Earth's Building Materials: From Atoms to Elements, Minerals, and Rocks

Summary

- The nucleus of an atom contains protons (positive electrical charge) and neutrons (no electrical charge).
- Moving in orbitals around the nucleus are electrons (negative electrical charge). The positive electrical charge on a proton is equal but opposite to the negative charge on an electron. The number of protons in a nucleus is the atomic number of an element.
- Orbital electrons have different energy levels, and the number of electrons that can occupy a specific energy-level shell is fixed: 2 in shell 1, 8 in shell 2, 18 in shell 3, 32 in shell 4.
- The forces that hold atoms together in minerals are called bondings, and there are four different kinds of bondings.
- Ionic bondings arise when atoms transfer to, or accept orbital electrons from, other atoms.

- Covalent bondings involve the sharing of electrons between atoms.
- Metallic bondings involve the sharing of electrons in higher energy-level shells between several atoms.
- Van der Waals bondings are weak, secondary attractions that form as a result of the sharing or transfer of electrons.
- Minerals are naturally formed, inorganic solids that have a definite composition and a specific crystal structure.
- Minerals can be either chemical elements, such as sulfur and diamond, or compounds of two or more chemical elements.
- The compositions of some minerals vary because of ionic substitution, whereby one ion in a crystal structure can be replaced by another ion having a like electrical charge and a like ionic radius.

- Some compounds have the same composition but different crystal structures. Each structure is a separate mineral. Minerals that have the same compositions but different structures are called polymorphs.
- The principal properties used to characterize and identify minerals are crystal form, growth habit, cleavage, luster, color and streak, hardness, and specific gravity.
- Approximately 4000 minerals are known, but of these only about 20 are commonly encountered. The common 20 make up more than 95 percent of the Earth's crust.
- Silicates are the most abundant minerals, followed by oxides, carbonates, sulfides, sulfates, and phosphates.
- The basic building block of silicate minerals is the silicate tetrahedron, a complex anion in which a silicon atom is covalently bonded to four oxygen atoms.

- The four oxygen ions sit at the apexes of a tetrahedron, with the silicon at its center. Adjacent silicate tetrahedra can bond together to form larger complex anions by sharing one or more oxygens. The process is called polymerization.
- The feldspars are the most abundant group of minerals in the continental crust, comprising approximately 60 percent of the volume.
- Quartz is the second most common mineral in the continental crust.
- Other silicate and non-silicate mineral groups were discussed.
- Rocks are grouped into three families according to the way they are formed. We rarely observe rocks being formed, however, so rocks are usually described in terms of their textures and mineral assemblages.
- Igneous rocks, or metamorphic rocks derived from igneous rocks, account for 95 percent of all rocks in the Earthís crust; sedimentary rocks account for 5 percent.

Background Material

- Atomic structure
  - Protons, neutrons, electrons
  - Electronic orbitals
    - Electronic structure and energy levels
    - Valence electrons
  - Atomic number and mass
    - Isotopes: same # or protons, different # of neutrons
      - carbon six protons, 6,7, or 8 neutrons: ^{12}C, ^{13}C, ^{14}C
  - Ions: add or loose electrons to fill shells
    - Cations: missing electrons, extra positive charge, small
    - Anions: added electrons, negative charge, larger

