Earth Materials, Second Edition

INTRODUCTION TO MINERALOGY AND PETROLOGY

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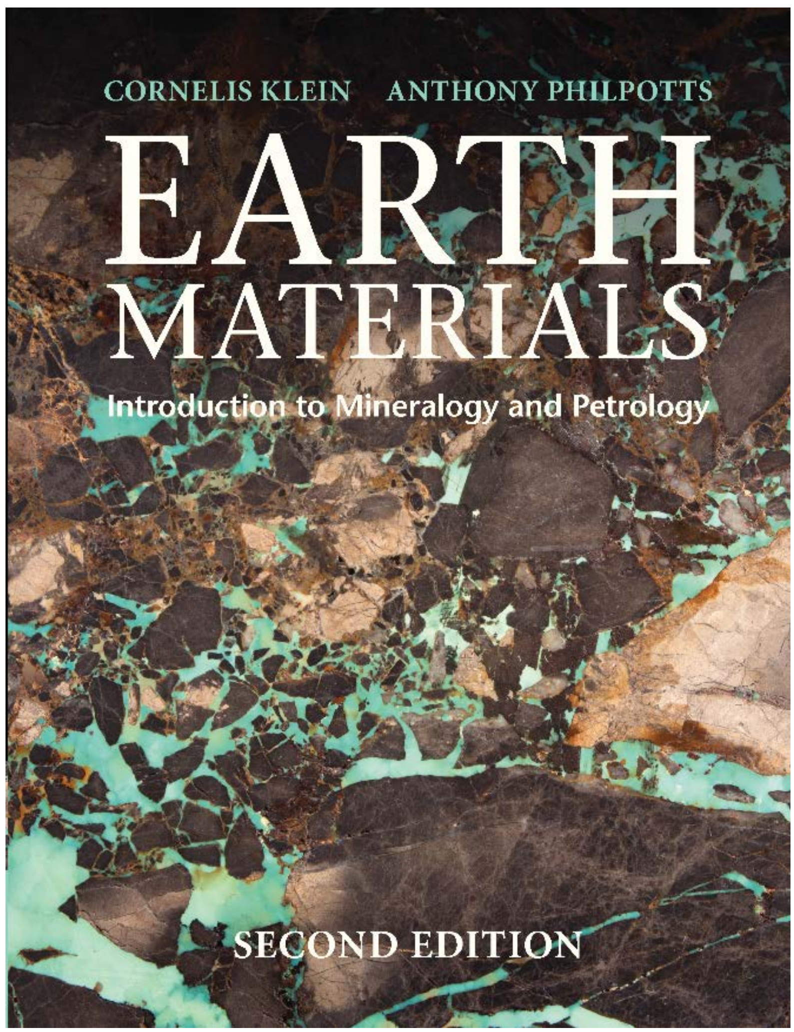
Solutions for review questions

CONTENTS



Solutions to Chapter 1 Problems

1. *Where were most of Earth's chemical elements formed?*

Most of the Earth's chemical elements were formed from interstellar dust that was thrown out from exploding stars known as supernovae. During these explosions, elements heavier than iron are formed by nuclear reactions.

2. *Why are the terrestrial inner planets small compared with the outer gas giant planets?*

The planets formed from solid materials that condensed from the solar nebula. Because the terrestrial planets formed near the Sun, where temperatures were relatively high, only refractory minerals could condense from the solar nebula. These minerals involve the less abundant heavy elements in the solar nebula, so the terrestrial planets are small. The outer gas giant planets formed farther from the Sun where temperatures were low enough for ices of water, carbon dioxide, ammonia, and methane to condense. Because these ices involve the more abundant elements in the solar nebula (H, O, C), these outer planets are much larger than the terrestrial planets.

3. *What is a chondrule, and why do we use the composition of chondritic meteorites to determine the composition of the Earth?*

Chondrules are millimeter-size spheres of extremely fine-grained silicates (olivine and pyroxene) that characterize chondritic meteorites, which are the most common type of meteorite. These small spheres were formed by sudden heating and cooling of dust particles in the solar nebula, and they consequently form one of the oldest known structures in the solar system. Chondritic meteorites all have absolute ages of 4.6 billion years. The Earth is believed to have formed by the accretion of the same material that formed chondritic meteorites. Their composition is therefore considered to be similar to the bulk-Earth composition.

4. *What caused the Earth to be so hot early in its history that its outer part would have been molten?*

Several sources of heat caused the Earth to have a hot beginning. To begin with, the kinetic energy of the accretionary process would have generated considerable heat. In addition, heat was generated by radioactive decay and the formation of the iron-nickel core (conversion of potential energy to heat). The amount of heat produced by these processes would have been sufficient to make the outer part of the Earth Molten.

5. *What are the major divisions of the Earth?*

The major divisions of the Earth are the following:
Core -- divided into inner solid and outer liquid parts.
Mantle -- divided into a lower and upper part, which may or may not interact through convection.
Crust – The thin outer part of the Earth, which under continents is of generally granitic composition and under oceans is of basaltic composition.

6. *What two important layers in the Earth are responsible for plate tectonics?*

Another important division in the outer part of the Earth is the distinction between the *lithosphere* and the *asthenosphere*. The relatively rigid 100 km-thick lithosphere is broken into eight major plates whose movement on the underlying less viscous asthenosphere creates plate tectonics, the process by which the Earth is able to convectively cool and, in so doing, create rocks.

7. *What are the main types of plate boundaries, and what types of rock might be formed there?*

There are three main types of boundaries between tectonic plates – divergent, convergent, and transform boundaries. At divergent plate boundaries, especially in oceanic areas, basalt is the main igneous rock formed. At convergent plate boundaries igneous rocks of andesitic composition are formed. Other important rocks are formed near convergent boundaries, including thick sequences of sedimentary rocks formed by sediment eroded from the mountains that characterize these boundaries. Heat and elevated pressures generated at convergent boundaries produce a variety of metamorphic rocks. Along transform boundaries, sedimentary rocks can form in pull-apart basins. Rocks along these boundaries become highly sheared.

Solutions to Chapter 2 Problems

1. *What is a mineral, and why is it important to specify naturally occurring?*

A mineral is a naturally occurring solid, with an ordered atomic arrangement, and a definite (but commonly not fixed) chemical composition. Almost all minerals are of inorganic origin.
"Naturally occurring" distinguishes minerals from those that are synthetic, meaning those that are made by laboratory techniques in research laboratories or by commercial processes.

2. *Why does table salt (NaCl) break into cube like cleavage fragments?*

The internal structure of halite is based on Na^+ and Cl^- ions in a cubic pattern. The bonds between the ions are relatively weak, leading to well-developed cleavage in three directions at 90° to each other (in the shape of a cube).

3. *What is the composition, shape, and electrical charge on the basic building unit of all silicate minerals?*

The basic building unit in all silicates is that of a tetrahedron, in which a central Si^{4+} ion is surrounded by four O^{2-} ions, located at the four corners of the tetrahedron.

4. *What are some common uses for the mineral quartz (SiO_2)?*

Quartz, SiO_2, in the form of quartz sand, is a major component of cement used in the construction industry. It is also a major source in the making of silica glass. Synthetic quartz is used in electronic applications, an example of which is the use thereof in quartz watches.

5. *How does the arrangement of silica tetrahedra in the crystal structures of quartz and talc differ?*

The atomic structure of quartz consists of an infinite framework of $(SiO_4)^{4-}$ tetrahedra without any other cations present. The structure of talc, on the other hand, is made of two infinitely extending tetrahedral sheets (linking tetrahedra in only two dimensions, not three, as in quartz) between which is an infinitely extending, well-bonded sheet of Mg^{2+} ions.

6. *Although the cation to anion ratio in garnet is fixed, what allows it to have a wide compositional range, and why are such widely different compositions still classified as the same mineral?*

A generalized formula for all garnets is $A_3B_2(SiO_4)_3$, where *A* and *B* represent atomic positions in which several different cations may be housed. The subscripts in this formula are 3: 2: 3 and these are the same for all garnet compositions. The *A* atomic site can house Mg^{2+}, Fe^{2+}, Mn^{2+}, or Ca^{2+} and the *B* site may house Al^{3+}, Fe^{3+}, or Cr^{3+}. Such variability in atomic site occupancy leads to a wide range of compositions all of which are based on the same atomic structure.

7. *Can minerals be synthesized in the laboratory?*

Yes, many minerals are routinely synthesized. Diamonds, rubies, sapphires, and emeralds are commonly produced for the gem trade. Synthetic quartz is used in electronic applications.

8. *On what basis are minerals classified into different chemical groups, and of these, which forms the largest group?*

Minerals are grouped chemically into native elements and the more complex compounds by the compositions of their anion or anionic group. For example, sulfides have S^{2-} as the anion; oxides have O^{2-} as the anion. The mineral group that contains $(SiO_4)^{4-}$ anionic tetrahedra, the silicates, is the largest mineral group.

9. *What is a crystal, and does the crystalline state require that crystal faces be present?*

A specific, well-formed crystal exhibits a combination of crystal faces that reflects the internal, ordered atomic arrangement of that crystal. A rounded grain of that same mineral lacks all evidence of external crystal form but the internal atomic arrangement inside that rounded grain is identical to that of the well-formed crystal. In other words, both a quartz crystal and a quartz sand grain possess the same internal crystallinity.

10. *What is a rock, and how does it differ from a mineral?*

A rock is made up of a mixture of minerals that are bound together to form a solid material. Sand might contain a mixture of minerals but it would not be considered a rock until it were cemented together, in which case it would become a sandstone.

11. *What is the difference between a rock's texture and structure?*

A rock's texture refers to the way in which its constituent grains relate to one another. It describes features that are visible at the scale of the individual grains. Structure, on the other hand, refers to larger-scale features, which commonly are produced by variations in the abundance of minerals at the hand-specimen our outcrop scale, such as layering in sedimentary rocks.

12. *From a geological map of the area where you live, determine how many rock-forming periods your home area has experienced and approximately what fraction of geologic time these periods represent.*

For most areas, only a few rock-forming periods will have occurred, and their total duration will be only a very small fraction of all geologic time.

13. *What single process has been operating continuously since the beginning of the Earth and has been responsible for the formation of most rocks and drives plate tectonics.*

Ever since the Earth was formed it has been cooling. Cooling drives the convection that moves tectonic plates. The formation of magma removes the latent heat of melting from the source region and releases it when the magma crystallizes to form an igneous rock. Heat is required to drive the reactions that produce metamorphic rocks.

14. *Give brief definitions of igneous, sedimentary, and metamorphic rocks, and describe how you might distinguish between them.*

Igneous rocks are formed from the solidification of molten rock—magma. If magma solidifies slowly beneath the surface, it typically crystallizes to a relatively coarse-grained rock in which early crystallizing minerals are commonly surrounded by later-crystallizing minerals. The rock owes its strength to the interlocking way in which its crystals form. If magma crystallizes rapidly on the surface as a volcanic rock, its grain size is fine, but commonly larger crystals (phenocrysts) that were growing prior to eruption are present in the fine-grained groundmass. If cooling is very rapid the igneous rock may be glassy.

Sedimentary rocks are formed by the cementing together of sedimentary particles. The particles may come from the disintegration of silicate rocks, in which case the main constituent is usually quartz, with lesser amounts of feldspar and other minerals. Near shores where marine life is abundant the sedimentary particles may consist of broken shells and corals, in which case the sediment is composed largely of calcium carbonate. Some sediment can form by direct precipitation of carbonates, sulphates, and chlorides from water as a result of evaporation. Most sedimentary rocks exhibit prominent sub-horizontal layering (bedding).

Metamorphic rocks are formed by the recrystallization of other rocks as a result of changes in the temperature, pressure, or composition of fluids in the environment. These changes can take place on a regional scale as a result of plate tectonic motions, especially near convergent plate boundaries. Recrystallization of rock in such environments develops a prominent foliation. Recrystallization can also take place near igneous intrusions as a result of heat released during cooling. These rocks do not develop a foliation but recrystallize to rock with polygonal-shaped grains.

15. *What general distinction can you make between the igneous rocks of the ocean floor and those of the continental crust?*

Igneous rocks of the ocean floor are predominantly volcanic rocks of basaltic composition. In contrast, the igneous rocks of continental regions tend to be of granitic composition.

16. *What sedimentary rock do we make the greatest use of in the modern world?*

Limestone is used in the manufacture of cement, which binds together concrete, the main construction material of the modern world.

17. *What feature characterizes most regionally metamorphosed rocks?*

Regional metamorphic rocks are typically formed near convergent plate boundaries. The recrystallization therefore takes place under compressive stresses, and minerals that are platy (e.g., mica) or needle-like (amphibole) tend to grow with their long axes perpendicular to the maximum compressive stress. This causes the rock to develop a strong foliation (e.g., slate or schist).

18. *Where does the largest production of new rock take place on Earth?*

The largest production of new rock takes place at midocean ridges, where basaltic magma rises in response to the dilation of the lithosphere, with production of dikes and lava flows.

19. *Water plays what important roles when circulating through fractures in newly formed oceanic crust?*

Water circulating through newly formed oceanic crust near midocean ridges cools the rock and converts some of the igneous minerals to hydrous alteration minerals. When the ocean floor is subducted at a convergent plate boundary, the increased pressure eventually causes metamorphic reactions to take place that release the water. This water then rises into the overlying mantle wedge where it lowers the melting point of the mantle peridotite, and andesitic magma is formed. This magma rises to form andesitic rocks, or it may pond at lower levels in the crust and cause melting of crustal rock to form bodies of granite.

20. *What common volcanic rock forms above subducting tectonic plates, and what role does water play in its origin?*

Andesite is the common volcanic rock formed above subduction zones. Melting of mantle peridotite under anhydrous conditions generates basaltic magma. As the water content is increased, however, the magma that is formed contains higher concentrations of silica and becomes andesitic. Andesite is consequently the hydrous melting product of mantle peridotite. The water in this magma is made evident when andesite erupts. The water comes out of solution in the magma and makes many andesitic eruptions explosive.

21. *Why are granite batholiths common above subducting tectonic plates?*

Basaltic or andesitic magma rising into the base of the crust above subduction zones may spread laterally near the base of the crust where the heat and fluids they release can cause melting of the lower crust to form bodies of granitic magma. This magma can rise to form granite batholiths.

22. *What is the source of sediment in forearc basins and what is a common characteristic of these sedimentary beds?*

The greatest relief on Earth is created at convergent plate boundaries, where oceanic trenches lie next to mountain chains. This relief results in the formation and transport of large quantities of sediment from the mountains toward the ocean trench. Some of the sediment may reach the trench, but most is trapped in forearc basins. Much of the sediment is deposited from turbidity currents, which create beds that are graded from coarse, dense particles at the base to the fine, less dense particles at the top.

23. *Why are the sedimentary rocks of rift valleys commonly red-colored and still contain a considerable amount of the relatively soft mineral feldspar?*

The sediment that is transported and deposited in rift valleys is normally in contact with air or groundwater that is in contact with air. Most of this sediment therefore accumulates under relatively oxidizing conditions, in which case iron is converted to the red Fe_2O_3. Transportation distances from the source of the sediment to the site of deposition are short, and there is insufficient time for the harder minerals to abrade and eliminate the softer minerals. Sandstones in rift valleys, therefore, commonly contain considerable amounts of feldspar in addition to quartz.

24. *From where do mantle plumes derive their heat?*

Mantle plumes are believed to derive their heat from deep in the mantle, possibly as deep as the core-mantle boundary. Mantle plumes appear to have very deep roots because they are unaffected by lithospheric plate motion. In addition, high concentrations of ^3He versus the more common ^4He over mantle plumes point to the tapping of a primitive source that has not been outgassed since formation of the planet.

25. *How are shallow epeiric seas that flood continents related to plate tectonics?*

During periods of exceptionally active ocean-floor spreading large quantities of new ocean crust are formed. This hot material has relatively low density and consequently floats high and displaces ocean water onto continents flooding them with shallow seas.

26. *What plate-tectonic processes deflect isotherms up or down in the Earth?*

Isotherms are deflected down and up at convergent and divergent plate boundaries, respectively. Subduction of cold ocean floor rocks at convergent plate boundaries deflects isotherms downward, taking cold rocks to considerable depth. This produces high-pressure low-temperature metamorphic rocks in these subduction zones. Release of water from the subducted slab causes melting in the overlying mantle wedge. When this magma rises into the crust it deflects isotherms upward. At divergent plate boundaries the mantle rises in response to the divergence, and this brings isotherms closer to the surface. As the mantle decompresses it partially melts and the rise of magma can move isotherms still closer to the surface.

27. *Trace the role played by water and carbon dioxide in metamorphic rocks in going from their formation near midocean ridges to the production of granite by partial melting of continental crust above subducting plates.*

Newly formed oceanic crust at a midocean ridge is cooled and altered by water circulating through fractures. Many hydrous and carbonate minerals are formed as a result of this hydrothermal activity. When these rocks experience increased pressure on being subducted, the alteration minerals are converted to higher-pressure minerals and eventually water and carbon dioxide are released from the subducting slab. These volatiles rise into the overlying plate where they participate in the formation of andesitic magma and metamorphic minerals. Magma rising from the mantle may pond at the base of the crust, where it can partially melt crustal rocks to form granitic magma.

