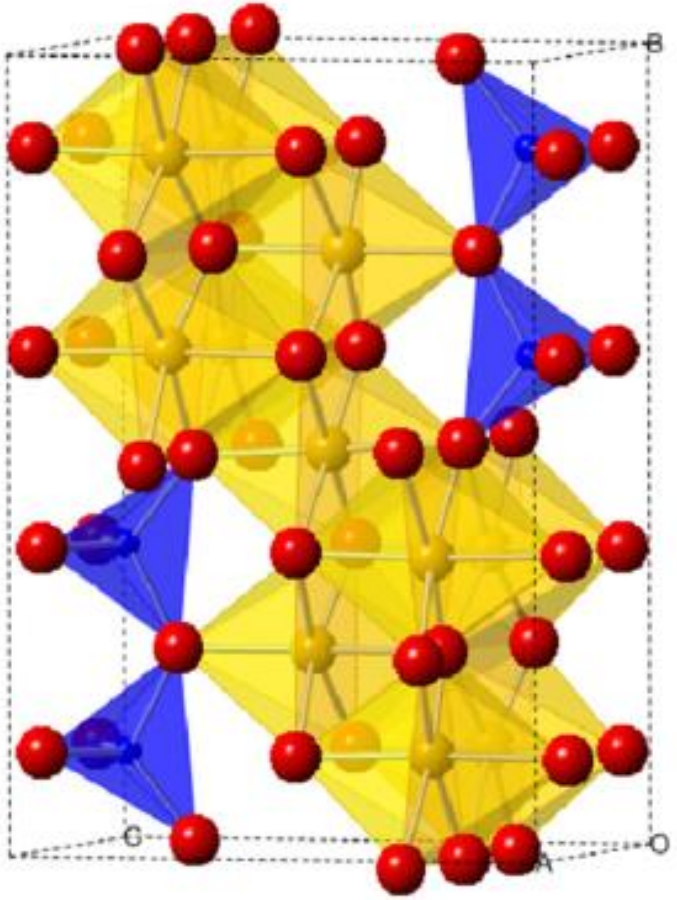
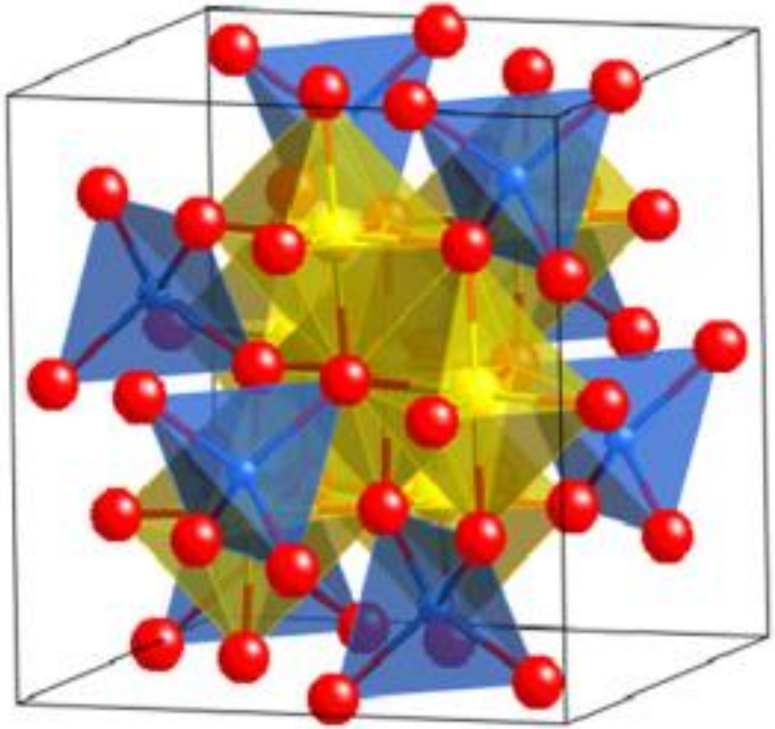
Phase Transitions in Olivine



olivine

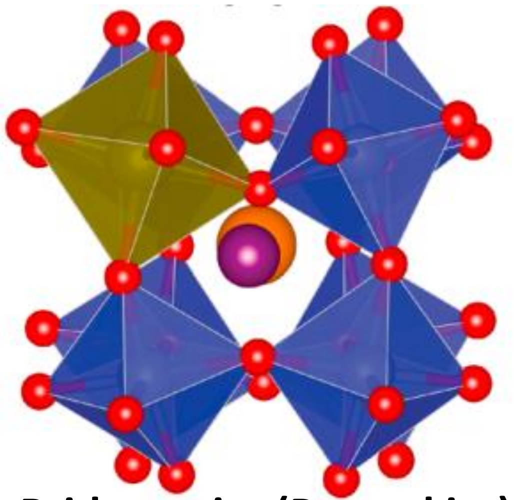


wadsleyite

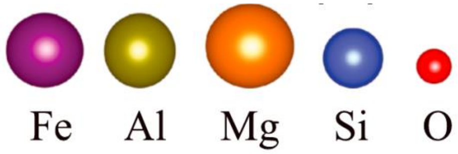


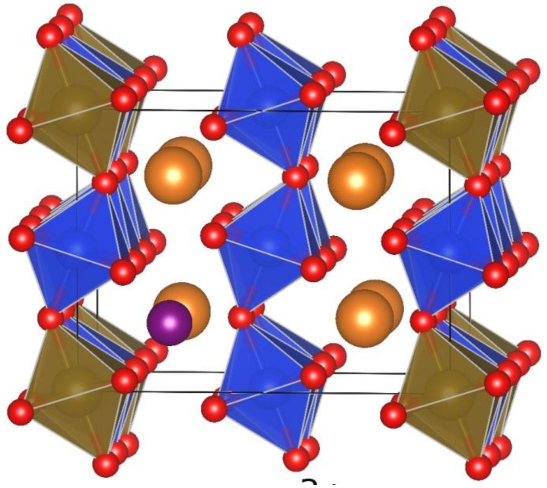
ringwoodite

Phase Transitions in Bridgmanite



Bridgmanite (Perovskite), Orthorhombic





Post-perovskite, Orthorhombic (expected to be in the D'' region)