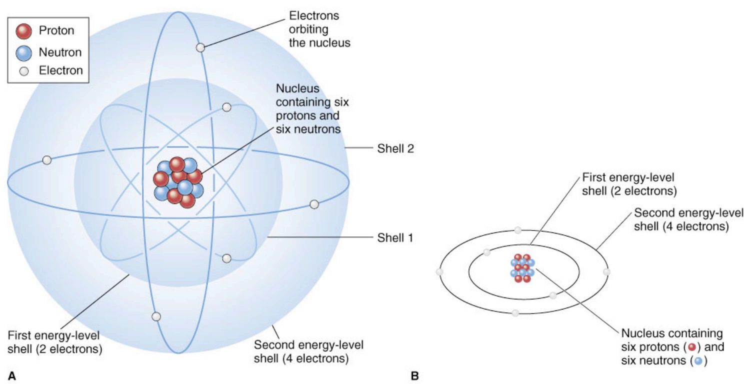
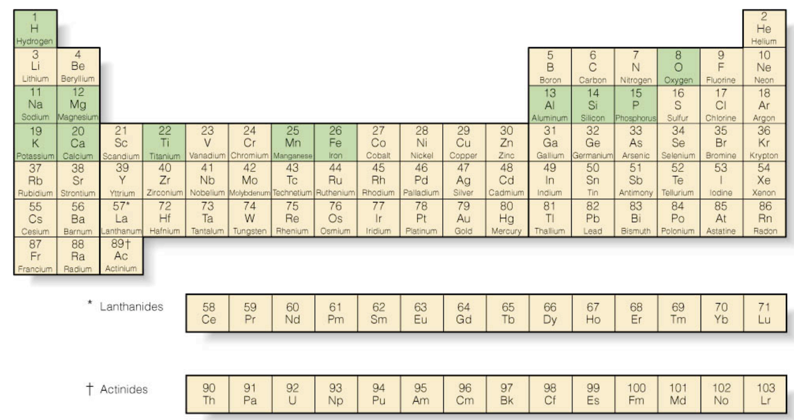


Figure 3.1



Elements present in continental crust in amounts equal to or greater than 0.1% weight.

Figure 3.6

Molecules, Compounds, Bonds

•Molecule: smallest unit with the distinctive chemical properties of a compound.
•Ionic bonding: electron transfers between atoms produce cations and anions
  •Na^+ and Cl^- form NaCl
•Covalent bonding: shared electrons in modified orbitals
  •strong bond – diamond is example
•Metallic bonding: some electrons become delocalized
  •No longer in orbital around a specific atom
  •high electrical conductivity
•Van der Waals bonding: weak secondary attraction
  •Graphite and talc

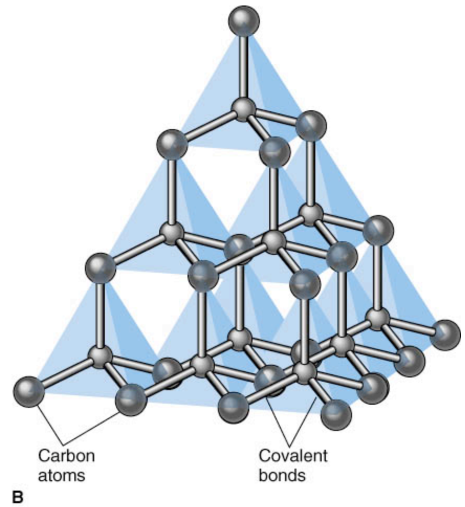


Figure 3.3 B

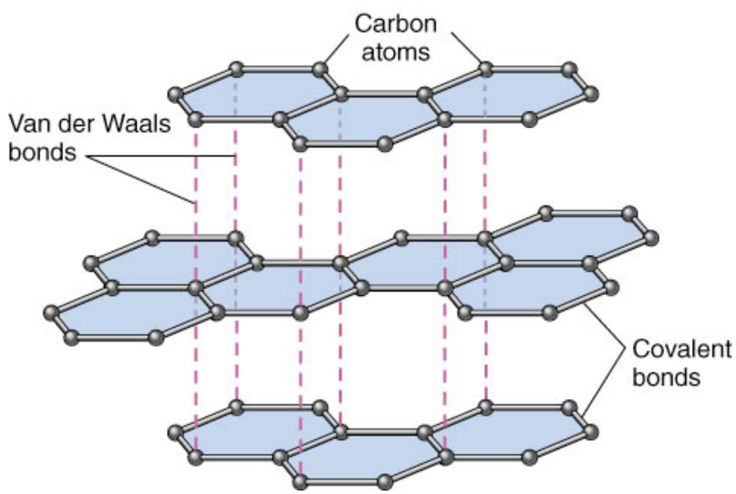


Figure 3.5

Complex Ions

- Two or more kinds of ions form such strong covalent bonds that the combined atoms act as if they were a single entity.
- Such a strongly bonded unit is called a complex ion.
  - Calcite ($CaCO_3$) -> Ca^{+2} and CO_3^{-2}
  - Gypsum ($CaSO_42H_2O$) -> Ca^{+2} and SO_4^{-2} and H_2O
  - Silica: SiO_4^{-4} -> basic building block for silcates

What Is A Mineral?