Solutions to Chapter 3 Problems

1. *What is meant by each of the following adjectives: prismatic, acicular, dendritic, granular, botryoidal, and oolitic?*

Prismatic means that the crystal has an elongate habit with the bounding faces forming a prism-like outward shape. Acicular describes a needle-like external habit. Dendritic refers to a mineral that occurs in a tree-like branching pattern. Granular applies to a rock or mineral specimen that consists of mineral grains of about equal dimensions. Botryoidal means that the mineral has an external surface pattern of spherical shapes, similar to that exhibited by a bunch of grapes. Oolitic describes the occurrence of mineral grains in rounded masses the size of fish roe.

2. *What distinguishes metallic from nonmetallic luster?*

A mineral is said to have metallic luster if all of the white light that strikes it is reflected and/or scattered. When most of the light that impinges on a mineral is transmitted, as in most light-colored translucent minerals, the luster is described as nonmetallic.

3. *What is meant by vitreous?*

Vitreous is used as a descriptive term when a mineral has the luster of that of glass.

4. *What is meant by the term chromophore elements?*

A chromosphore element is a chemical element that is responsible for causing color. Chromosphore elements, including Cr, Mn, and Fe, are part of a group of elements known as transition elements.

5. *If in white light a specific mineral specimen exhibits a yellow-green color (e.g., the gem olivine named peridot), which part of the optical spectrum is least absorbed?*

The yellow-green color of peridot, an Mg-rich olivine, is caused by the strong absorption of white light mainly in the infrared region with most pronounced transmission in the green and yellow range in the visible range of the electromagnetic spectrum (see Fig. 3.6).

6. *What is meant by the term labradorescence?*

Labradorescence is an internal iridescence that is expressed as a range of color flashes in the plagioclase feldspar known as labradorite.

7. *What is asterism?*

Asterism is an optical phenomenon, seen as a six-rayed star that results from the reflection of light by minute inclusions, inside a mineral, arranged in a star-like (six-rayed) pattern.

8. *Halite has excellent cubic cleavage – what does that mean?*

Excellent cleavage in halite is expressed by the formation of a large number of small cubic fragments as a result of a hammer blow (or percussion from a knife blade) on the original, larger halite specimen.

9. *Members of the mineral group mica have perfect planar cleavage – how does that show itself?*

Planar cleavage, along well-defined planar surfaces, is a diagnostic property of the mica group of minerals. Medium- to coarse-grained micas commonly occur as “books” that can be peeled apart into thin sheets because of excellent planar cleavage.

10. *What is the name of the relative hardness scale? What is the range of numbers on that scale?*

The relative hardness scale is known as Mohs hardness scale. The scale ranges from 1 to 10 reflecting the relative hardnesses of ten common minerals.

11. *Metallic and nonmetallic minerals respond very differently to a hardness test. What are these differences?*

The response of a metallic mineral to abrasion or indentation is generally very different from that of a non-metallic mineral. Metallic minerals tend to show grooves as a result of scratching (due to their ductility and malleability) whereas non-metallic minerals behave in a brittle fashion, developing micro-fractures and subsequent breakage.

12. *Specific gravity (or density) is a function (1) of an atomic property as well as (2) a crystal structure arrangement? What are these?*

Specific gravity (or relative density) is directly related (1) to the atomic weights of the chemical elements in a crystal structure, and (2) to the way in which the elements are packed together. A tighter atomic packing generally leads to higher specific gravity.

13. *What mineral groups tend to have high values of specific gravity?*

High specific gravity values are found in minerals with high atomic weights (of the constituent elements) and close atomic packing. Both occur in metallic minerals such as native elements and sulfides.

14. *A mineral is listed as having **H** = 1 and excellent planar cleavage. What mineral is this?*

Talc has **H** = 1 and exhibits excellent planar cleavage.

15. *Another mineral has **H** = 10 and perfect octahedral cleavage. Which is this?*

Diamond has **H** = 10 and upon impact exhibits excellent octahedral cleavage.

Solutions to Chapter 4 Problems

1. *Why is oxygen the first element listed in Table 4.2? Give two reasons.*

Oxygen is the first element listed in Table 4.2 because it is the largest as well as the most abundant element in Earth materials.

2. *How is the radius of a cation obtained in an oxygen-rich compound if the radius of oxygen is known?*

The radius of an oxygen ion is variable. The experimentally determined radius ranges from 1.26 to 1.42 Å. If a specific radius value in that range is assumed, then the distance between the center of the oxygen ion to the center of the adjoining cation can be obtained by X-ray diffraction, or electron beam methods, using the equation $R_X = d - R_A$. d = interatomic distance; R_X = radius of cation; R_A = radius of oxygen anion.

3. *What is meant by coordination number (**C.N.**)?*

Coordination number (**C.N.**) is the number of closest neighbors that surround a specific atom or ion in an atomic structure.

4. *What is a coordination polyhedron?*

A coordination polyhedron is the geometric shape of how the closest-neighboring anions surround a central cation, or of how closest-neighbor cations surround a central anion. The change in shape and volume of a coordination polyhedron are a function of the relative sizes of the cations and anions involved.

5. *Give the range of shapes of coordination polyhedra.*

Coordination polyhedra range in shape from triangular, to tetrahedral, to octahedral, to cubic, and finally to what is known as *closest packing* (in which a central atom or ion is surrounded by twelve closest neighbors of the same size). See Fig. 4.3 and Boxes 4.1 and 4.2.

6. *If Mg^{2+} occurs in 6-fold coordination in a crystal structure, how is that written out in the scientific notation used in Table 4.4*.

Mg^{2+} in 6-fold coordination is stated as $Mg^{2+\,[VI]}$.

7. *What is the size of that same* Mg^{2+}*?*

Mg^{2+} in 6-fold coordination has a size of 0.86 Å (see Table 4.4).

8. *What is meant by closest packing?*

Closest packing refers to two different atomic packing schemes that are possible when the cation and anion sizes are the same. This occurs most commonly in native metals where the central atom is surrounded by atoms of the same element and therefore the same atomic radius.

9. *What are two different closest packing schemes?*

The two *closest packing* schemes are known as hexagonal closest packing (HCP) and cubic closest packing (CCP). HCP results when a set of two closest packed atomic layers is infinitely stacked in a mode represented by ABAB…. CCP is the result of infinite stacking of a packet of three closest packed layers as represented by ABCABC… (see Boxes 4.1 and 4.2).

10. *How is bond strength defined?*

Bond strength (or electrostatic valency, e.v.) is defined as Z/**C.N.**, where Z is the charge on the ion, and **C.N.** is the coordination number (the number of closest neighbors).

11. *What is the strength of the bonds that surround a central* Fe^{2+} *in octahedral coordination with oxygen?*

The strengths of the bonds (e.v.) around a central Fe^{2+} (in octahedral coordination) are $2^+/6 = 1/3$, which represents an absolute value (no + or – sign).

12. *Why do tetrahedra consisting of* (SiO_4) *only share corners, not edges, or faces?*

Tetrahedra of $(SiO_4)^{4-}$ tend to preferentially share corners only, not edges or faces. This is the result of the repulsive forces that come into play when Si^{4+} ions (that are centered in these tetrahedra) are brought closer together. Sharing of edges or faces forces the central cations closer together resulting in repulsive forces (see Fig. 4.11).

13. *What is meant by the term mesodesmic?*

Atomic (or ionic) structures are described as mesodesmic when the e.v. of the linkage between coordination polyhedra via a "bridging oxygen" = 1. In silicates, the e.v. of bonds between a central Si^{4+} and four surrounding oxygens is $4^{+}/4 = 1$, meaning that the remaining charge on the four oxygens is exactly one half of that of oxygen (which is -2) and as such is 1.

14. *In the structures of what mineral group do mesodesmic bonds occur?*

Mesodesmic bonding is characteristic of the silicate group of minerals.

15. *What electrons, in the nuclear structure of elements, are of prime importance in chemical bonding?*

The valence electrons, the outer electrons in the electronic configuration of the elements, are responsible for chemical bonding in crystal structures.

16. *What happens to electrons in a covalent bond?*

A covalent bond is the result of electron sharing of valence electrons in the outer shells of two or more elements.

17. *What happens to electrons in an ionic bond?*

An ionic bond is the result of electron transfer (exchange) of electrons in the outer shell of two or more elements.

18. *What is the role of electrons in metallic bonding, where there is malleability and high electrical conductivity?*

The outer valence electrons in the relatively large electron clouds of metal atoms tend to owe little or no affinity to any particular nucleus, allowing them to drift freely through the metal structure (this bonding mechanism involves no sharing or exchange of electrons). Metallic bonding expresses itself in metals in their ductility, low hardness, metallic luster, and high electrical and thermal conductivity.

19. *What silicate mineral group has weak structures due to van der Waals bonding?*

Van der Waals bonding is pronounced in the silicates known as clay minerals.

20. *What are two basic parameters that allow for ease of atomic substitution of one ion for another?*

Easy atomic substitution occurs when the originally present ion and the new substituting ion have similar ionic sizes and the same electric charge (valence).

21. *What is meant by coupled substitution?*

Coupled substitution results when the substituting ion has a similar size as but different charge than the originally present ion. If Na^{+} is to substitute for Ca^{2+} (as in plagioclase feldspar) a simultaneous substitution of Al^{3+} for Si^{4+} must occur to keep the overall structure electrically neutral. This can be written as: $Na^{+} + Si^{4} \leftrightarrows Ca^{2+} + Al^{3+}$.

22. *Why does an increase in temperature of a solid (a mineral) allow for increased atomic substitution by various elements (or ions)?*

Increasing the temperature of a solid mineral causes expansion of the various atomic sites in the crystal structure of that mineral. This size increase is most pronounced just below the melting temperature while the mineral is still solid. This increase in size of the atomic sites at higher temperature means that the atomic structure is more tolerant of divergent ionic (or atomic) sizes than at lower temperature.

23. *What is meant by interstitial solid solution?*

Interstitial solid solution refers to the process by which an atom (or ion or ionic group) substitutes in a normally vacant site of an atomic structure. An interstice is defined as a space that intervenes between things. As such the term is used for an open space between other occupied atomic sites.

24. *What is meant by omission solid solution?*

Omission solid solution refers to the presence of unfilled or vacant atomic sites in a crystal structure that would normally be occupied. Such structures are commonly referred to as defect structures.

Solutions to Chapter 5 Problems

1. *Give a short definition of a mirror, rotation axis, center of symmetry, and rotoinversion axis.*

A *mirror* reflects an object (a crystal face or a unit of structure) into its mirror image.
A *rotation axis* is an imaginary line about which an object (a crystal face or unit of structure) is rotated and repeats itself once or several times during a complete (360°) rotation.
A *center of symmetry*, also known as inversion, is present in a crystal if every face on the crystal has an equivalent parallel face on the opposite side of the crystal.
A *rotoinversion axis* is an imaginary line about which an object (a crystal face or a unit of structure) is rotated as well as inverted. The angles of rotation shown by rotation and rotoinversion axes are the same.

2. *In the evaluation of the symmetry content of a morphological crystal, you can make a list of all of the symmetry elements or you can use an internationally accepted shorthand notation. Which of these two approaches did you use in your course? (refer to Table 5.1).*

When you were first introduced to the concept of symmetry elements in crystals, you probably began by listing all the symmetry elements you observed (in a wooden block model of a crystal) as in the first column in Table 5.1. Subsequently you may have been introduced to the "shorthand" of such a list as used in the Hermann-Mauguin notation in the second column of Table 5.1.

3. *If you were introduced to the Hermann-Mauguin notation (Box 5.1), what is so useful about this approach?*

If the Hermann-Mauguin notation was used in your class its advantages are as follows. The symbols for the various symmetry elements are listed according to their location with respect to the location of the crystallographic axes appropriate to the overall symmetry content of a crystal. Some experience with this system of notation helps in the quick recognition of the total symmetry content of a crystal class as part of one of the six crystal systems.

4. *All combinations of possible symmetry elements (and some single elements) are referred to six crystal systems. Which are these six?*

The six crystal systems, in decreasing order of total symmetry content are: isometric, hexagonal, tetragonal, orthorhombic, monoclinic, and triclinic.

5. *The concept of crystal axes is basic to the evaluation of the position of a specific crystal face on a morphological crystal. Why is this so?*

Crystallographic axes are three (or four as in the hexagonal system) imaginary reference lines that serve as reference axes for the evaluation of the position of symmetry elements (in crystals and crystal structures) as well as of the external faces on a well-developed crystal.

6. *In the isometric system all three crystal axes are of equal lengths. In the orthorhombic crystal system the axes are all of unequal lengths. Explain what determines the difference in crystal axis lengths in these two examples.*

Both the isometric and orthorhombic crystal systems are described in terms of three crystallographic axes, all at 90° to each other. In the isometric system each of these three axes reflects 4-fold (or in some cases 2-fold) symmetry about each with additional 3-fold rotoinversion axes at specialized locations. Such high internal symmetry content restricts the length of the three axes in the isometric system to just one repeat length common to all three axes. In the orthorhombic system the three perpendicular axes reflect only 2-fold symmetry about each of the three axes with no additional symmetry axes elsewhere. This total symmetry content is therefore less restrictive than in the isometric system. In the orthorhombic system, three axes of unequal lengths are chosen.

7. *What is meant by* ***Miller index****, or* ***Miller-Bravais index****? Explain why these two index systems differ.*

A Miller index is a type of shorthand that depicts the orientation of a crystal face on a crystal, or of a crystallographic plane inside a crystal structure. It consists of three digits, or letters (such as *h*, *k*, and *l*) inside parentheses. The digits are obtained through the inversion of (most commonly) estimated distances along the three crystallographic axes used in the description of five of the six crystal systems. A Miller-Bravais index consists of four digits (or four letters such as *h*, *k*, *i*, and *l*) and is used only for crystals in the hexagonal system, which is most commonly described in terms of four crystallographic axes.

8. *What is the definition of* ***form****?*

In crystallography the definition of *form* is as follows: a form consists of a group of like crystal faces, all of which have the same relationship to the symmetry elements. The six faces of a cube, in the isometric system, make up one form.

9. *What is meant by the term* ***general form****? Give an example of its Miller index.*

A general form is a form in which all the faces (of that form) intersect the crystallographic axes at different lengths. A general form is described by a Miller or Miller-Bravis index notation such as (*hkl*) or $(hk\bar{i}l)$. This notation reflects the fact that the actual intersection distances along the various crystallographic axes are undefined.

10. *What is meant by a stereogram?*

A stereogram is a circular (two-dimensional) diagram that results when the location of faces on a crystal (a three-dimensional object) as well as its symmetry content are projected (in a specialized manner) onto a page.

11. *How does one arrive at the stereogram of a morphological crystal? Explain the process.*

Crystal faces in the northern hemisphere of a crystal are projected downward onto the page and crystal faces in the southern hemisphere of that same crystal are projected upward.

12. *Why is a stereogram such a useful illustration?*

A stereogram is a two-dimensional visualization of the location of the face poles of crystal faces on a well-developed crystal as well as the symmetry elements contained in it. A stereogram of the symmetry elements in a specific crystal class, without the location of any face poles, can provide a quick visualization of the symmetry content of that crystal as given by its Hermann-Mauguin notation.

13. *What is meant by the term crystal class (or point group)?*

A crystal class (or point group) is one of the thirty-two unique combinations of symmetry elements (or operations) exhibited by minerals.

14. *How many crystal classes are there in total, and how many were systematically described in this text.*

There are thirty-two crystal classes and only seven of these, in which a large number of common minerals crystallize, are treated in detail in this text.

15. *Give an example of a point group (crystal class) notation, using the Hermann-Mauguin system, for an orthorhombic crystal.*

The crystal class (point group) with the highest overall symmetry content in the orthorhombic system is 2/*m* 2/*m* 2/*m*.

16. *What is the definition of a twinned crystal?*

A twinned crystal (or twin) is the result of the rational symmetrical intergrowth of two or more crystals of the same substance.

17. *What are the three different twin types?*

Three different twin types are: contact, penetration, and repeated (or multiple) twins.

18. *What are the three new elements (or operations) encountered in space groups and what are their notations that were not seen in point groups?*

Three symmetry operations that are encountered in crystal structures and their space group notations are translations, screw axes, and glide planes. The various subscripts to rotation axes in screw axis notations and letters that replace *m* for mirrors all reflect translation.

19. *Pure translation is described by the first letter entry in a space group notation. Give some examples of this purely translational element.*

Bravais lattice types, and the letters by which they are listed, represent translation in three dimensions. The symbols are:

P = primitive
F = all-face centered
I = body-centered
C = *c*-face centered
R = rhombohedral

Unit cells are the smallest three-dimensional units of structure that can be infinitely repeated to form the overall structure. Their axial dimensions (along *a*, *b*, *c*, or a_1, a_2, a_3 and *c*) are purely translational (measured in Å).

20. *Some screw axis pairs are referred to as enantiomorphous. What is meant by that? Give an example of such a pair.*

Enantiomorphous screw axes are pairs of screw axes with the same rotational angle (e.g., both with 90° or both with 120°) but differ from each other by one being right-handed and the other left-handed. In other words, the two screw operations relate to each other in opposite directions. An example of such a pair is 3_1 and 3_2.