- **Mineral**
  - **Naturally formed solid material with a specific chemical composition and a characteristic crystalline structure.**
- **Rock**
  - **Naturally formed, coherent mass of one or more minerals.**

Key Characteristics of Minerals

- Minerals have two key characteristics.
  - **Composition:**
    - **The chemical elements that compose a mineral, and their proportions.**
  - **Crystal structure:**
    - **The organized way in which the atoms of the elements are packed together in a mineral.**

Composition of Minerals

- Can be a single element :
  - diamond, graphite, gold, copper, and sulfur.
- Most are compounds, containing more than one element and in some cases a complex ion
  - Halite (salt): $NaCl$
  - Olivine: Mg_2SiO_4
  - Calcite: $CaCO_3$

Crystal Structure

- **Regular, geometric pattern of atoms**
  - **Crystalline.**
- **A lack crystal structure: amorphous.**
  - **glass and amber**
- **Predominantly ionic bonding**
  - **Large ions (the anion) determine the structure**
    - **Cations fill voids between anions**

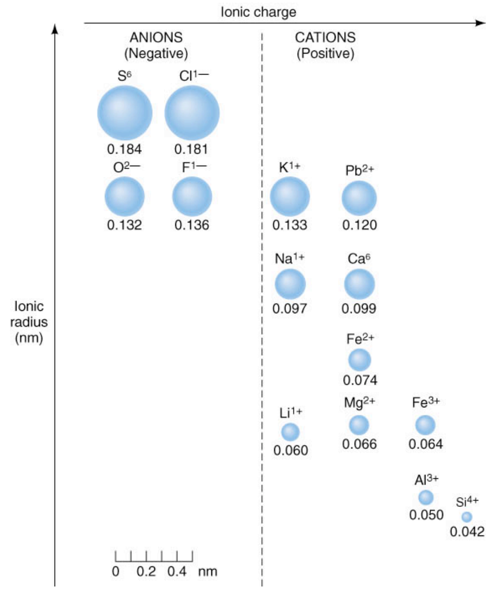


Figure 3.8

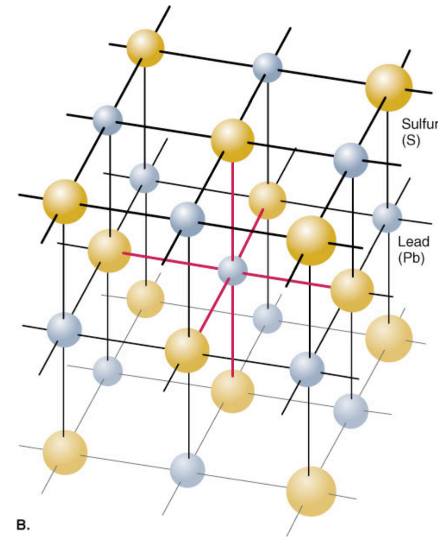


Figure 3.7

Ionic Substitution

- Substitution of one ion for another depends on:
  - Crystal structure
  - Ion size
  - Ion electrical charge.
- Olivine group as an example
  - Mg_2SiO_4 Forsterite, Fe_2SiO_4 Fayalite
    - Mg and Fe fill same void in structure, same charge, almost same size – $(Mg,Fe)_2SiO_4$

Pressure and temperature determines state of matter

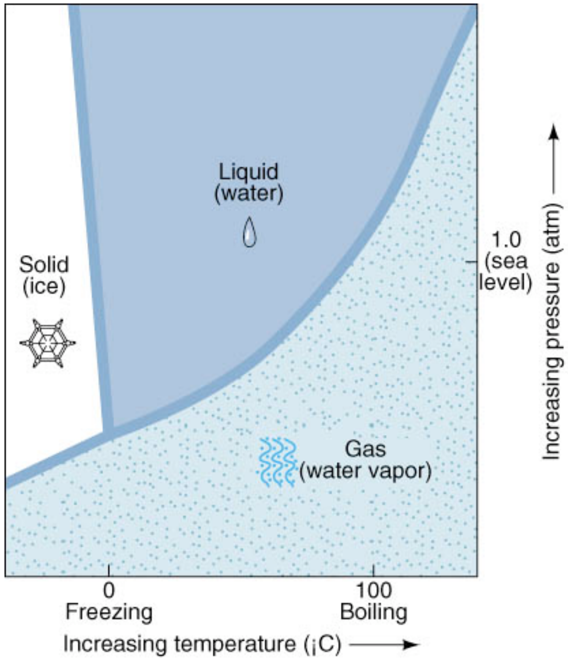


Figure B3.1

Crystal Form

- Crystal form
  - Crystal: any solid body that grows with planar surfaces.
  - The interfacial angle in any crystalline structure remains constant.

Growth Habit and Polymorphism

- Growth habit:
  - The characteristic crystal form of each mineral.
- Polymorphism:
  - Some elements and compounds form two or more different minerals:
  - C Graphite, Diamond
  - $CaCO_3$ Calcite, Aragonite
  - FeS_2 Pyrite, Marcasite
  - SiO_2 Quartz, Cristobalite
- Metastability:
  - diamond at low pressure, cristobalite at low T

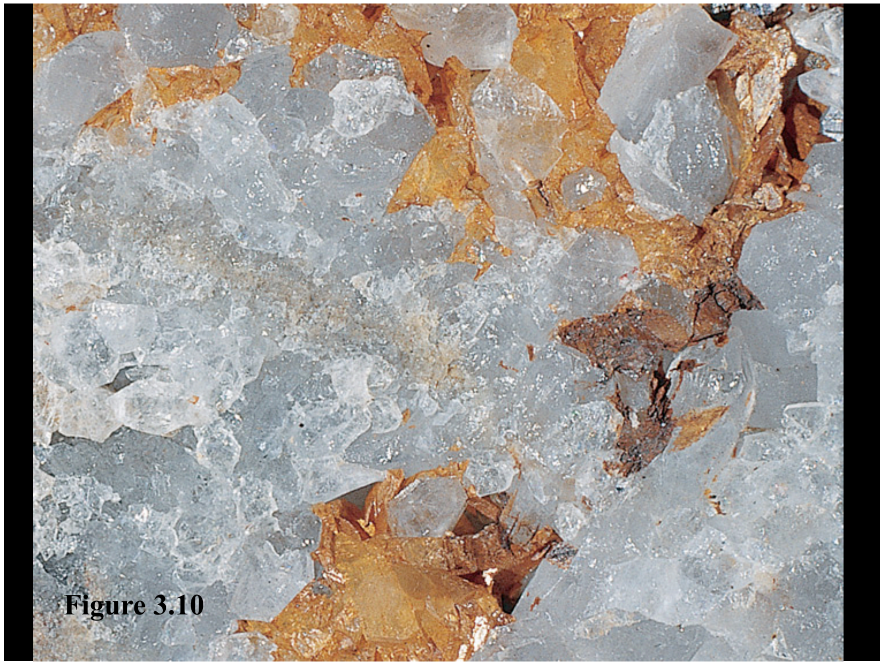


Figure 3.10

Figure 3.12

Cleavage

- Cleavage: tendency to break in preferred directions along bright, reflective planar surfaces.
- A cleavage surface: breakage surface
- Directions along which cleavage occurs are governed by the crystal structure.
  - They are planes along which the bonding between atoms is relatively weak.