21. *In the evaluation of the symmetry content of crystal classes (point groups), mirror operations are represented by m. What letters are used in space group notation for glide planes?*

Mirror planes (or mirror operations) as seen in crystals or crystal structures are represented by *m*. If this same mirror is combined with a translational operation (glide planes, as seen in crystal structures) different letters are given instead of *m*:

a, *b*, or *c*: represent axial glide planes, parallel to an *a*, *b*, or *c* axis, respectively
n: a diagonal glide plane, and
d: a diamond glide plane (see Fig. 5.29).

22. *From Table 5.3 select two space groups from two different crystal systems (e.g., isometric and tetragonal) and derive the appropriate (translation-free) point group therefrom.*

The last one listed in the isometric group is $I4_1/a\bar{3}2/d$, which is isogonal with point group $4/m\bar{3}2/m$. The last entry in the tetragonal group is $I4_1/a2/c2/d$, which is isogonal with $4/m2/m2/m$.

23. *What is meant by the term polymorph?*

A polymorph is the occurrence of a mineral (or chemical compound) in more than one crystal structure.

24. *Give the names for three different polymorphic processes.*

Reconstructive, displacive, and order-disorder polymorphism.

25. *What happens in the polymorphic transition from high to low quartz?*

The transition from low to high quartz, and vice versa, is one of displacive polymorphism in which there is only some adjustment of bond angles ("kinking") without breaking of bonds.

26. *How many polymorphs are there for Al_2SiO_5? Give their mineral names*.

The three polymorph of Al_2SiO_5 are andalusite, sillimanite, and kyanite.

Solutions to Chapter 6 Problems

1. *Do longer wavelengths of light have more or less energy than short wavelengths?*

According to Equation 3.1, the energy of electromagnetic radiation is inversely related to its wavelength. Therefore, long wavelengths of light have less energy than shorter wavelengths of light.

2. *What was Henry Sorby's contribution to the development of the microscope?*

Sorby passed polarized light through extremely thin sections of rock and then viewed the magnified image through another polarizer at right angles to the first polarizer. The crossed polars allowed him to see interference effects between the polarized light and the crystal structure of minerals. The modern petrographic microscope uses polarized light to study rocks in the manner introduced by Sorby.

3. *What is the refractive index of a mineral?*

The refractive index of any material is the ratio of the velocity of light in air to the velocity of light in the material; that is, R.I. = $v_{air}/v_{material}$.

4. *What is the refractive index of air?*

The refractive index of air is 1.

5. *The refractive index of fluorite is 1.43, whereas that of a garnet is 1.8. How much faster does light travel in fluorite than in garnet?*

If the refractive index of fluorite is 1.43 and that of garnet is 1.8, then, using the definition of refractive index, we can express the velocity of light in air as:
Velocity in air = 1.43 × velocity in fluorite
Velocity in air = 1.8 × velocity in garnet
Therefore,
1.43 × velocity in fluorite = 1.8 × velocity in garnet
velocity in fluorite = (1.8/1.43) × velocity in garnet
velocity in fluorite = 1.26 × velocity in garnet.

6. *If a light ray with an angle of incidence of 30° passes from air into fluorite and into garnet with refractive indexes of 1.43 and 1.8, respectively, what would the angle of* *refraction be in both minerals? Through what angle would the light ray be bent in passing into each mineral?*

Because the refractive index of air is one, the angle of refraction of light entering the fluorite is given by Snell's law as

$\sin r = \sin 30 / 1.43.$

Hence the angle of refraction (r) is 20.5°.

Similarly, we can write for the garnet

$\sin r = \sin 30 / 1.8$

from which it follows that $r = 16.1°$.

The light ray, in passing from air into fluorite, would be bent through 39.5° (i.e., 60 – 20.5) and the ray entering the garnet would be bent 43.9° (i.e., 60 – 16.1).

7. *Why does the Becke line move into the mineral of higher refractive index when the microscope stage is lowered (distance between stage and lens increases)?*

A mineral with a higher refractive index than its surroundings tends to act as a lens and refracts light crossing its margins into the grain. Hence, when we focus the microscope slightly above the grain, we see this refracted light producing a brighter line (Becke line) just inside the grain boundary.

8. *When you say a mineral has positive relief, with what refractive index are you comparing the mineral?*

The comparison is made with the refractive index of the common mounting medium for thin sections, Canada balsam, which has a refractive index of 1.537.

9. *What materials are isotropic?*

All crystals belonging to the isometric system and all amorphous materials such as glass are isotropic; that is, they have only one refractive index regardless of the direction in which light passes through them.

10. *Calcite is birefringent with maximum and minimum refractive indexes of 1.66 and 1.49, respectively. What are the relative velocities of light traveling in the directions that give these two refractive indexes?*

Using the definition for refractive index, we can write

$1.66 \times \text{slow velocity} = 1.49 \times \text{fast velocity}$

The fast velocity is therefore 1.11 times the slow velocity.

11. *Why do birefringent minerals create interference colors under crossed polarizers?*

When polarized light enters a birefringent mineral, it is forced to vibrate in two mutually perpendicular planes, one in which the light travels slower than in the other. When these two vibration directions are recombined in the upper polarizer they are out of phase, because of their different velocities, and this produces interference colors.

12. *Why does the order of the interference color increase as the birefringence increases?*

As the birefringence increases, the velocity of the fast and slow vibration directions in the mineral become increasingly different. When the upper polarizer combines these two vibration directions, the greater the velocity difference the more the waves are out of phase, and the higher is the order of the interference color.

13. *What is a first-order-red interference filter and what is the normal orientation of its fast- and slow-vibration directions?*

A first-order-red interference filter is a piece of quartz or gypsum that is ground to a thickness that produces a first order red interference color. Its fast-vibration direction is usually oriented parallel to the length of the accessory plate.

14. *When a mineral is in extinction, what can we say about the orientation of its fast- and slow-vibration directions?*

If a mineral is in extinction, its fast- and slow-vibration directions must parallel the polarizers. To determine which is fast and which is slow, the grain must be rotated through 45° and the accessory plate inserted so that the fast and slow vibration directions in the accessory plate can be compared with those in the mineral (addition or subtraction).

15. *All micas are length slow. What does this mean, and what test could you apply with an interference filter to check that a grain is length slow?*

Crystals of mica tend to be plate like, with the prominent basal cleavage (001) paralleling the plates. When sliced at a random angle, plates tend to give an elongated section through the crystal. The slow-vibration direction travels in this basal plane and the fast-vibration direction travels perpendicular to the basal cleavage. Elongated crystals of mica are consequently always length slow; that is, the slow-vibration direction parallels the length of the crystal. To determine if a grain is length slow the grain can be rotated to the 45° position, so that it parallels the fast-vibration direction of the first-order-red accessory plate or quartz wedge and subtraction will occur; that is, the order of the interference color of the grain will decrease.

16. *If you have a centered uniaxial optic axis figure (a cross) and you insert a first-order-red interference filter and the northwest and southeast quadrants turn blue and the northeast and southwest quadrants turn yellow, what is the optic sign of the mineral?*

Because the ordinary and extra-ordinary rays add to the fast and slow vibration directions in the accessory plate in the northwest quadrant, the extra-ordinary vibration direction is fast. Because the extra-ordinary ray is faster than the ordinary ray, it has a lower refractive index. The indicatrix is therefore oblate and the mineral is negative.

17. *A centered biaxial optic axis figure has a curved isogyre extending from the northwest to southeast quadrants and is convex toward the northeast quadrant. On inserting a first order red interference filter, the region to the northeast of the isogyre turns yellow and to the southwest of the isogyre turns blue. What is the optic sign of the mineral?*

To the right of the curving isogyre, the *y* vibration direction trends from northwest to southeast and is parallel to the tangent to the isogyre at the center of the field. Because the interference color in this region turns yellow when the first-order-red interference filter is inserted, the *y* direction must not match the fast-vibration direction in the filter; consequently, *y* must be slow and the vibration direction at right angles to it must be fast and hence be the *x*-vibration direction. This means that z must lie in the acute bisectrix, and by definition, this means the mineral is positive.

Solutions to Chapter 7 Problems

1. *What are the differences between major, minor, and trace elements?*

Major elements are present in a chemical analysis in large amounts (over one weight percent). *Minor elements* range in abundance from 1.0 to 0.1 weight percent. *Trace elements* occur in much smaller amounts (less than 0.1 weight percent) and are commonly reported as parts per million (ppm) or parts per billion (ppb).

2. *In what components are the chemical analyses of silicates most commonly expressed?*

Components of chemical analyses of silicates are most commonly presented as oxides.

3. *Recalculate the following chemical analysis of an alkali feldspar into its formula: SiO_2 = 65.67, Al_2O_3 = 20.84, CaO = 0.50, Na_2O = 7.59, and K_2O = 5.49 weight %. Remember to look up the number of oxygens per formula unit for feldspar.*

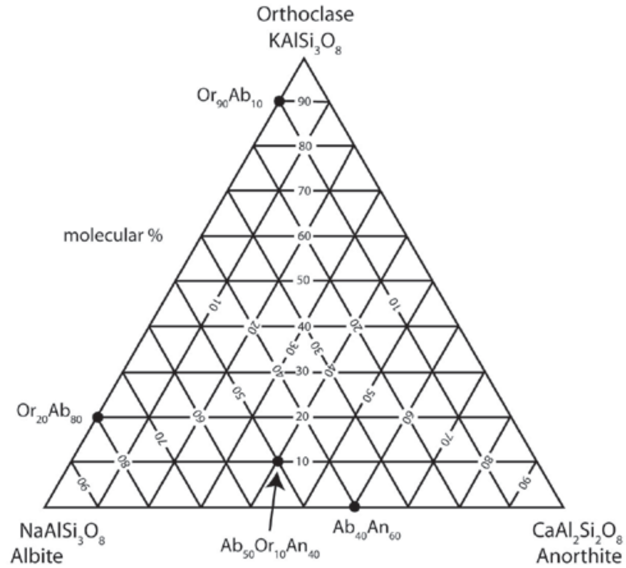
Chemical Analysis (weight %)		Molecular weights	Molecular proportions	Cation proportions	Number of oxygens	Number of cations per 8 oxygens
SiO_2	65.67	60.08	1.0930	1.0930	2.1860	2.934 } 4.03
Al_2O_3	20.84	101.96	0.2044	0.4088	0.6132	1.097
Na_2O	7.59	61.98	0.1225	0.2450	0.1225	0.658 } 0.97
K_2O	5.49	94.20	0.0583	0.1160	0.0583	0.311

Total oxygens = 2.980

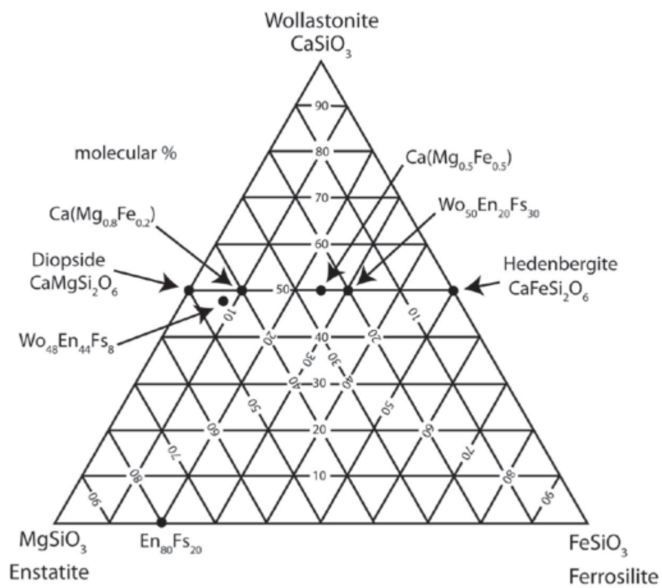
Oxygen factor $\frac{8}{2.980}$ = 2.6846

Final alkali feldspar formula: $(Na, K)_1(Al, Si)_4O_8$

4. *On a triangular diagram, corners represent the feldspar end members: $KAlSi_3O_8$ (at the top), $NaAlSi_3O_8$ (at the lower left), and $CaAl_2Si_2O_8$ (at the lower right). On this diagram plot the following compositions: $Or_{90}Ab_{10}$; $Or_{20}Ab_{80}$; $Ab_{40}An_{60}$; and Ab_{50} Or_{10} An_{40}*



5. *On a triangular diagram having corners representing $CaSiO_3$ (top), $MgSiO_3$ (lower left) and $FeSiO_3$ (lower right), plot the end-member compositions of diopside and hedenbergite. Also plot the following: En_{80} Fs_{20}; $Ca(Mg_{0.5}$ $Fe_{0.5})$ Si_2O_6; $Ca(Mg_{0.8}$ $Fe_{0.2})$ Si_2O_6; also Wo_{48} En_{44} Fs_8 and Wo_{50} En_{20} Fs_{30}*



6. *What are the three polymorphs of K-feldspar?*

The three polymorphs of K-feldspar are microcline, orthoclase, and sanidine.

7. *How do these three differ in atomic structure, and what is the main factor that controls these structures in the first place?*

The main difference between these three structures is the way in which Al^{3+} is housed in the infinitely extending framework of tetrahedra. In microcline one Al^{3+} occupies one specific tetrahedral site (as one $A1^{3+}$ tetrahedron linked to three other Si^{4+} occupied tetrahedra; as in the formula $KAlSi_3O_8$). In orthoclase the one Al^{3+} ion is statistically evenly distributed over two tetrahedra, each with a site occupancy of (Si ½ Al ½), and in sanidine the Al^{3+} ion is statistically evenly distributed over four tetrahedral sites each with site occupancy of (Si ¾ Al ¼). The Al distribution in microcline is referred to as ordered; that in orthoclase as partial order (or partial disorder); and that in sanidine as total disorder. The extent of ordering is a function of the temperature at which the K-feldspar formed. Microcline represents low temperature of formation, and sanidine high temperature of formation as in volcanic rocks.

8. *What are the end-member formulas of the plagioclase feldspar series?*

The end-member formulas for plagioclase are: $NaAlSi_3O_8$ and $CaAl_2Si_2O_8$.

9. *What is a highly diagnostic physical property of the plagioclase series?*

The presence of polysynthetic twinning, also known as albite twinning, is a highly diagnostic physical property of the plagioclase series.

10. *The most common occurrence of SiO_2 is as quartz. What are the names of the other four polymorphs?*

The other four relatively common polymorphs of quartz are tridymite, cristobalite, coesite, and stishovite.

11. *Which of these represent high-temperature forms of SiO_2, and which represent high-pressure forms?*

Tridymite and cristobalite are high-temperature polymorphs of SiO_2, and coesite and stishovite are high-pressure polymorphs.

12. *What are three colored gem varieties of quartz?*

Colored gem varieties of quartz are amethyst, citrine, and rose quartz.

13. *How do the crystal structures of nepheline and leucite differ from those of the feldspars?*

The crystal structures of nepheline and leucite are framework silicates with a somewhat more open spacing than that found in feldspars.

14. *To what silicate group do nepheline and leucite belong?*

Both are members of the feldspathoid group of silicates.

15. *What are three common igneous pyroxenes?*

Three common igneous pyroxenes are enstatite (a member of the orthopyroxenes), augite, and aegirine (both members of the clinopyroxenes).

16. *How do the structures of pyroxenes and amphiboles differ?*

Pyroxenes and amphiboles are both members of the structural group of silicates known as chain silicates, or inosilicates. In both groups the chains are infinitely extending tetrahedral chains. However, in pyroxenes they are single chains, whereas in amphiboles they are double chains.

17. *What are three common igneous silicates that tend to be dark green in color?*

Three common green igneous silicates are augite, aegirine, and hornblende.

18. *What are three common igneous members of the mica group?*

Common igneous members of the mica group are: muscovite, phlogopite, and biotite.

19. *What distinguishes the crystal structures of micas from those of the pyroxenes and amphiboles?*

The structural difference between micas and pyroxenes and amphiboles is the presence of infinitely extending tetrahedral sheets in mica instead of tetrahedral chains (single and double) as in the chain silicates. Micas are part of the structural silicate group known as layer silicates or phyllosilicates.

20. *The t-o-t layer in muscovite is described as dioctahedral; that in phlogopite is described as trioctahedral. What is the difference?*

Layer silicates are divided into two groups: dioctahedral and trioctahedral. This division reflects the atomic (ionic) site occupancy in the octahedral sheet that is “sandwiched” between two opposing tetrahedral sheets. In a dioctahedral sheet two adjacent octahedra are occupied by Al^{3+}, and a third octahedron is vacant. In a trioctahedral sheet all octahedra are occupied by Mg^{2+} and none are vacant. This is the result of the difference in the e.v. of Al-(OH) and Mg-(OH) bonds.

21. *Give the end-member compositions of the olivine series. What is meant by the gem name peridot?*

The olivine series extends chemically from Mg_2SiO_4 to Fe_2SiO_4. Peridot is a gem quality Mg-rich member of the olivine series.

22. *Give the chemical formula for zircon. Many zircons are described as metamict. What is meant by that?*

The formula for zircon is $ZrSiO_4$. Many zircons are referred to as metamict because their atomic structures have been damaged over time by “self irradiation” caused by the radioactive decay of small amounts of U and Th that are commonly housed in the zircon structure.

23. *The mineral tourmaline is most commonly black (schorl), but several gem varieties have very different colors. Why do tourmalines have so many different colors?*

Tourmaline is a ring silicate or cyclosilicate structure with a large number of atomic sites over which a range of chemical elements can be distributed. The abundant presence of one element over another, in a specific atomic site, is responsible for its wide range of colors.