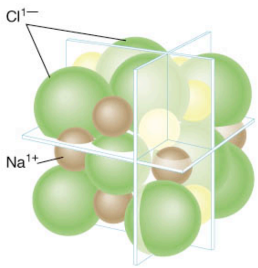


Figure 3.13

Luster

- The quality and intensity of light reflected from a mineral.
- The most important lusters are:
  - Metallic (polished metal surface).
  - Vitreous (glass).
  - Resinous (resin): the look of dried glue or amber.
  - Pearly (pearl): the iridescent look of a pearl.
  - Greasy (as if the surface were covered by a film of oil).

Color and Streak

- Color is determined by several factors, but chemical composition is often important.
  - Unreliable for identification.
- Streak is the thin layer of powdered material left when a specimen is rubbed on an unglazed ceramic plate.
  - Much more reliable than color for identification.

Figure 3.18

Hardness and the Mohs Scale

- Hardness is a mineral's relative resistance to scratching.
- The Mohs relative hardness scale uses ten minerals, each with its distinctive hardness:
  - scale indicate relative hardness.

Figure 3.16 A

Figure 3.16 B

Figure 3.16 C

Hardness and the Mohs Scale

- Common objects for testing hardness:
  - Finger nail
    - Hardness of 2.5 (harder than gypsum or graphite)
  - copper penny
    - Hardness of 4 == fluorite
  - steel knife blade
    - hardness of 6 == feldspars

Density and Specific Gravity

- Density is mass per unit volume (g/cm^3)
- High density: close-packed high mass atoms
  - Iron (7.9), Gold (19.3), osmium (22.6)
- Low density: widely spaced lower mass atoms
  - Water ice (.9)
- Specific gravity: density divided by density of pure water (1 g/cm^3)
  - (S.G. is density in g/cm^3 without the units)

Mineral Properties and Bond Types

- Ionic and covalent bonds are strong, making minerals hard and strong.
- Metallic and van der Waals bonds are much weaker.

Elements, Minerals, Earth Composition

- O, Mg, Fe, Si, Al, Ca -> 99% of Earth's mass
- Add six more (H, Na, K, Ti, Mn, P) -> 99% of crustal mass.
- Crust is constructed mostly of a limited number of minerals.
  - Approximately 4,000 minerals have been identified, but only about 30 are commonly encountered.

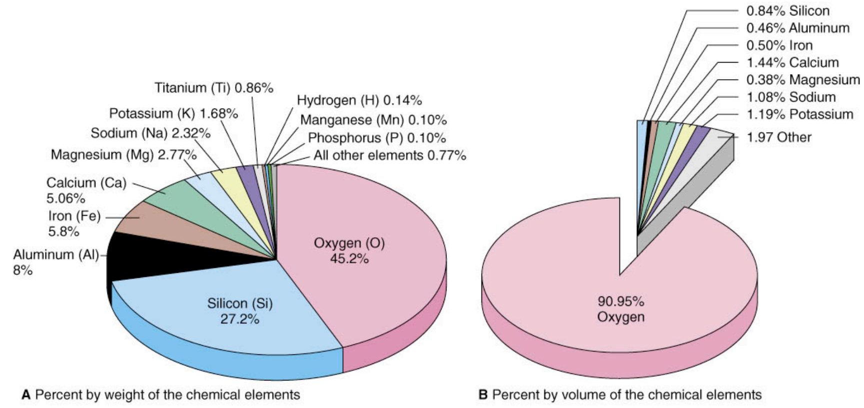


Figure 3.19

Three Mineral Groups

- Silicate minerals $(SiO_4)^{4-}$, the most abundant in Earth's crust.
- Carbonate $(CO_3)^{2-}$, phosphate $(PO_4)^{3-}$, and sulfate $(SO_4)^{2-}$ minerals.
- Ore minerals, sulfides (S^{2-}) and oxides (O^{2-}) that contain valuable metals.

Silicates: The Largest Mineral Group

- Two elements, oxygen and silicon, make up more than 70% of mass of the continental crust.
- Polymerization:
  - silicate tetrahedra linked by oxygen sharing
  - Produces endless chains, rings, sheets

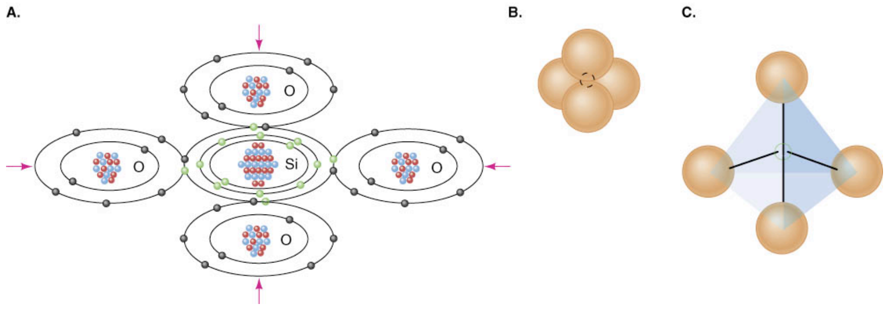


Figure 3.20

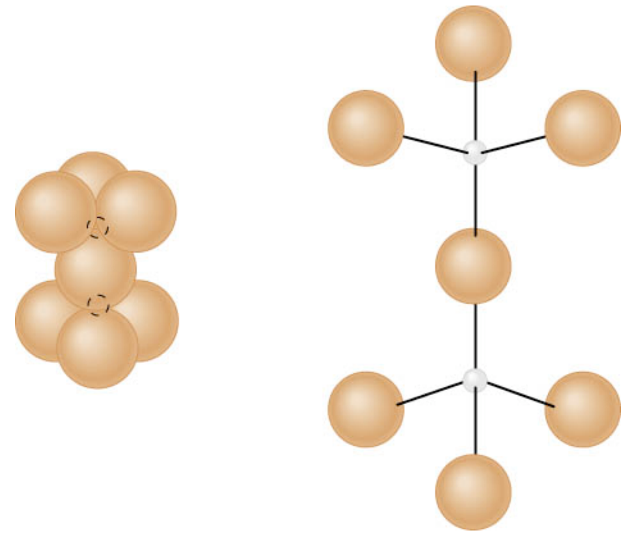


Figure 3.21

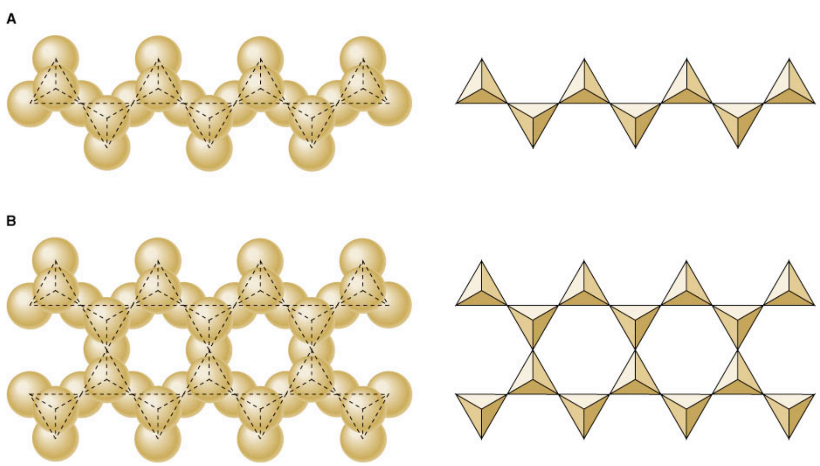


Figure 3.22

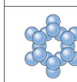
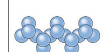
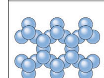
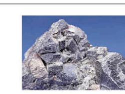
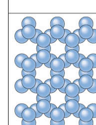
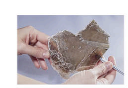
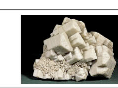
Silicate Structure	Mineral/Formula	Cleavage	Example of a Specimen
 Single tetrahedron	Olivine Mg_2SiO_4	None	
 Hexagonal ring	Beryl (Gem form is emerald) $Be_3Al_2Si_6O_{18}$	One plane	
 Single chain	Pyroxene group $CaMg(SiO_3)_2$ (variety: diopside)	Two planes at 90°	
 Double chain	Amphibole group $Ca_2Mg_5(Si_4O_{11})_2(OH)_2$ (variety: tremolite)	Two planes at 120°	
 Sheet	Mica $KAl_2(AlSi_3)O_{10}(OH)_2$ (variety: muscovite) $K(Mg,Fe)_3(AlSi_3)O_{10}(OH)_2$ (variety: biotite)	One plane	