24. *What is a unique aspect of the crystal structure of tourmaline?*

A unique aspect of the structure of tourmaline is the presence of six-membered tetrahedral (Si_6O_{18}) rings and three-membered (BO_3) rings interconnected by Na and Al in octahedral coordination.

25. *What are the names of three metallic oxides that may be present in igneous rocks as accessory minerals?*

Magnetite, hematite, and/or ilmenite.

26. *What are the names of two sulfides that occur as accessory minerals in igneous rocks?*

Pyrite and pyrrhotite.

27. *What is the name of the symbolic notation that is printed above the illustrations of the various crystal structures?*

Space group notation.

28. *How do you derive the notation of the crystal class (or point group) from what you answered in question 27?*

By removing all the operators in the space group notation that involve translation and replacing them with translation-free symmetry operations, the notation of the equivalent point group (or crystal class) is obtained.

Solutions to Chapter 8 Problems

1. *Is a steaming cup of hot coffee a closed or open system, where the cup defines the boundary of the system? Explain your answer.*

Because both heat and steam can leave the cup, the system is open.

2. *Lava, on crystallizing and cooling to ambient temperature, shrinks and commonly develops polygonal fractures (Fig. 10.14). According to the sign convention used in this book for work (W), does the lava shrinkage constitute a positive or negative amount of work?*

As the lava cools its volume decreases; that is, the change in volume is negative ($-\Delta V$). If the lava is on the surface of the Earth where the pressure is the ambient atmospheric pressure, the work done is $P \times -\Delta V$ or $-W$. So the work done on the system is negative.

3. *The molar enthalpies of formation of the two polymorphs of Al_2SiO_5, kyanite and andalusite, at standard temperature and pressure (STP), are –2593.1 and –2588.8 kJ, respectively. If one mole of kyanite were to change into one mole of andalusite at STP, would the reaction be exothermic or endothermic?*

It is important to start by writing the direction of the reaction as Kyanite → Andalusite. The change in enthalpy is therefore final minus the initial:

$$-2588.8 \text{ kJ} - (-2593.1 \text{ kJ}) = +4.3 \text{ kJ}$$

The change in enthalpy (ΔH) is therefore positive, which means heat was taken into the system during the reaction, and therefore the reaction is endothermic.

4. *In Section 5.8 we saw that potassium feldspar has three polymorphs: microcline, orthoclase, and sanidine. In microcline, Al^{3+} occupies only one of the four tetrahedral sites, whereas in sanidine it can occupy any of the four sites. Which of these two minerals has the higher entropy, and which would be stable at higher temperature?*

Al^{3+} has only one possible tetrahedral position in the structure of microcline but four in sanidine. The entropy of sanidine is therefore higher than that of microcline because of the increased number of ways of arranging the atoms. The higher entropy means that the Gibbs free energy of sanidine will be lower at higher temperatures than that of microcline ($(\Delta G/\Delta T)_P = -S$) and will therefore make sanidine more stable than microcline at high temperature.

5. *The mineral jadeite ($NaAlSi_2O_6$) (Sec. 16.18) has a composition intermediate between albite and nepheline, so it is possible to write a reaction for its formation as follows:*

$$NaAlSi_3O_8 + NaAlSiO_4 \Rightarrow 2\ NaAlSi_2O_6$$

albite nepheline jadeite

At low pressure, albite and nepheline are stable together, and only at high pressure does jadeite become stable (see Ch. 15). a) At low pressure, what can you say about the Gibbs free energy of albite + nepheline versus that of jadeite? b) If jadeite is to become stable at high pressure, what must happen to the free energy of these minerals with increasing pressure? c) Knowing how the Gibbs free energy varies with pressure, what can you say about the molar volumes and consequently densities of albite and nepheline versus that of jadeite?

a) Because ($(\Delta G/\Delta T)_P = -S$) are more stable than jadeite at low pressure their Gibbs free energy must be lower than that of jadeite.

b) If jadeite is to become more stable than albite + nepheline at high pressure its Gibbs free energy must decrease more rapidly with increasing pressure than that of albite + nepheline.

c) The change in free energy with pressure at constant temperature is equal to the molar volume of these minerals ($(\Delta G/\Delta P)_T = V$). For jadeite to become the stable phase at high pressure, its molar volume must be smaller than the combined molar volumes of albite + nepheline. This means that jadeite is a denser mineral.

6. *If the chemical potential, μ_i, is the intensive measure of the contribution of component i to the Gibbs free energy of a system, what is the extensive variable by which it must be multiplied to give its actual energy contribution to the system?*

The extensive variable by which the intensive variable μ_i must be multiplied is the number of moles of that component, n_i.

7. *When a system is at equilibrium, what can you say about the intensive variables? List all of the common intensive variables that might apply to the plagioclase crystal in Figure 8.13(B). Explain why this crystal cannot be at equilibrium.*

When a system is at equilibrium all intensive variables must be the same throughout the system. These variables would include temperature, pressure, and chemical potential (hence composition). The plagioclase crystal in Figure 8.13(B) is strongly zoned so cannot be at equilibrium. Given time, diffusion would try to homogenize this crystal.

8. *When ice changes to water, the entropy obviously increases because of the more random structure of water. However, unlike almost all other solid to liquid* *transitions, water has a smaller volume than ice (ice floats in water). What can you conclude about the slope of this transition in a P-T phase diagram?*

The slope of a reaction line in a *P-T* phase diagram is given by the Clapeyron equation ($\Delta P/\Delta T = (\Delta S_{\text{reaction}})_P$ / $(\Delta V_{\text{reaction}})_T$). For the ice to water reaction the ΔS is positive but the ΔV is negative, so the slope of the reaction in a *P-T* phase diagram is negative; that is, ice will tend to melt with increasing pressure.

9. *If you were able to lower a thermocouple into a cooling and crystallizing lava to measure its temperature, how might you detect when that lava reached a eutectic temperature? (Hint; think of the Gibbs phase rule).*

At the eutectic, the number of phases present is at a maximum and the degrees of freedom are zero. Therefore the temperature cannot change while crystallization proceeds. The temperature indicated by the thermocouple would therefore remain constant at a eutectic.

10. *Why is the eutectic of importance in determining the composition of magmas?*

The eutectic is the lowest possible temperature at which an assemblage of minerals can melt. Because the Earth does not have excess amounts of heat, only in rare situations does the temperature reach the beginning of melting of rocks. At this temperature only liquids of eutectic composition can form. As a result most magmas have near-eutectic compositions. An exception occurs where melting involves a peritectic (incongruent melting), in which case the minimum melting composition would have the peritectic composition.

11. *What is a porphyritic rock, and what does it tell you about the composition of the magma from which it formed relative to the eutectic composition?*

A porphyritic rock contains large crystals set in a finer-grained groundmass. These large crystals, known as phenocrysts, crystallized from the melt first and had time to grow to a larger size than later formed crystals. Phenocrysts are composed of minerals that were present in the melt in proportions in excess of those in the eutectic mixture. They therefore crystallized earlier before the residual liquid reached a eutectic composition. The presence of phenocrysts also indicates that an igneous rock could not have been superheated (a temperature above the liquidus) at the time of its formation; that is, the magma’s temperature must have been between the liquidus and solidus.

12. *Using the lever rule, measure the proportion of liquid to anorthite in the magma of composition z in Figure 8.9 at a temperature of T_1.*

According to the lever rule, the proportion of liquid to anorthite is given by the relative lengths of the lines *za* to l_1z respectively. The relative lengths of these two lines are 34/20 or 1.7/1.

13. *What evidence indicates that magmas are rarely superheated?*

Most volcanic rocks are porphyritic, which indicates that the magma from which they formed was on the liquidus of the phenocrystic phase when it cooled. If magmas were super-heated, one would expect to find rapidly quenched volcanic rocks that contained no phenocrysts. Such rocks are extremely rare.

14. *Using the phase diagram for nepheline-quartz (Fig. 8.10), explain how igneous rocks can be classified as either alkaline or tholeiitic.*

In the nepheline-quartz phase diagram, the congruently melting mineral albite divides the diagram in two, with melts having compositions on the quartz side of albite eventually crystallizing at the albite-quartz eutectic, and melts having compositions on the nepheline side of albite eventually crystallizing at the albite-nepheline eutectic. The composition of albite in this diagram, therefore, provides a natural division between magmas that eventually crystallize either quartz (tholeiitic) or nepheline (alkaline). Even magmas that contain very low concentrations of the minerals in this phase diagram, such as basalt, eventually crystallize a small amount of residual liquid that plots at one or the other of these eutectics.

15. *If rock containing a 50/50 weight % mixture of forsterite and enstatite (Fig. 8.11(A)) were heated just to the beginning of melting and the liquid was removed to form a magma that rose toward the surface, what mixture of minerals would this magma eventually crystallize on cooling?*

Melting of this mixture would produce a peritectic liquid (P in Fig. 8.11(A)). If this liquid were separated from the solids from which it formed, it would, on cooling, first crystallize enstatite until it reached the eutectic with quartz, whereupon a eutectic mixture of enstatite and quartz would crystallize. The weight proportion of enstatite to quartz in the final rock would be 94% to 6%, respectively.

16. *If olivine liquid containing 50 weight % forsterite (x in Fig. 8.12) were cooled slowly until it was 50% crystallized, and then all of the crystals were separated from the* *liquid (perhaps as a result of crystal settling) what composition would the remaining liquid have (use the lever rule)?*

Chose a point on the vertical line below x in Figure 8.12 where the distance from this line to the solidus and to the liquidus are equal. At this temperature the initial liquid x is 50% crystallized. The composition of the remaining liquid can then be read by dropping a vertical line from the liquid to the horizontal axis at the base of the diagram. This composition is 35 weight % forsterite – 65 weight % fayalite.

17. *In light of your answer to question 16, what general conclusion can you draw about the effect of fractional crystallization on the composition of magmas?*

Fractional crystallization in the olivine system leads to enrichment of the residual melt in the fayalite component; that is, the residual liquid becomes enriched in iron.

18. *Can you think of a reason why olivine phenocrysts show very little compositional zoning, whereas plagioclase phenocrysts are almost always zoned, despite the similarity in the phase diagrams for these two solid solution series (Figs. 8.12 and 8.13)?*

Zoning of crystals belonging to a solid solution series crystallizing from a melt is caused by the failure of the crystals to homogenize their composition so as to be in equilibrium with the liquid as it cools. Although the rim of a crystal might be able to equilibrate with the liquid, the core of the crystal may not because diffusion through the crystal is a slow process. Olivine has to adjust its Mg^{2+}/Fe^{2+} as it crystallizes, whereas plagioclase, because of coupled substitution (see Sec. 4.6.1), has to adjust its $(Ca^{2+}+Al^{3+})/(Na^{+}+Si^{4+})$. The diffusion of these components through plagioclase, especially Al^{3+} is very much slower than the diffusion of Mg^{2+} and Fe^{2+} through olivine. As a result, there is usually not enough time for plagioclase to adjust its composition, whereas olivine can homogenize itself quite rapidly.

19. *Discuss the differences between hypersolvus and subsolvus granites, and explain why subsolvus granites are less likely to rise to the surface than hypersolvus granites.*

Hypersolvus granites crystallize at high temperatures above the alkali-feldspar solvus; they therefore crystallize a single alkali feldspar, which may exsolve on cooling to form a perthitic intergrowth. Subsolvus granites crystallize at lower temperatures below the alkali-feldspar solvus; they therefore crystallize two types of feldspar, a potassium-rich and a sodium-rich alkali feldspar. The difference in crystallization temperatures reflects differences in water content, hypersolvus granites being relatively dry and subsolvus granites being relatively wet. Water requires high pressure to be soluble in magma. As magma rises toward the surface and the pressure decreases, the water comes out of solution, and the magma crystallizes. Wet magmas therefore cannot rise far without solidifying. Dry hypersolvus granite does not have the same restriction.

20. *The following questions relate to magma of composition y in Figure 8.15(B). a) What mineral first crystallizes from this magma? b) When the magma first arrives at the cotectic, what percentage of the magma has crystallized? c) When the magma first arrives at the eutectic, what percentage of crystals is present and what composition do they have?*

a) Because the composition *y* plots in the liquidus field of mineral B, crystals of B will form first.
b) The percentage of magma crystallized when the liquid composition reaches the cotectic is given by the ratio of the lengths of the line B*y* to B*l*, where *l* is the composition of the cotectic liquid at the point of intersection of a straight line drawn from the apex B through y to its intersection with the cotectic; that is, % crystallized = 100 × B*y*/B*l*. Measuring from the diagram in millimeters gives % crystallized = 100 × 23/38 = 60.5%.
c) When the liquid first arrives at the eutectic, the only minerals that would have crystallized so far would be B and C. Therefore, their bulk composition must plot on the B-C side of the triangle. This mixture of B and C, when added to the remaining eutectic liquid, must add up to the starting composition *y*. According to the lever rule, the percentage of crystals formed when the liquid first reaches the eutectic would be determined from the relative lengths of the line drawn from the eutectic to point *y* ($l_e y$) to the line from the eutectic through *y* to the BC side of the triangle (l_eBC). This indicates 66.7% crystallization. The proportions of B and C that have crystallized is given by the point of intersection of this line with the B-C side of the triangle, which indicates 80% B and 20% C.

21. *What do all transport laws have in common?*

They all have two terms; one expresses the force causing the movement and the other indicates the resistance to movement. The product of these two terms, normally expressed as a flux, gives the quantity of the material transported per square meter per unit of time.

22. *Why do the rates of chemical reactions increase dramatically with increasing temperature?*

The rates of many reactions obey an Arrhenius type relation, where an activation energy sets a barrier that must be exceeded for the reaction to proceed. The fraction of atoms that exceed this barrier is exponentially related to temperature. Thus a small increase in temperature creates a large increase in reaction rate.

23. *What four ways can radioactive nuclides decay?*

The four ways in which radioactive decay can occur are: 1) Emission of an alpha particle (helium nucleus –2 protons and 2 neutrons from the nucleus of the atom; 2) Emission of a beta particle (electron) from the nucleus of an atom, converting a neutron into a proton; 3) Capture of an electron by the nucleus, converting a proton into a neutron; and fission of the atom into two nuclei of approximately equal atomic mass.

24. *What mechanisms must be involved in the decay of* $^{232}_{90}\mathrm{Th}$ *to* $^{208}_{82}\mathrm{Pb}$*?*

Because this decay causes the atomic mass to decrease by from 232 to 208, this mass loss of 24 means that 6 alpha particles must have been emitted. However, the loss of 6 alpha particles would result in a loss of 12 protons, which means the atomic number would have been reduced from 90 to 78. However the lead has 82 protons. Four more protons must therefore be gained, which is accomplished by 4 neutrons in the thorium changing into protons by emitting 4 beta particles. The total decay of $^{232}_{90}\mathrm{Th}$ to $^{208}_{82}\mathrm{Pb}$ must involve the emission of 6 alpha and 4 beta particles.

25. *What is an isochron and how does it give you both an age and an initial isotopic content of the daughter isotope on which the age is based?*

A problem in determining the absolute age of a mineral or rock from the abundance of a radioactive nuclide and its daughter product is that some of the daughter isotope may already have been present at the time of formation of the mineral or rock. Without knowledge of this initial content of the daughter isotope an age cannot be determined. However, if several minerals or rocks with different contents of the radioactive nuclide were formed at the same time, and it is assumed they all contained the same initial content of the daughter isotope, then their age can be determined. This is obtained by plotting the abundance of the radioactive parent versus the abundance of the daughter isotope, both of which are expressed as a ratio to the abundance of a stable isotope of the daughter element. Because the different minerals and rocks have different amounts of the radioactive parent, the data are spread out in an array in the graph. However, because all of the data points are the same age, a statistically fit line through these points is referred to as an isoochron (equal age). The slope of this line gives the age of the samples, becoming steeper as time progresses. The intercept of this line with the axis on which the daughter isotope is plotted gives the initial value of the daughter isotope.

Solutions to Chapter 9 Problems

1. *What is the evidence that Earth's crust and mantle are normally solid?*

The transmission of seismic shear waves, which will not pass through a liquid, are able to pass through the crust and mantle. These regions must therefore be largely solid. Low seismic velocities in the asthenosphere probably result from the presence of small amounts of melt, which wets grain boundaries and is unable to escape from this zone.

2. *How do we know that the upper mantle is composed of peridotite?*

Samples of rocks from the upper mantle are brought to the surface in diatreme breccias, which are pipe-like bodies of rock that are emplaced explosively from great depth. The breccia consists of a mixture of fragments of all the rocks the diatreme passes through on the way to the surface. The presence of high-pressure minerals, including diamond (the high-pressure polymorph of carbon), indicates that some of the fragments come from considerable depth. The most common type of fragment with minerals indicating an upper mantle source are composed predominantly of olivine and pyroxene and are therefore the rock type peridotite.

3. *If the geotherm is normally well below the beginning of melting temperature of anhydrous mantle peridotite, what three mechanisms can cause melting of this peridotite?*

The peridotite can be heated by a mantle plume, undergo decompression, or have its melting point lowered by the addition of water.

4. *What plate tectonic settings provide the conditions for the three different melting mechanisms of mantle peridotite, and what composition magmas are generated at each?*

Heating of mantle peridotite can occur in the vicinity of a mantle plume, which brings up heat from possibly as deep as the core-mantle boundary. Melting of the mantle over a mantle plume generates basaltic magma.