Too complex to draw. Three-dimensional network	Feldspar $KAlSi_3O_8$ (variety: orthoclase)	Two directions at 90°	
	Quartz SiO_2	None	

Figure 3.23

Olivines and Garnets

- Silicate tetrahedra are isolated.
- Olivine is the most abundant mineral to depth of 400 km
  - 60% plus of the upper mantle $(Mg,Fe)_2SiO_4$
  - Gem quality olivine: peridote
- Garnet: 10% of upper mantle
  - Contains most Al and Ca in upper mantle
  - Also in igneous and metamorphic crustal rocks

Chains: Pyroxenes and Amphiboles

- Pyroxenes: single-chain linkages.
  - The most common crustal pyroxene is augite
  - 30% of upper mantle is enstatite:
    - $(Mg,Fe)SiO_3$
- Amphiboles: double chains.
  - Most common amphibole is hornblende
  - Structure contains water anions (OH^{-1})

Chains: Pyroxenes and Amphiboles

- Pyroxenes and amphiboles can be hard to tell apart.
  - The cleavages in pyroxene are right angles (90°).
  - The cleavages in amphibole are at 120°.

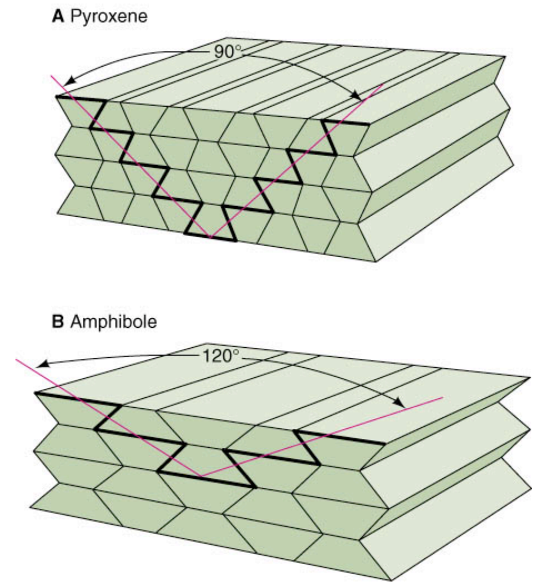


Figure 3.24

Sheets: Clays, Micas, Chlorites, and Serpentines

- Kaolinite, $Al_4Si_4O_{10}(OH)_8$, is one of the most common clays.
- Muscovite, $KAl_2(Si_3Al)O_{10}(OH)_2$, is a common mica.
- Chlorite, which contains Mg^{2+} and Fe^{2+} cations, is usually greenish in color.