Decompression melting occurs at divergent plate boundaries, where the asthenosphere rises in response to the divergence of the plates to produce basaltic magma.

As hydrothermally altered ocean-floor rocks are metamorphosed during subduction at convergent plate boundaries water is released into the overlying mantle wedge. The water lowers the melting point of the mantle peridotite, with formation of andesitic magma.

5. *What is the latent heat of fusion, and why does it limit the amount of melting that takes place in the Earth?*

When any solid is converted to liquid, a certain amount of heat is required to change the solid into liquid. This heat does not change the temperature but supplies only the energy necessary for the change in structure between the solid and liquid states. This is known as the latent heat of fusion. The latent heat of fusion of rocks is large (400 kJ/kg). Because the Earth does not have excess heat, if a rock is able to get to the melting point, the large latent heat of fusion results in only a small amount of melt forming.

6. *Calculate the pressure at the base of an 11 km-thick oceanic crust with an average density of 3000 kg/m*^{3}*. Make the calculation for an oceanic ridge that just reaches the ocean surface (e.g., Iceland) so no account need be taken of the density of water.*

The pressure at the base of the crust can be calculated using Equation in Section 9.3.1.

$P = 3000 \times 9.8 \times 11 \times 10^3 \quad (\text{kg/m}^3) \times (\text{m/s}^2) \times \text{m} = 0.3234\ \text{GPa}$

7. *Why does the melting point of anhydrous rock increase with increasing pressure?*

The change from rock to liquid involves an increase in volume, so increasing the pressure causes the liquid to change into solid, so the melting point increases with increasing pressure.

8. *Why does the melting point of hydrous rock decrease with increasing pressure?*

The melting temperature of a rock is decreased by having water dissolve in the melt, in the same way that salt lowers the melting point of ice. Water, however, requires pressure to dissolve in magma. Therefore as the pressure increases, the amount of water that is held in solution can increase, and the melting temperature decreases.

9. *Explain explosive volcanism in terms of the solubility of volatiles in magma.*

As magma approaches the surface, the decrease in pressure causes dissolved volatiles to exsolve. The formation of gas bubbles increases the buoyant force on the magma but increases its bulk viscosity, making it more difficult for the magma to flow. Continued exsolution and growth of the gas bubbles eventually allows the bubbles to touch one another, at which point the gas becomes the continuous phase in which are suspended particles of melt. The pressure generated by the exsolution of gas eventually ruptures the overlying rocks, and an explosive eruption ensues.

10. *Why do most calderas sink about 0.5 km?*

Most calderas are formed by rock sinking into the volatile-rich upper part of magma chambers. In the upper part of these bodies, volatiles may exsolve to form vesicles, creating a low density foam into which the roof rocks can collapse. At greater depth, the volatiles are held in solution and so the magma is denser. The thickness of this low-density frothy upper zone of the magma chamber is what probably limits the distance many calderas sink.

11. *Why are the viscosities of basaltic and rhyolitic magma so different?*

The viscosity of magma is strongly dependent on its silica content because this increases the abundance of polymerizing tetrahedrally coordinated silica groups. These groups form strong bonds that literally tie the melt structure in knots and increase the viscosity. Thus, rhyolite, with a relatively high content of silica, has a high viscosity. Basalt, in contrast, has a lower silica content, and its higher contents of iron and magnesium help isolate the silica tetrahedral groups and decrease its viscosity.

12. *What determines the grain size of an igneous rock?*

The grain size of an igneous rock is determined by the number of nuclei that form. If a large number of nuclei forms, a large number of crystals will result and the crystals will be small. If only a few nuclei form, they will grow to form only a few crystals, which will consequently be large. In general, rapid cooling produces more nuclei and hence finer-grained rocks.

13. *What determines the rate at which basaltic magma can escape from partially molten mantle peridotite?*

When basaltic liquid is first formed in the mantle it exists as thin films along grain boundaries in the mantle peridotite. Even though it may experience buoyant forces, it can flow only by porous flow, which obeys Darcy's law. However, the buoyant rise of liquid must be balanced by the sinking of an equivalent volume of solids. It is the rate of compaction of these solids that determines the rate at which the liquid can rise.

14. *Why does buoyant material segregate into regularly spaced domes when it begins to rise?*

When buoyant material rises, dense material must sink to conserve volume. The materials are trading places. This transfer could take place at all scales from minute dribbles to huge anticlines and synclines. The scale that dominates any given set of viscosities and layer thicknesses is the one that transfers material the most efficiently. The regularly spaced domes that result are an example of a Rayleigh-Taylor instability.

15. *You have been asked to walk out onto a newly crusted over lava lake in Hawaii 7.5 days (648 000 s) after the eruption. It is planned to bring in a helicopter with a large drilling rig as soon as the crust is 2 m thick. You carry a small portable drill, which allows you to determine that the crust is 1 m thick. How long will it be before the helicopter and drilling rig can land on the surface of the lava lake?*

The distance the crust has progressed beneath the surface is proportional to the square root of the cooling time. If we express the time in seconds, we can ratio these proportions for the 1 m and 2 m depths;

$\frac{1}{\sqrt{648000}} = \frac{2}{\sqrt{t}}$, which rearranges to give $t = \left(\frac{2 \times \sqrt{648000}}{1}\right)^2 = 259200$ s = 30 d*ays*

The helicopter should be able to land safely in one month.

16. *If plagioclase is neutrally buoyant in a basaltic magma, how can compaction of crystal mush lead to its concentration in the lower part of an igneous body?*

If plagioclase is intergrown with pyroxene to form a crystal mush, the bulk density of the mush will be greater than that of the interstitial liquid. The mush will be able to undergo compaction, with concentration of both pyroxene and plagioclase in the zone of compaction and expulsion upward of the residual liquid.

17. *If magmas do not have excess heat, where does heat come from to cause melting of included blocks of country rock?*

The heat needed for melting must come from the crystallization of primary minerals in the magma; that is, a balance must exist between the latent heat of fusion of country rock and the latent heat of crystallization of minerals in the magma. Thus, the production of melt in the country rock is accompanied by an equivalent amount of crystallization of the magma.

18. *Explain the difference in the rates at which the $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratios evolve in continental crust relative to the bulk Earth.*

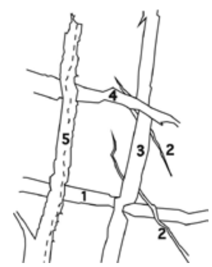
The continental crust has been formed by partial melts that separated from the mantle. One major period of crust formation occurred 2.5 billion years ago. When partial melting occurs in the mantle, certain elements partition more strongly into the melt than others. Samarium and neodymium are both rare earth elements, but neodymium, having a larger ionic radius, partitions more strongly into the melt than samarium. This means that the crust formed by the extraction of these melts will have a lower Sm/Nd ratio. Because it is ^{147}Sm that decays to ^{143}Nd, the ratio of $^{143}Nd/^{144}Nd$ will evolve more slowly in the crust than it would have in the bulk Earth or mantle. In contrast, rubidium partitions more strongly into melts than does strontium, and because it is 87 Rb that decays to 87 Sr.

Solutions to Chapter 10 Problems

1. *How do intrusive igneous bodies make room for themselves?*

Intrusive bodies make room for themselves by forcing aside the rocks they intrude. In regions undergoing extension, as for example near divergent plate boundaries, the magma intrudes as thin sheets oriented perpendicular to the extension direction. These sheets solidify to form dikes. Near the surface, especially in sequences of sedimentary rocks, where the minimum stress direction is vertical magma may form thin sheets parallel to the sedimentary layering and form sills. At great depth in the crust where rocks are plastic, buoyant magma may force aside rocks and rise as a diapir. Near the surface where rocks are brittle magma can ascend by stoping pieces from the roof of the magma chamber.

2. *From the crosscutting relations in Figure 10.2, deduce the chronology of intrusive events seen in this outcrop.*



The sequence of dikes and sills are numbered from 1 (oldest) to 5 (youngest). The felsic part (dashed line) of the composite dike is taken to be approximately the same age (very slightly younger) as the mafic part of dike 5.

3. *How do magma density and viscosity affect the shape of intrusive bodies?*

For magma to rise, its density must be less than that of the intruded rocks. The density of crustal rocks generally decreases toward the surface. Often magma rises to a level where its density matches that of the crustal rocks and then spreads laterally (level of neutral buoyancy). The buoyancy of magma provides the force needed to force aside the intruded rocks. The more viscous a magma, the more force is needed to intrude it. The viscous drag is greater in narrow conduits than wide ones. Fluid magma, such as basalt, can rise in narrow dikes, whereas extremely viscous magma, such as granite, rises more easily in large diapirs.

4. *Contrast the eruptive styles of Hawaiian, Strombolian, Vulcanian, Plinian, and Peléan volcanoes.*

These volcanic eruption styles show increasing degrees of explosive activity from Hawaiian to Peléan. Hawaiian eruptions are mainly of lava. Strombolian eruptions eject blobs of magma that land to form bombs. Vulcanian eruptions eject particles that are largely solid. Plinian eruptions eject columns of ash high into the atmosphere. Peléan eruptions consist largely of ash flows, which travel rapidly and are still hot when they stop flowing, and consequently the ash welds itself together to form a welded ash-flow tuff.

5. *How does magma viscosity affect the shape of volcanoes?*

With increasing viscosity, lava travels more slowly, and also it cannot rid itself of gas bubbles as easily. Consequently, viscous lavas do not travel as far as less viscous ones. The bubbles in more viscous lava may cause it to erupt explosively. Fluid basalt, therefore, can flow great distances upon eruption. This produces broad flat-topped shield volcanoes. Andesitic magma is more viscous, so the lava cannot travel far from the vent, and also it commonly erupts as ash to produce steep-sided conical composite volcanoes. Extremely viscous rhyolitic magma cannot flow at all unless it is extremely thick. It therefore erupts to form domes, with a crust that continuously cracks as the dome inflates itself from within.

6. *What is the difference between a mode and a norm?*

The mode is the actual volume percentage of minerals observed in a rock. It is normally determined by examining the area occupied by minerals in thin section. The norm expresses the percentage of simple anhydrous igneous minerals that are calculated from a chemical analysis of a rock following a prescribed set of rules. The CIPW norm is the most commonly used norm.

7. *Using the normative compositions of rocks in Table 10.1, plot each rock in Figure 10.25 and determine whether it has been correctly named according to the IUGS classification of igneous rocks.*

The norms given in Table 10.1 agree with those using the CIPW norm calculation on the US Geological Survey Volcano Hazards Program's Web site. The granite plots in the granite field but toward the granodiorite side. The nepheline syenite might plot in the nepheline monzosyenite field. The nepheline syenite norm contains 29.45% plagioclase of An_{11} composition. If we take approximately half of this plagioclase as being $<An_5$, and combine it with the normative orthoclase to form alkali feldspar, the rock plots at 24% along the AP line. This places the rock in the nepheline monzosyenite field. The granodiorite plots in the granodiorite field. The tonalite, with only 16% normative quartz and feldspars that plot 81% along the AP line would place it in the quartz monzodiorite field. The diorite, with 10% normative quartz and feldspar that plots at 84% along the AP line also plots in the quartz monzodiorite field. The gabbro, which contains 0.7% normative quartz and the feldspars plot at 90% along the AP line just makes it into field

10, and because the normative plagioclase is An_{57} the rock is correctly classified as gabbro.

8. *What name would you give to a rock composed of 50% olivine, 25% orthopyroxene, and 25% clinopyroxene? Much of the Earth's upper mantle is thought to have this composition.*

This rock is the type of peridotite known as lherzolite.

9. *What are the main rocks in an ophiolite suite, and how are they formed?*

The ophiolite suite consists of a group of rocks that are formed on the ocean floor but get obducted onto continents. From the top down they consist of chert, pillow lavas, sheeted dikes, layered gabbros, and serpentinized ultramafic rocks. The igneous rocks are formed at midocean ridges.

10. *Why are igneous rocks at midocean ridges so altered to hydrous minerals?*

Newly formed oceanic crust at divergent plate boundaries is cooled by ocean water circulating through it. This hot water alters many of the primary igneous minerals to hydrous minerals.

11. *How are sulfide ore deposits formed near midocean ridges?*

As ocean water circulates through hot newly formed oceanic crust, it is able to dissolve sulfides from the rocks. When this hot water flows back into the cold seawater, sulfides are precipitated. These build sulfide chimneys on the ocean floor known as *black smokers*. Plumes of sulfide-laden water rise from these chimneys and sink down onto the ocean floor forming a sulfide deposit.

12. *Why are so many oceanic islands generated over hot spots capped with alkaline rocks, even though the main volcano-building period erupts tholeiitic rocks?*

Only toward the end of the volcano building period, as the island moves off the hot spot, do the magmas become alkaline. This results from smaller degrees of melting and usually at greater depth. The final capping of an oceanic island is therefore often alkaline.

13. *What is a large igneous province, and what rock type characterizes such regions?*

Large igneous provinces are thought to develop above mantle plumes where large-scale melting of the mantle produces tholeiitic magma that erupts as flood basalts.

14. *What is inverted pigeonite, and how does it form?*

Inverted pigeonite is orthopyroxene that contains exsolution blebs and lamellae of augite that indicate the mineral originally crystallized as the clinopyroxene pigeonite. On slow cooling, the pigeonite inverts to orthopyroxene, which cannot hold as much augite in solution, so it exsolves the excess augite.

15. *What are some titanium-bearing minerals that form in alkaline rocks as a result of their high titanium content?*

Titanium enters pyroxene in alkaline rocks to form titanaugite. Common accessories are ulvöspinel (Fe_2TiO_4) dissolved in magnetite, ilmenite ($FeTiO_3$), and titanite ($CaTiO(SiO_4)$).

16. *What is kimberlite, and why is it of economic interest?*

Kimberlite is a phlogopite-rich rock that forms the matrix of some diatreme breccias. It is of economic interest because it brings up mantle nodules that may contain diamonds.

17. *What is carbonatite, and what economic mineral deposits are associated with it?*

Carbonatite is an igneous rock composed largely of calcite. It commonly contains the mineral pyrochlore, which is the chief ore mineral for the element niobium.

18. *What are the main calcalkaline rocks erupted in the volcanic arc above subduction zones, and what are their plutonic equivalents?*

The main calcalkaline rocks erupted in volcanic arcs are high-alumina basalt, andesite, dacite and rhyolite (BADR), and their plutonic equivalents are gabbro, diorite, granodiorite, and granite.

19. *What difference is there between volcanic rocks erupted on island arcs involving convergent oceanic plates and volcanic arcs developed on continental plates, and what is the likely cause of the difference?*

Calcalkaline rocks developed on continental plates have a larger percentage of felsic rocks than those developed on oceanic plates. The felsic rocks are most likely generated by melting of crustal rocks.

20. *What can you conclude about the history of an andesite (or diorite) from the complex zoning patterns in its plagioclase phenocrysts?*

The zoning patterns in plagioclase phenocrysts in andesites and diorites show that they have experienced multiple changes in temperature and have been in contact with magmas of different composition. Many are not in equilibrium with the melt in which they are found. These complexities point to magma mixing.

21. *What importance is attached to the ubiquitous occurrence of basaltic inclusions in rhyolite and granite?*

The ubiquitous presence of basaltic inclusions in rhyolite and granite indicates that intrusion of basaltic magma into the base of granitic magma chambers may be critical in providing the heat needed to keep them molten and to allow them to ascend.

22. *What is a komatiite, and what textural evidence shows that it was derived from an olivine-rich liquid?*

Komatiite is an ultramafic lava that formed only in the Archean. Its olivine occurs as long dendritic crystals that formed by rapid quenching of the lava. These quench crystals show that the liquid was olivine rich and that the olivine was not enriched by accumulation of early crystallized olivine from a basaltic magma.

23. *What distinguishes plagioclase in massif-type anorthosites from plagioclase in most other plutonic rocks?*

Plagioclase in massif-type anorthosites forms unusually large crystals that show no compositional zoning. The composition of plagioclase also remains almost constant across entire massifs.

Solutions to Chapter 11 Problems

1. *What is the number of polymorphs exhibited by ice?*

Ice occurs in six polymorphs as shown in Fig. 11.3(A). The one type of ice (ice IV) that is not shown (or listed) is a metastable transitional type between ice V and ice VI.

2. *What is the crystallographic system of ice that forms normally under freezing conditions?*

The ice that forms under normal freezing conditions (at atmospheric pressures) is ice I.

3. *What is the crystal form of ice and how is it exhibited?*

The crystal system of ice I is hexagonal as is clearly shown by the large variety of snowflakes with six-rayed patterns.

4. *What is the chemical formula of goethite?*

The formula for goethite is FeO(OH).

5. *What is the oxidation state of iron in goethite?*

The oxidation state of iron in goethite is Fe^{3+} in octahedral coordination with oxygen.

6. *Kaolinite can be pseudomorphous after what feldspar? Give the chemical formula of kaolinite.*

Kaolinite can be pseudomorphous after K-feldspar. K-feldspar is $KAlSi_3O_8$ and the formula for kaolinite is $Al_2Si_2O_5(OH)_4$.

7. *Kaolin is a major constituent of what commercially produced products?*

Kaolinite is a constituent of brick, paving brick, sewer pipe, draining tile, pottery and chinaware. It is also a filler in paper.

8. *Calcite and three other carbonates are isostructural. What does that mean, and which are the other three? What are their names and chemical formulas?*

Calcite, magnesite, siderite, and rhodochrosite are isostructural. This means that all four carbonates have the same atomic structural arrangement even though the major cations in these four minerals are different. Calcite = $CaCO_3$; magnesite = $MgCO_3$; siderite = $FeCO_3$; and rhodochrosite = $MnCO_3$.

9. *What is the main commercial use of limestone or calcite?*

Limestone or calcite are used extensively in the manufacture of cements and mortars. Limestone and its metamorphosed equivalent, marble, are commonly used in the building industry as dimension stone.

10. *What is the chemical formula of dolomite?*

The formula of dolomite is $CaMg\,(CO_3)_2$.

11. *What is different in the dolomite crystal structure as compared with that of calcite?*

There is considerable similarity between the structures of calcite and dolomite, but because of the large difference in size between Ca^{2+} and Mg^{2+}, the two cations are arranged in separate layers in the dolomite structure instead of substituting for each other in the Ca^{2+} position in the calcite structure.

12. *Halite is also known as table salt. What other major commercial uses does halite have?*

In addition to the use of halite in food products halite is a major source for the production of sodium and chlorine as well as hydrochloric acid.

13. *Agates can be very aesthetically appealing and are commonly on exhibit in museums of natural history and for sale in rock and mineral shops. What is so appealing about them?*

Agates are composed of microcrystalline to cryptocrystalline quartz, which allows for the preservation of many types of fine scale banding as well as color variations. When polished, or sliced and polished, agates can be highly desirable as artistic ornaments. Unique textured material is used in the jewelry industry.

14. *Phosphorites are mined for their content of what mineral? Give that mineral's name and chemical formula.*

Phosphorites are the main commercial source of fluorapatite, $Ca_5(PO_4)_3(F)$, which is a major constituent of fertilizer.

15. *Soils commonly show various horizontal soil horizons. How do these various layers differ?*

Soils are described in terms of soil horizons. The upper layer of the **A horizon** is usually enriched in organic matter relative to other horizons. The lower **B horizon** is typically enriched in clays such as kaolinite and montmorillonite. The **C horizon** is the lowermost horizon and consists generally of essentially unmodified parent material, bedrock.

Solutions to Chapter 12 Problems

1. *Explain how CO_2 in the atmosphere plays a role in weathering igneous rocks.*

Carbon dioxide combines with water in the atmosphere to form carbonic acid, according to Eq. 12.1. The carbonic acid is then able to react with the primary minerals of igneous rocks to produce hydrous minerals such as kaolinite and bicarbonate ions. The CO_2 can also react with minerals directly to produce carbonates.

2. *What are the typical weathering products of granite?*

The primary minerals of granite are quartz and alkali feldspar with possibly minor hornblende or biotite. On weathering, quartz remains stable and forms detrital grains. Alkali feldspar is converted to kaolinite, soluble K^+ and Na^+ ions, and siliceous acid. Hornblende and biotite also break down to form clay minerals, and though some of the iron may be removed in solution, some may be oxidized in the weathering zone and form limonite. Accessory minerals in the granite, such as magnetite and zircon, remain unaffected and form small detrital grains.

3. *If sediment is well sorted, what does this tell you about its grain-size distribution?*

It tells you that most of the grains have approximately the same diameter. If the grain-size distribution is plotted as a histogram on a phi scale (lognormal) and the distribution is normal, its standard deviation would be small.

4. *What features characterize mature sediment?*

Mature sediment has undergone considerable transport or been exposed to wave action for an extended period. The result is that the sediment is well sorted, and grains have been abraded to a sub-angular shape.

5. *What polymorph of $CaCO_3$ is most commonly precipitated by organisms to build their hard parts and does this change after the sediment is changed to limestone?*

Most organisms precipitate aragonite, which is the high-pressure polymorph of $CaCO_3$. During diagenesis, most aragonite is converted to calcite, which is the polymorph found in most limestones.

6. *Although calcareous plankton can be found throughout the oceans, why is no calcareous ooze found on the deepest ocean floor?*

As the tests of calcareous organisms sink toward the bottom of the deep ocean, the increased pressure and lower temperature cause CO_2 to become more soluble in the water, which increases the concentration of carbonic acid. This causes the calcareous organisms to dissolve before reaching the bottom.

7. *The faunal explosion at the beginning of the Cambrian produced many organisms that built hard parts of $CaCO_3$, and limestone becomes common in the geologic record, whereas before that it is relatively rare. What effect would this faunal explosion have had on the CO_2 content of the atmosphere?*

Prior to the Cambrian faunal explosion, the CO_2 content of the atmosphere in the Precambrian must have been much higher. The formation of limestones during the Phanerozoic has steadily decreased the CO_2 content of the atmosphere from 5000 ppm at the beginning of the Paleozoic to 390 ppm at present.

8. *What is meant by the oil window?*

The oil window is the temperature interval (60-120°C) in which organic material buried in sediment is converted to petroleum. If the temperature rises above this, petroleum is converted to natural gas, and if it is heated above 200°C it is converted to graphite

9. *Why, if NaCl is more abundant than $CaSO_4$ in seawater, is halite not more abundant than anhydrite (or gypsum) in evaporite deposits?*

Although NaCl is more abundant in seawater than $CaSO_4$, halite is very much more soluble than anhydrite or gypsum. Consequently, anhydrite and gypsum precipitate at a much earlier stage of evaporation from seawater than does halite. Only when evaporation is carried to extremes does halite start precipitating.

10. *Why is glacial till so poorly sorted?*

The rock debris that is moved along the base of a glacier includes everything from boulders to clay. The glacial ice scrapes off the bedrock surface and does not discriminate grain sizes any more than a bulldozer would. Only when glacial ice melts does flowing water start to separate grains of different size.

11. *How can you tell from Stokes' law (Box 9.5) that grain size is more important than density in determining settling rates?*

In Stokes' law, the diameter of a grain is squared, whereas all other terms are directly proportional to the settling velocity. Thus, doubling the diameter of a grain would quadruple its settling velocity, whereas doubling its density contrast would only double its settling velocity.

12. *How might you use mud cracks in a vertically dipping folded sedimentary rock to determine the original top?*

Mud starts drying out from the surface downward. Therefore, cracks start on the surface and propagate downward. Because the surface mud will have dried and shrunk more than the deeper mud the crack is wider at the top. If the layer of mud completely dries, the polygons may begin to curl and produce concave surfaces toward the top.

13. *How might you use cross-bedding in a vertically dipping folded sedimentary rock to determine the original top?*

Cross-beds tend to become horizontal and parallel to the main bedding plane at their lower end, but their upper end is truncated by the next overlying bed.

14. *How might you use a turbidity current in a vertically dipping folded sedimentary rock to determine the original top?*

Turbidity currents produce graded beds with coarse material at the base grading to fine material at the top.

15. *What are Milankovitch cycles, and how might they be recognized in a sequence of sedimentary rocks?*

Milankovitich cycles are climatic fluctuations produced by variations in the amount of solar energy received at any given latitude due to changes in the eccentricity (100 000 year) of the Earth's orbit around the Sun, and the tilt (40 000 years) and precession (21 000 years) of the Earth's axis. Because Milankovitch cycles are regular, sequences of sediment reflecting changes in climate should also take place on a regular basis. These variations could reflect changes from arid to wetter climate or from colder to warmer climate.

16. *What would a fining upward sequence of sediments tell you about changes in sea level?*

A fining up sequence is formed when sea level rises and transgresses the continent. Where previously sands had been deposited in shallow water, mud is now being deposited in deeper water.

17. *Why can passive continental margins have thick sequences of sediments?*

Passive continental margins are formed when continents rift apart. As new ocean crust formed at the divergent margin cools, it becomes denser and slowly subsides. The subsidence makes room for the deposition of sediment eroded from the continent and builds out a continental shelf.

18. *Why do sediments in rift and pull-apart basins lack maturity?*

Sediments are eroded rapidly from the surroundings of these basins because of the great relief formed by the faulting, and the sediment does not have far to go before being deposited in a basin. As a result, there is insufficient time for much sorting or weathering of feldspar. The sediment is therefore poorly sorted and contains considerable amounts of feldspar, two of the main characteristics of an immature sediment.

19. *Explain the role of pressure solution in the compaction and cementing of sediment.*

The solubility of grains is increased by pressure. Where compacting mineral grains impinge on each other, pressures are considerably higher than in the surrounding pore fluid. The grains consequently dissolve at these points of contact and precipitate on parts of the grains where they can grow into pore spaces. Pressure solution, consequently, plays two important roles; it allows grains to fit together more closely (compaction), and it fills in the pores with cement. The result is a solid rock.

Solutions to Chapter 13 Problems

1. *Sedimentary rocks can be divided into three main groups. What are these groups, and what are the main rock types in each?*

Siliciclastic sedimentary rocks include mudrocks, sandstones and conglomerates.
Biogenic sedimentary rocks include limestones, dolostones, cherts, and coal.
Chemical sedimentary rocks include evaporites, carbonate rocks, phosphorites, and banded iron-formations.

2. *What are siliciclastic sedimentary rocks, and from what type of sediment are they formed?*

Siliciclastic sedimentary rocks include mudrocks, sandstones, and conglomerates. They are formed from the detritus that is produced from the weathering of older rocks. They are composed predominantly of quartz and clay minerals, but may contain feldspars or rock fragments if they have not been exposed to lengthy transport and wave action, which tend to destroy these components. They may also contain concentrations of resistant dense minerals, such as magnetite, garnet, and zircon.

3. *What simple test allows you to determine whether mudrock contains silt- or clay-size particles?*

If you bite a mudrock between your teeth, silt-size particles will produce a grinding sensation, whereas clay-size particles won't.

4. *What makes shale fissile?*

Shale contains a large fraction of clay minerals. Clay minerals form small flakes, which on settling through water tend to align themselves parallel to the surface on which they are deposited. Mud containing a large percentage of clay minerals initially contains a high water content. On compaction and expulsion of the water, the clay particles become more strongly aligned parallel to the bedding. This preferred orientation of the clay particles in shales causes them to break apart parallel to the bedding, giving the rock a prominent fissility.

5. *What destroys fine-scale laminations in mudrocks?*

Organisms burrowing in mud destroy fine-scale laminations. This is known as bioturbation.

6. *What determines the color of mudrocks?*

The color of mudrocks is determined primarily by the oxidation state of iron in these rocks. In mud that is deposited in shallow water, where there is contact with the atmosphere, iron is in the ferric state, and mudrocks are brown to red. However, if mud is deposited in deeper water, especially if the mud contains abundant organic remains, the conditions become anoxic, and iron is reduced to the ferrous state. This makes the mudrock green, or in the case of a high organic content, black.

7. *How do rip-up clasts form?*

When a layer of mud dries out, it shrinks and forms mud cracks. When water next flows across the mud cracks, pieces of the desiccated layer can be ripped up and transported along with the other sediment being carried by the water. These fragments are then deposited as rip-up clasts.

8. *Where do the thickest mudrocks occur, and what plate tectonic significance do such deposits have?*

The thickest accumulations of mudrocks occur in forearc basins at convergent plate boundaries, where they commonly form graded beds, which indicates deposition from turbidity currents. The relief on mountain ranges at convergent plate boundaries provides an ample source for this detrital sediment.

9. *The object of this question is to determine the percentage of clay matrix in the photomicrograph of Potsdam Sandstone shown in Figure 13.7(A) using the NIH ImageJ program. First, download the photomicrograph from the textbook's Web site (www.cambridge.org/earthmaterials) and import the image into the ImageJ program. Follow the instructions given in Box 6.2 to determine the percentage of clay matrix. (Answer ~9.2%)*

By following the instructions in Box 6.2, the percentage of clay matrix in this sandstone can be determined to be approximately 9.2%. The precise value obtained will depend on where the thresholds are set.

10. *If your answer to question 9 had indicated more than 15% matrix, what would you have called this sandstone?*

If the amount of matrix had exceeded 15%, the sandstone would have been called a wacke.

11. *What features indicate that a sandstone is chemically and texturally mature?*

A mature sandstone is formed from sand that has either undergone considerable transport or has been washed by waves for an extended period of time. This tends to remove feldspar, both by abrasion and by chemical weathering, and hence increasing its quartz content. The abrasion that the sand undergoes during transport rounds off the sharp corners of detrital grains. So a mature sandstone contains little feldspar and the quartz grains are subangular to subrounded or rounded in the case of supermature sandstone.

12. *What are the differences between quartz arenite, feldspathic arenite, and litharenite?*

A quartz arenite is a sandstone composed almost entirely of quartz (<5% feldspar). A feldspathic arenite contains more than 25% feldspar, which is mainly alkali feldspar. This rock is also known as arkose. Lithic arenite is a sandstone containing more than 25% lithic clasts but less than 15% mud matrix.

13. *What bedding differences distinguish feldspathic arenite from wacke, and what does this tell you about the site of deposition?*

Feldspathic arenites are immature sedimentary rocks that commonly exhibit cross-bedding and are red, which indicates they were deposited rapidly in a fluvial environment. Wackes are also immature sedimentary rocks, but they are commonly characterized by graded beds and are typically a dark green or gray color, which indicates deposition in relatively deep water by turbidity currents.

14. *What is the difference between a clast-supported and a matrix-supported conglomerate, and what do these rocks tell you about the environment of deposition?*

In clast-supported conglomerates, the individual clasts make contact with each other, whereas in a matrix-supported conglomerate, the clasts are suspended in the matrix. A clast-supported conglomerate indicates deposition in a high energy environment where large particles could be transported – beach surf zones and rapidly flowing rivers. Matrix-supported conglomerates are formed when there is no separation of fine particles from coarse particles. Glacial till would be an example of such a conglomerate as would rock formed from a mud slide where large particles could be carried along in the mud.

15. *Why are mudrocks, sandstones, and conglomerates commonly interlayered in fluvial deposits?*

Rivers are the main transporters of detrital sediment. Consequently, we commonly find fluvial deposits containing mudrocks, sandstones, and conglomerates. Mudrocks are typically formed from sediment that was carried in suspension in rivers and was deposited during floods as overbank deposits on the flood plain. Cross-bedded sandstones are formed from the sediment that was carried as bedload in the river. Conglomerates are formed from sediment that was transported by rapidly flowing water or formed as a lag deposit when finer particles were washed away. Conglomerates are also formed from coarse sediment in alluvial fans.

16. *What conditions favor the growth of calcareous organisms that form limestone, and what restrictions does this place on their sites of deposition?*

Calcareous organisms that form limestone prefer warm clean water. Thus, they prefer low latitudes where water is far removed from any large influx of siliciclastic sediment, which could make water muddy and decrease the amount of light needed for growth.

17. *How do we classify carbonate sedimentary rocks?*

Carbonate sedimentary rocks are classified on the basis of their content of three distinct textural types of carbonate, which are: (1) primary carbonate grains, such as shell fragments, which are known as allochems; (2) fine-grained carbonate mud matrix; and (3) coarser-grained carbonate cement filling pore spaces.

18. *How would you distinguish carbonate cement from an allochem or calcareous mud?*

The carbonate cement that fills pore spaces in limestones and dolostones tends to form large clear crystals. Large carbonate grains that form fragments of organisms commonly have a dusty brown appearance in thin section due to minute inclusions. The calcareous mud matrix differs from the cement in being extremely fine grained.

19. *What is the connection between the enormous amount of chalk formed during the Cretaceous Period and plate tectonics?*

Rapid ocean-floor spreading during the Cretaceous caused mid-ocean ridges to grow higher, and this displaced water out of the oceans onto the continents to form epeiric seas. In these shallow seas, warm clean water provided an ideal environment in which the pelagic organisms that form chalk could thrive.

20. *What are the three main types of coal, and which releases the most heat upon combustion?*

Low-rank coal or lignite. Intermediate-rank coal or bituminous coal. Highest-rank coal or anthracite. Anthracite releases the most heat on combustion.

21. *What three types of rock are needed to form an oil field?*

First, a source rock is required, which is commonly an organic-rich black shale. Next, a highly porous and permeable reservoir rock is needed in which the oil can accumulate; this is commonly a porous sandstone or carbonate rock. Finally, an impermeable cap rock, such as shale or an evaporite deposit, is required to prevent the oil from escaping.

22. *What is the difference between porosity and permeability?*

Porosity is a measure of the percentage of voids in a rock. Permeability is a measure of how well-connected the pores are.

23. *What are some typical traps in which oil reservoirs may form?*

Anticlines, angular unconformities, and layers draped around salt domes can all provide traps for oil.

24. *What is the sequence of precipitation of evaporite minerals from seawater as it evaporates?*

As seawater evaporates, minerals precipitate in a sequence determined by their concentrations in seawater and by their solubilities. If seawater is steadily evaporated, the following minerals appear in sequence: first, calcite, followed by gypsum and anhydrite, then halite, and finally sylvite.

25. *What is the probable source of phosphorus in phosphorites?*

The apatite in phosphorites is precipitated from circulating groundwater that probably derives the phosphorus from animal remains that accumulate in shallow marine environments.