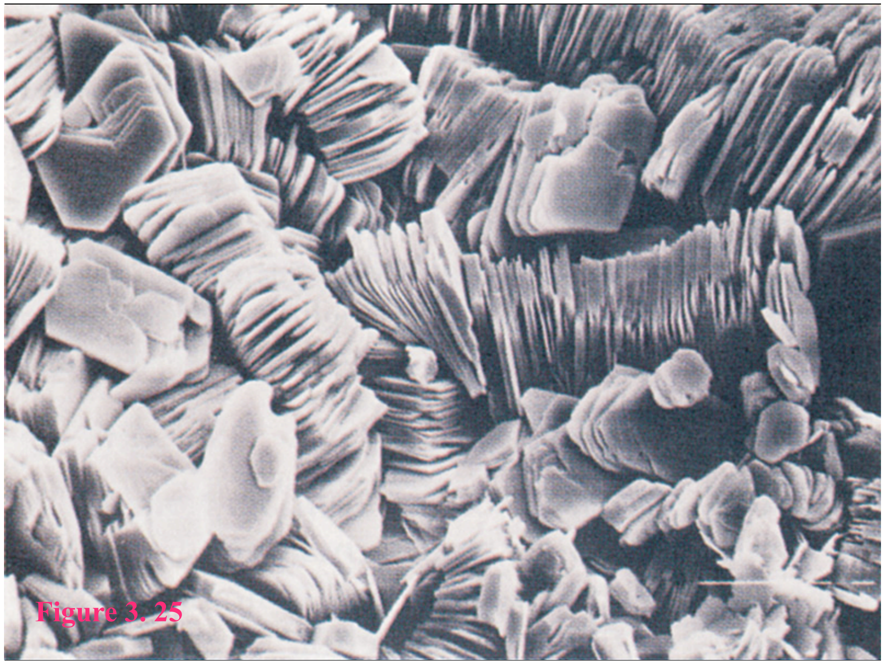


Figure 3. 25

Sheets: Clays, Micas, Chlorites, and Serpentines

- Serpentine group consists of three polymorphs with the formula $Mg_6Si_4O_{10}(OH)_8$.
  - Contains 15% water by weight
  - Hydration product from olivine
  - Chrysotile is the white asbestos of commerce.

Quartz

- Quartz: pure SiO_2 – a 3-D framework of tetrahedra – all corners linked
  - Forms six-sided crystals.
  - Found in many colors.
  - Colors from minute amounts of iron, aluminum, titanium, and other elements.
  - Fine grain forms of quartz are called chalcedony:
    - Agate
    - Flint (gray)
    - Jasper (red)

Figure 3. 26

Feldspar Group — The Most Common Minerals in Earth's Crust

- Feldspar:
  - Accounts for about 60 percent of all minerals in the continental crust.
  - Feldspar and quartz constitute 75 percent of the volume of the continental crust.
  - Feldspar structure is 3-D framework of silica tetrahedra with some Si^{+4} replaced with Al^{+3}
    - Extra cations (Ca, Na, K) balance charge

Figure 3. 28

The Carbonates Group

- Carbonates:
  - Carbonate anion, $(CO_3)^{2-}$, forms three common minerals:
    - Calcite. $(CaCO_3)$
    - Aragonite. $(CaCO_3)$
    - Dolomite. $(MgCa(CO_3)_2)$
  - Calcite reacts vigorously to HCl.
  - Limestone and dolomite are ubiquitous

Figure 3.29

Phosphate Mineral Groups

- Apatite most important phosphate mineral.
  - Contains the complex anion $((PO_4)^{3-}$.
  - Common "accessory" mineral in many varieties of igneous and sedimentary rocks.
  - Main source of the phosphorus used for making phosphate fertilizers.

Sulfate Mineral Group

- Sulfates:
  - All sulfate minerals contain the sulfate anion, $(SO_4)^{2-}$
  - Two common sulfates:
    - Anhydrite($CaSO_4$);
    - Gypsum ($CaSO_4 \cdot 2H_2O$).
      Gypsum is the raw material used for making plaster.

Ore Mineral Group—Source for Metals

- Sulfides:
  - Pyrite (FeS_2) and pyrrhotite (FeS) are common.
  - Galena (PbS), sphalerite (ZnS), chalcopyrite ($CuFeS_2$).
  - Familiar metals extracted from sulfide ore minerals are cobalt, mercury, molybdenum, and silver.

Oxides

- Oxides;
  - magnetite (Fe_3O_4) and hematite (Fe_2O_3)
    - Hematite is red when powdered.
  - Other oxide ore minerals are:
    - Rutile (TiO_2), the principal source of titanium;
    - Cassiterite (SnO_2), the main ore mineral for tin;
    - Uraninite (U_3O_8), the main source of uranium.
  - metals extracted from oxide ore minerals: chromium, manganese, niobium, and tantalum.