26. *What is banded iron-formation and what must happen to it to make it iron ore?*

Banded iron-formation is a Precambrian sedimentary rock of chemical origin that consists of thin beds of iron-bearing minerals commonly interlayered with chert. Although they typically contain only 30 weight % Fe, leaching of silica during supergene enrichment can increase this percentage to ore grade. Some metamorphosed iron-formations that have not undergone supergene enrichment are mined and converted to ore-grade material by beneficiation process that concentrate the iron minerals.

Solutions to Chapter 14 Problems

1. *How would you define the term* ***metamorphic mineral****?*

A metamorphic mineral is one that forms as a result of changes in temperature, pressure, and composition of fluids in the environment. Metamorphism causes the transformation of an existing rock type, which may be igneous, sedimentary, or metamorphic, into a new mineral assemblage.

2. *List six very common metamorphic minerals and/or mineral groups.*

Several common metamorphic minerals or mineral groups are garnets, chlorite, members of the mica group, three polymorphs of Al_2SiO_5 (andalusite, sillimanite, and kyanite), staurolite, diopside, and members of the amphibole group.

3. *What metamorphic minerals are common in Al-rich bulk compositions?*

The three polymorphs of Al_2SiO_5 are common in Al-rich bulk compositions, as are garnet, staurolite, and muscovite.

4. *What metamorphic minerals develop in calcium carbonate-rich bulk compositions?*

Common metamorphic reaction products of Ca-rich bulk compositions are diopside, tremolite-actinolite, and wollastonite.

5. *What type of amphibole (name and composition) might you expect in a metamorphosed iron-formation?*

Metamorphosed iron-formations are rich in iron and therefore iron-rich metamorphic minerals such as members of the cummingtonite-grunerite series (of amphiboles) and members of the orthopyroxene series would be expected to form.

6. *What are the acronyms for the two major compositional series of the garnets?*

The two major compositional series of garnets are known by the acronyms *pyralspite* and *ugrandite*.

7. *How were the acronyms for the two major groups of garnet arrived at?*

Pyralspite groups three garnet end-member composition names, namely those of pyrope, almandine, and spessartine. *Ugrandite* combines the names of uvarovite, grossular, and andradite. The pyralspite group represents those garnet compositions in which Mg^{2+}, Fe^{2+}, and Mn^{2+} substitute for each other in a specific atomic site referred to as the *A* site. The ugrandite group includes those garnet compositions in which Al^{3+}, Fe^{3+}, and Cr^{3+} substitute for each other in the *B* atomic site.

8. *What are some of the commercial uses of garnet?*

Garnet is used as an abrasive, as in garnet paper. Because of the wide color variations among garnets, they are widely used in the jewelry industry.

9. *What are the structural differences among the three polymorphs of Al_2SiO_5?*

The structural differences among the three polymorphs of Al_2SiO_5 are as follows: in andalusite the Al occurs in (AlO_6) octahedra as well as in 5-fold coordinated polyhedra; in sillimanite the Al is housed in (AlO_6) octahedra and (AlO_4) tetrahedra; and in kyanite the Al is positioned only in (AlO_6) octahedra.

10. *Which of the three polymorphs of Al_2SiO_5 is indicative of high-pressure metamorphism at low to moderate temperature?*

Kyanite is stable over a range of temperatures at high pressures.

11. *What is chiastolite?*

Chiastolite is a variety of andalusite with graphite inclusions arranged in a regular pattern forming a cruciform design.

12. *Staurolite is monoclinic in symmetry but is commonly referred to as pseudo-orthorhombic. Why?*

Staurolite has monoclinic symmetry, but because the ß angle (between the *a* and *c* axes) is so close to 90° (it ranges from 90.0 to 90.45°), the three crystallographic axes are essentially perpendicular to each other, as is the case in orthorhombic symmetry.

13. *What is the compositional difference between diopside and augite?*

Diopside is an end member of the clinopyroxene group, with formula $CaMg(Si_2O_6)$. Augite is structurally similar to diopside but has more chemical elements in substitution.

Some of the most common are Fe and Al substituting for some of Mg, Al substituting for some of the Si, and Na in partial substitution for Ca.

14. *Give some examples of light beige to brown amphiboles.*

Examples of light brown colored amphiboles are anthopyllite and members of the cummingtonite-grunerite series.

15. *Dark-green actinolite closely resembles dark-green hornblende. What are the main compositional differences between the two?*

Dark green actinolite is a member of the tremolite-actinolite series in which Fe substitutes for some of the Mg in the end-member composition of tremolite, $Ca_2Mg_5Si_8O_{22}(OH)_2$. Hornblende is commonly also dark green in color but is compositionally more complex than members of the tremolite-actinolite series. Hornblende contains significant amounts of Al^{3+}, which is distributed over tetrahedral sites, where it substitutes for Si^{4+}, and octahedral sites, where Mg^{2+}, Fe^{2+} are housed in actinolite. Hornblende may also contain considerable Na^+ and K^+ in the *A* atomic site, which is vacant in tremolite-actinolite.

16. *What is the most common amphibole asbestos?*

The most common amphibole asbestos is crocidolite, the asbestiform variety of riebeckite.

17. *Rhodonite is commonly recognized by its pink color. What is another Mn-containing pink mineral?*

Another Mn-containing pink mineral is rhodochrosite, $MnCO_3$.

18. *The crystal structure of talc, a layer silicate, is said to be trioctahedral. What is meant by that?*

In the atomic structure of talc, two tetrahedral sheets enclose between them an octahedral sheet, forming a *t-o-t* layer. The octahedral sheet houses the Mg^{2+}, which fills all octahedral positions in that sheet without intervening vacancies.

19. *What are some of the commercial uses of talc?*

Talc finds many applications commercially. It is used as a filler in paint and in paper production. It is a common constituent of ceramic tiles and plastic products. In the cosmetics industry, it is a major component of baby and body powders, facial products, and creams and lotions.

20. *What type of illustrations in this chapter show conclusively the very different crystal structures of the two polymorphs of serpentine?*

The two polymorphs that are referred to are antigorite and chrysotile. Their very different atomic structures are illustrated by photographs obtained by electron beam techniques. The structure of antigorite is shown by a high-resolution electron microscope (HRTEM) image in Figure 14.25(A), and that of chrysotile, by a transmission-electron-microscopy (TEM) photograph in Figure 14.27.

21. *What is chrysotile?*

Chrysotile is a common asbestos mineral, which constituted about 90% (or more) of all asbestos products prior to 1980.

22. *Cordierite is classified as a ring silicate. What is meant by that?*

Cordierite is classified as a ring silicate (or cyclosilicate) because of the presence of six-fold tetrahedral rings that house Al^{3+} and Si^{4+}.

23. *Among all the minerals listed as metamorphic only one is an oxide. What is its name and composition?*

The oxide is corundum, Al_2O_3.

24. *The oxide referred to in question 23 forms very high-end gemstones. Which are they?*

The gemstone varieties of corundum are ruby and sapphire.

25. *One of the gemstones in question 24 is blue. What is that color due to? Refer to Figure 3.7 to obtain your answer.*

A common color of sapphire is blue, although it is found in many other colors as well. The blue color is the result of strong absorption of white light in the infrared region but high transmission especially in the blue region of the visible part of the electromagnetic spectrum.

Solutions to Chapter 15 Problems

1. *What is metamorphism, and what are the main factors that cause it?*

Metamorphism is the sum of all those changes that occur in a rock as a result of changes in temperature, pressure, and composition of fluids in the environment. Changes in temperature can be caused by burial in the Earth, heat escaping from igneous bodies, friction in zones of intense shearing, and in rare cases, by meteorite impact. Changes in pressure are caused by burial and erosional exhumation, and in rare cases, by meteorite impact. In zones of tectonic-plate convergence directional stresses can cause minerals to grow with long axes normal to the maximum compressive stress, which produces foliated metamorphic rocks. Fluids escaping from buried sedimentary rocks or from metamorphic rocks undergoing reactions that release fluids carry many elements in solution which can change the composition of rocks through which they pass.

2. *What is the difference between regional metamorphic rocks and contact metamorphic rocks?*

Regional metamorphic rocks are formed in zones of tectonic plate convergence, where new platy and acicular minerals grow normal to the maximum compressive stress, which gives the rocks a prominent foliation (e.g., slate, schist, and gneiss). New contact metamorphic minerals that grow in the aureole of an igneous intrusion do not experience this directed stress and are therefore free to grow in any direction. Contact metamorphic rocks therefore lack foliation, and are often very massive and hard and are referred to as hornfels.

3. *What major constituents are lost during prograde regional metamorphism and what important roles do they play?*

The major constituents lost during prograde regional metamorphism are H_2O and CO_2. Most metamorphic reactions in pelitic sedimentary rocks release H_2O, and those that take place in carbonate rocks release CO_2. These volatiles are less dense than their surroundings and consequently migrate upwards. As they do so, they transport material in solution and also transfer heat, which affects the metamorphism taking place in overlying rocks. Veins of quartz and calcite are the result of the channelized flow of these escaping fluids.

4. *What is the Gibbs free energy and what happens to it during a metamorphic reaction?*

The Gibbs free energy is that energy which decreases during a natural process occurring at constant pressure and temperature and involving only work of expansion, such as a metamorphic reaction, and will reach a minimum value when the process achieves equilibrium (see Sect.8.4).

5. *How can we define equilibrium in the case of a metamorphic reaction?*

When a metamorphic reaction reaches equilibrium, no further decrease in the Gibbs free energy is possible; that is, the Gibbs free energy is at a minimum. In complex materials, such as minerals, rocks, magmas, and fluids, each component making up that material contributes to the total Gibbs free energy of the material; its contribution per mole to the Gibbs free energy is known as the chemical potential. At equilibrium, there can be no gradients in chemical potential, otherwise diffusion would take place and lower the Gibbs free energy. Nor can there be gradients in temperature or pressure (see Sect. 8.6 and 8.7).

6. *What determines the rate of a metamorphic reaction?*

The rate at which a metamorphic reaction occurs depends on how far and how rapidly atoms must travel to effect the reaction. Diffusion rates therefore control the rates of metamorphic reactions. Diffusion rates increase exponentially with temperature and they are far more rapid through fluids than through solids. High temperatures and the presence of fluids therefore accelerate metamorphic reactions (see Sect. 8.10.2).

7. *What does Gibbs phase rule tell you about the number of minerals you might expect to find in a metamorphic rock?*

Gibbs phase rule tells us that there is a simple relation between the number of minerals present (phases) in a rock, the number of components making up those minerals, and the degrees of freedom to change pressure, temperature, or composition (see Box 8.3). It predicts that, for rocks where the pressure and temperature can be changed without changing the mineral assemblage, the number of minerals present can be only two more than the number of components present. Thus, metamorphic rocks should contain a small number of minerals, if they are equilibrium assemblages.

8. *What are metamorphic index minerals and how do they relate to isograds?*

In a progressively metamorphosed terrane, increasing metamorphic grade is marked by the first appearance of a sequence of minerals, which are known as index minerals. Later, lines on maps marking the first appearance of these index minerals were thought to indicate equal grades of metamorphism and hence became known as isograds.

9. *What is a metamorphic mineral facies, and how is it used to determine metamorphic grade?*

A metamorphic mineral facies comprises rocks that have formed under temperature and pressure conditions that are so similar that a definite bulk-rock chemical composition results in the same set of minerals. If that bulk-rock chemical composition produces a different set of minerals, it must belong to a different metamorphic mineral facies. The important difference between the metamorphic facies principle and the metamorphic index mineral is that it is the entire mineral assemblage that is important, not the appearance of a single mineral.

10. *What is a metamorphic facies series?*

In progressively metamorphosed terranes, metamorphic facies appear in definite series. Three main series are recognized, one marked by low pressure and high temperature, another by high temperature and high pressure, and a third by high pressure and low temperature.

11. *What causes most rocks to become coarser-grained during metamorphism and are there exceptions?*

Most metamorphic rocks increase their grain size during metamorphism, because this decreases the amount of grain surface area, with which higher Gibbs free energy is associated. In zones of intense deformation, such as fault zones, so many nucleation centers for growth of new unstrained grains are formed that the resulting rock can be extremely fine grained.

12. *Why do contact metamorphic rocks known as hornfels commonly consist of polygonal grains that are bounded by faces that intersect at ~120°?*

When contact metamorphic rocks recrystallize they attempt to minimize surface free energies. For grains that have similar surface free energies on different faces (i.e., not strongly anisotropic), minimizing surface free energies is achieved by adjusting grain boundaries so that they intersect at 120°, similar to a cluster of soap bubbles.

13. *What textural feature characterizes most regionally metamorphosed rocks?*

Most regionally metamorphosed rocks are characterized by a strong foliation due to the growth of plate like or needlelike minerals normal to the maximum compressive stress. Slates and schists are prime examples of rocks with such foliation.

14. *What evidence indicates rocks can lose material during the development of metamorphic foliation?*

At foliation planes, primary features in rocks, such as fossils, ooids, and pebbles are commonly truncated, which indicates that material has been removed by solution. The geometry of crenulation schistosity and the disappearance of quartz from the crenulated zones is also evidence of removal of silica during development of the secondary foliation.

15. *Although the rock name mylonite comes from the Greek word for a "mill," the fine-grain size of this rock is not due to breaking and grinding of grains. What causes mylonite to be extremely fine-grained?*

The extremely fine-grain size of mylonite results from the large number of nucleation sites created for growth of new minerals in these zones of intense deformation along faults. Because so many centers for growth of new unstrained grains are formed by the intense deformation, the resulting rock is extremely fine grained.

16. *What is a petrogenetic grid, and how can it be used to determine the conditions under which a metamorphic rock formed?*

A petrogenetic grid is a set of reaction lines on a pressure-temperature diagram that accounts for all possible reactions that can take place between a set of metamorphic minerals. Because these lines tend to have different slopes, they intersect and produce a type of grid known as a *petrogenetic grid*. Between the lines are regions of pressure-temperature space in which one specific mineral assemblage is stable. If a metamorphic rock contains such a mineral assemblage, it can be concluded that the mineral assemblage must have formed under these same conditions of pressure and temperature.

17. *Starting with the triangular diagram indicating the stable mineral assemblages in any divariant field in Figure 15.19 work your way clockwise around the diagram until you come back to the starting diagram and check that only one change occurs in the mineral assemblages in crossing from one divariant field to the next.*

Answering this question involves simply taking care that when a reaction line is crossed, only one change in the mineral assemblages takes place according to the reaction line that has been crossed. If this is done you will return to the starting divariant field with the mineral assemblages you started with. The point of this question is to show that each divariant field has a unique set of mineral assemblages, which can be used to narrow down the pressure-temperature conditions under which a metamorphic rock was formed.

18. *The Thompson projection is a convenient way of showing pelitic mineral assemblage in terms of Al_2O_3-FeO-MgO. From what mineral is the projection made, and what other minerals must be present in the rock in addition to those shown in the projection?*

The Thompson projection involves projecting a rock composition from the Al_2O_3-FeO-MgO-K_2O tetrahedron onto the Al_2O_3-FeO-MgO triangular face from the mineral muscovite. Muscovite is an extremely common mineral in metamorphosed pelitic rocks. If it is accepted that muscovite is present in a rock, it is not necessary to plot it in diagrams. By projecting compositions from muscovite onto the triangular face the plotting of mineral assemblages is greatly simplified. The Thompson projection also requires that quartz be present; that is, the mineral assemblages must include the mineral quartz, even though it is not plotted in the diagram.

19. *From the Thompson projections for any two of Barrow's adjoining zones in Figure 15.22, write a reaction that must take place in going from one grade of metamorphism to another. Recall that reactions can be spotted from a switch in tie lines or if a mineral plots within a phase triangle.*

There are many reactions that can be used to answer this question. As an example, let us use the appearance of the index mineral *staurolite* in rocks that already had reached Barrow's *garnet* zone. In Figure 15.22, one such rock that would fit this category has chlorite coexisting with garnet; that is, chlorite and garnet are joined by a tie line. As the temperature increases, this assemblage crosses a reaction line and the tie line switches to staurolite-biotite. The reaction must involve:

$$\text{chlorite} + \text{garnet} \Rightarrow \text{staurolite} + \text{biotite}$$

Biotite contains potassium, but chlorite and garnet do not. Therefore, the full reaction must also involve muscovite:

$$\text{chlorite} + \text{garnet} + \text{muscovite} \Rightarrow \text{staurolite} + \text{biotite}$$

Silica may also be required to balance this reaction, but because the Thompson projection is used for rocks that contain quartz, quartz can either be released or consumed in the reaction without disturbing the mineral assemblage.

20. *Using the petrogenetic grid in Figure 15.23, determine the possible pressure and temperature ranges over which the mineral assemblages in the three different pelites in Figure 15.24 are stable.*

Figure 15.24 (A) Chloritoid-muscovite-chlorite-quartz
Figure 15.24 (B) Staurolite-garnet-muscovite-biotite-quartz
Figure 15.24 (C) Sillimanite-cordierite-K-feldspar-biotite-quartz
All assemblages include quartz. Assemblages in (A) and (B) include muscovite, and (C) includes K-feldspar. The Thompson projection can therefore be used with mineral assemblages in (A) and (B) being projected from muscovite and in (C), from K-feldspar. By examining the stability ranges for these mineral assemblages in Figure 15.23 we can set the following pressure and temperature limits:

(**A**) This assemblage has no low-temperature limit in Figure 15.23, but at high temperature it is limited by the reaction:

chloritoid ⇒ chlorite + garnet + staurolite.

At 0.2 GPa this reaction occurs at 518°C. At 0.4 GPa it occurs at 545°C.

(**B**) This assemblage is bounded at low temperature by the reaction:

chlorite + garnet ⇒ staurolite + biotite

and at high temperature by the reaction:

staurolite ⇒ garnet + biotite + Al_2SiO_5

These two reactions set the following pressure-temperature limits:
At 0.2 GPa the temperature would be between 538°C and 590°C, and at 0.4 GPa it would be between 555°C and 635°C.

Little can be concluded about the pressures under which the assemblages in (A) and (B) formed. To determine the pressure under which these rocks formed, mineral assemblages in other rocks from the same locality would be needed that are sensitive to pressure. For example, an assemblage containing an Al_2SiO_5 polymorph would help restrict the pressure range.

(**C**) No upper-temperature limit can be set for this assemblage in Figure 15.23, but a low-temperature limit is set by the reaction:

chlorite ⇒ cordierite + biotite + sillimanite

Pressure limits are set by the fact that the rock contains sillimanite and not kyanite or andalusite. The low pressure-temperature limits for this reaction are therefore, 0.27 GPa at 572°C and 0.675 GPa at 638°C.

21. *Write a balanced reaction for tremolite reacting with calcite to produce diopside and forsterite. From the proportions of CO_2 and H_2O produced in the reaction, calculate the mole fraction of CO_2 in the fluid at the reaction's maximum stability, and what would be the shape of the reaction in Figure 15.28? To balance the reaction, let the amounts of tremolite, calcite, diopside and forsterite be a, b, c, and d respectively. Then write equations equating the amounts of Ca, Mg, and Si on both sides of the reaction, and solve for the coefficients.*

The balanced reaction is:

$$3Ca_2Mg_5Si_8O_{22}(OH)_2 + 5CaCO_3 = 11CaMgSi_2O_6 + 2Mg_2SiO_4 + 5CO_2 + 3H_2O$$

tremolite calcite diopside forsterite fluid

CO_2 and H_2O are produced in the ratio of 5:3, so the reaction will have its maximum stability when the mole fraction of CO_2 is 0.625. The reaction curve in Figure 15.28 is convex upward, with a maximum at a mole fraction of CO_2 of 0.625.

22. *Why does migmatite formation normally put a cap on metamorphic temperatures?* The latent heat of fusion of rocks is large (~400 kJ/kg), so that when melting begins in migmatite zones it uses up the heat that would otherwise be available to raise metamorphic temperatures.

23. *What are Fe-Mg exchange reactions, and how are they used as geothermometers?*

Many minerals belong to solid solution series that involve substitution of iron for magnesium. When metamorphic reactions involve minerals belonging to solid solution series they do not take place at a single temperature but instead occur over a range of temperature with exchange of iron and magnesium between the reactants and the products. The partitioning of iron and magnesium between coexisting minerals, such as garnet and biotite is sensitive to temperature, so that from electron microprobe analyses of these coexisting minerals, it is possible to determine their temperature of equilibration. For this reason, these coexisting minerals are known as geothermometers.

24. *Why do metamorphic rocks in some young mountain belts occur in paired metamorphic belts, with a high-pressure, low-temperature belt nearest the subduction zone and a low-pressure, high-temperature belt farther into the overriding plate?*

At subduction zones, cool oceanic crust is subducted into the mantle. The rate of subduction is greater than the rate of heat transfer into the subducting slab. Consequently, the subducting slab experiences increases in pressure with little increase in temperature. This leads to the formation of high-pressure, low-temperature metamorphic rocks. As an oceanic plate is subducted into the mantle, metamorphic reactions take place that release water, which rises into the overlying mantle wedge. The water in this wedge acts as a flux that causes melting of the mantle peridotite, with formation of andesitic magma. As this magma rises toward the surface, it heats previously cool crustal rocks and causes low-pressure, high-temperature metamorphism. In this way pairs of high-P, low-T and low-P, high-T metamorphic belts are formed.

Solutions to Chapter 16 Problems

1. *Which five chemical elements are found in the native state, namely as native elements?*

The five chemical elements found in the native state as minerals are Au, Ag, Cu, C, and S.

2. *Three of the native elements are referred to as native metals. These have unusual physical properties. What are these, and what type of chemical bond do these properties reflect?*

Three of the elements listed in the answer above are referred to as native metals. They are gold, silver and copper. They exhibit the properties conveyed by the metallic bonding mechanism, such as malleability, ductility, and high conductivity of electricity and heat.

3. *Diamond is one of the above five native elements. What is its hardness and what is the bonding type that causes the hardness?*

Diamond has a **H** = 10, which is the result of very strong covalent bonding.

4. *The space group of diamond is* $F4_1/d\,\bar{3}\,2/m$*. What is the equivalent point group (crystal class)?*

The equivalent ("isogonal") point group (or crystal class) is $4/m\,\bar{3}\,2/m$.

5. *What is the meaning of F in this notation? Explain the arrangement of the carbon atoms.*

The *F* notation stands for all-face centered, which means that carbon atoms in the diamond structure are located not only at the corners of the lattice but also at the centers of the cube faces of the lattice.

6. *What do* 4_1 *and d, respectively, represent?*

The notation 4_1 and *d* are space group elements that involve translation. The 4_1 is a right-handed screw operation and *d* is a diamond glide operation.

7. *What are the two main uses of diamond?*

Diamond is used industrially in cutting and drilling operations as well as an abrasive. It is also the most important gemstone in jewelry.

8. *What are the two main ore minerals for lead and zinc? Give their names and formulas.*

The two main ore minerals are galena, PbS, and sphalerite, ZnS.

9. *What are the two copper sulfides described in this chapter? Give their names and formulas.*

Two copper sulfides are bornite, Cu_5FeS_4, and chalcocite, Cu_2S.

10. *What is an additional copper sulfide that was described earlier in Chapter 7 among igneous minerals? Give its name and formula.*

An additional Cu-sulfide is chalcopyrite, $CuFeS_2$.

11. *The foregoing three Cu-Fe sulfides commonly occur together in hydrothermal vein deposits. What is meant by the phrase "of hydrothermal origin"?*

Hydrothermal origin means, in the most general sense, that a mineral or rock type is the result of deposition from a hot water source. This commonly occurs near volcanic activity, but can also be the result of deep crustal intrusions, orogenic activity, and metamorphism.

12. *We described two additional metallic, gray minerals. One is a sulfide and the other a sulf-arsenide. Give their names and formulas.*

Two other gray sulfur-containing ore minerals are arsenpyrite, FeAsS, and molybdenite, MoS_2.

13. *What is the name of the Earth material that is the main source of aluminum? Explain its makeup with names and formulas.*

Bauxite is the main source of aluminum. It is a mixture of three minerals: diaspore, $\alpha AlO(OH)$, gibbsite, $Al(OH)_3$, and boehmite, $\gamma AlO(OH)$.

14. *Give the chemical formula for fluorite and describe its most common crystal habit.*

Fluorite, CaF_2, is commonly found in cubic crystal form, reflecting isometric symmetry.

15. *Which mineral is the main source of barium? Give its name and formula*.

Barite, $BaSO_4$, is the main source of barium.

16. *What is barite most commonly used for?*

About 90% of the world's barite production is used in the petroleum industry as a major ingredient of the heavy fluid called "drilling mud." The mud is used to lubricate the drill bit; to carry rock cuttings from the bottom of the drill hole; to prevent blow-outs and cave-ins of friable rock; to maintain hydrostatic pressure in the borehole, and to help support the weight of the drill rods.

17. *We described two lithium silicates. Give their names*.

Two lithium-containing silicates are spodumene, $LiAlSi_2O_6$, and lepidolite, $K(Li, Al)_{2-3}(AlSi_3O_{10})(OH, F)_2$.

18. *For what application will lithium be in great demand in the near future?*

Lithium-ion batteries for electric cars (see section 17.5).

19. *Give the names of three gem minerals that are commonly green?*

Green gem minerals are emerald, jade, and tourmaline, as well as demantoid, a green gem variety of garnet. The gem variety of olivine, peridot, is also green.

20. *Ruby and sapphire are gem varieties of which relatively common oxide? Give its name and formula*.

Ruby and sapphire are both gem varieties of corundum, Al_2O_3.

21. *Emerald is a highly prized variety of which rock-forming mineral? Give its name and formula.*

Emerald is the green gem variety of beryl, $Be_3Al_2(Si_6O_{18})$.

22. *Which rock-forming mineral, in its gem varieties, displays a very wide range of colors?*

The gem varieties of tourmaline show a very wide range of colors.

23. *Precious opal is commonly referred to as amorphous in the literature. This is not really correct. Explain why with reference to its internal architecture*.

Aspects of the internal, ordered arrangement inside precious opal were discussed in Section 3.3.1. Precious opal is not amorphous, nor does it have a well-defined crystal structure. Instead, it consists of amorphous silica, SiO_2, in spheres of about 3000 Å diameter that are stacked in a regularly packed array (see Figs. 3.9 and 3.10).

Solutions to Chapter 17 Problems

1. *What are the main ages of human cultural evolution, and what Earth material characterizes each?*

The ages of human cultural evolution are named after the main material used for making tools during that period. These ages and the material they used for tools (in parentheses) are, from oldest to most recent: Stone Age (stones, especially fine-grained ones, such as chert and obsidian); Challcolithic Age (a combination of stones and copper); Bronze Age (copper and tin); Iron Age (iron); Nuclear Age (radioactive material, in particular uranium).

2. *What has been the most commonly used building stone throughout history, and why?*

The most commonly used building stone has been limestone. Being composed largely of calcite, it is soft and is easily worked, but it has considerable strength.

3. *What is the most commonly used construction material in large buildings today, and what Earth materials are used in its preparation?*

The most widely used construction material today is concrete, which is commonly reinforced with steel bars. Concrete is a mixture of approximately two-thirds sand, gravel, or crushed stone and one-third Portland cement. Portland cement is made by firing limestone and clay to drive off CO_2 and H_2O, respectively. When water is added to this mixture, CaO reacts with aluminum silicates to produce hydrous aluminum silicates.

4. *Why are sand, gravel, and crushed stone such valuable natural resources?*

Approximately two-thirds of concrete is made of sand, gravel, or crushed stone; the remainder is Portland cement. Crushed stone and gravel are also mixed with approximately one-third asphalt to form the material commonly used for surfacing roads. The construction industry therefore creates a huge demand for sand, gravel, and crushed stone.

5. *Name three countries that are very large producers of iron ore.*

Major producing countries of iron ore are China, Australia, Brazil, and India

6. *Iron ore is the product of leaching and supergene enrichment of iron-formation assemblages. What is the geologic age of such iron-formations?*

Iron-formations, which are the precursors to the formation of iron ore, are of Precambrian age.

7. *What three iron minerals make up the bulk of iron ore?*

The three main iron-ore minerals are hematite, magnetite, and goethite.

8. *The clay mineral kaolinite is an alteration product of what primary rock-forming mineral?*

Kaolinite is the alteration product of K-feldspar, $KAlSi_3O_8$.

9. *Montmorillonite is also a clay mineral. This is the alteration product of what volcanic material?*

Montmorillonite is the alteration product of volcanic ash or tuff.

10. *Porphyry copper deposits are mined because of the presence of what two primary copper minerals?*

Two primary copper minerals are chalcopyrite and bornite.

11. *These deposits may also contain one or two supergene copper minerals. Which are these?*

Two supergene copper minerals are chalcocite and covellite.

12. *Acid mine drainage (AMD) can be a serious environmental problem as a result of large piles of waste rock and tailing ponds. What is meant by AMD, and which mineral group is mainly responsible for this problem? Try to give a chemical equation that defines this process.*

Acid mine drainage (AMD) involves atmospheric interaction with sulfides that occur in mine waste and tailings. A key reaction in this process is: $FeS_2 + 7/2\ O_2 + H_2O \rightarrow Fe^{3+} + 2\ (SO_4)^{2-} + 2H^+$.

13. *Lithium-containing silicates may be present in pegmatites. Give the names of two of these that were described in Chapter 16.*

Two lithium minerals mined from pegmatites are spodumene and lepidolite.

14. *Which three countries have the largest-known reserves of lithium brines?*

Three countries with the largest known reserves of lithium are Argentina, Chile, and Bolivia.

15. *What elements are part of what is referred to as the rare earth elements (REEs)?*

Rare earth elements (REE) include 17 closely related elements referred to as the lanthanide series (from lanthanum, La, to lutetium, Lu) as well as yttrium, Y, and scandium, Sc.

16. *What radioactive element is commonly present in REE ores that makes their mining and mining waste disposal environmentally dangerous?*

Thorium is commonly associated with REE ores.

17. *Give the name and chemical formula of a zeolite that was described in Chapter 14.*

The zeolite is chabazite, $Ca_2Al_2Si_4O_{12}\cdot 6H_2O$.

18. *What is meant by cation exchange property as applied to zeolites? Give an example of a common commercial application.*

Cation exchange is possible using zeolites. This involves the absorption of ions and gases in the large open structural sites of zeolites. It finds application in the water softening process.

19. *A zeolite structure can lose all of its water but can regain it all as well when immersed in water after complete dehydration. How is this property used in commercial applications?*

The water molecules, which are weakly bonded to the framework structure of zeolites, can be slowly driven off by heating. Such a dehydrated structure can be rehydrated subsequently by absorption of water. This rehydration property allows zeolites to be used as desiccants in the petroleum industry.

20. *What is meant by the term molecular sieving?*

Molecular sieving is the process of sieving materials as a function of molecular size. Different ions, as well as gases, can be separated from each other based on their ionic or molecular size. The molecular sieve (a specific zeolite) lets through those molecules that are smaller than the size of the sieve mesh of the zeolite but filters out those that are larger. The sieve is the regular mesh of holes inside the silicate framework structure of the zeolite.

21. *What is meant by fossil fuel? Give the main types of fossil fuels.*

Fossil fuels include oil, natural gas, and coal, all of which were formed by the burial of organic material in sediments. These organic materials are converted to oil, natural gas, or various ranks of coal by heat when buried in the Earth.

22. *Give the number of years the present reserves of each of the main types of fossil fuels are likely to last at current usage rates.*

Oil reserves are expected to last about 45 years at current consumption rates.
Natural gas reserves are expected to last about 60 years.
Coal reserves are expected to last about 200 years.

23. *Why will environmental concerns become important as reserves of conventional fossil fuels dwindle?*

As conventional sources of fossil fuels are depleted, more use will be made of other sources such as tar sands and oil shales. Extraction of oil or natural gas from these sources may cause environmental problems. Hydraulic fracturing of black shales has raised concern that some of the fluids that are pumped into the shale to open up fractures may contaminate drinking water supplies. Open-pit mining of oil shales produces large quantities of waste rock, from which acid mine drainage can pose serious problems.

24. *Although nuclear energy is considered green, what serious environmental problems are associated with its use?*

The most serious problem with the use of nuclear energy is disposing of the highly radioactive spent nuclear fuel. At present, spent nuclear fuel is usually stored at the nuclear power plant where it is generated. Considerable research is being done to build long-term storage sites for the spent nuclear fuel.

25. *From where does geothermal power derive its energy?*

Geothermal energy can be extracted from hydrothermal waters in volcanic terranes, where the heat ultimately comes from the cooling of magma. Geothermal energy can also be derived from hot dry rocks, where the heat is generated from radioactive decay.

26. *How is geothermal power extracted from hot dry rocks?*

To extract geothermal power from hot dry rocks, it is necessary to fracture the source rock by hydraulic fracturing. Then, water is pumped into the fractured rock from an injection well, and the hot water extracted from a recovery well.

27. *How might you explore for hot rocks in nonvolcanic regions? What geologic conditions would be needed to create a suitable geothermal source in such a region?*

It would be necessary to find a rock with a high content of radioactive elements. This typically would be a granite. Next, a location must be found where this radioactive granite is covered by an insulating layer of rock, such as quartz-rich sandstone.

Solutions to Chapter 18 Problems

1. *What is the most abundant element obtained from Earth materials in our body, and what function does it play there? What are some other important elements that our bodies derive from the Earth?*

Phosphorus is the most abundant element that our bodies obtain from Earth materials. It is used to make hydroxylapatite, the building material of bones and teeth, but it is also used in the growth of many cells and the building of DNA. Other elements that are also important for a healthy body are Mg, K, Ca, Fe, Zn, and Cu.

2. *What makes a soil fertile?*

A fertile soil is one in which important elements that are necessary for plant growth have not been depleted by heavy rainfall or soil aging. Fertile soils are geologically young; that is, they contain a significant fraction of new fine particles that can release nutritional elements to the soil. This fine material may be generated as volcanic ash, sediment from newly exposed rock in young mountain chains, finely ground rock from glaciated regions, or as wind-blown material from deserts (loess).

3. *Why is it necessary to add fertilizer to land that is heavily cultivated? What elements must be added?*

The repeated harvesting of crops from agricultural land depletes soils in elements that are used for plant growth. Fertilizers must then replace these elements. The three most important elements are nitrogen, phosphorus, and potassium. Other less abundant but still important elements include calcium, sulfur, and magnesium.

4. *To which mineral group does erionite belong?*

Erionite is a fibrous member of the silicate group known as zeolites.

5. *Where in the world is there a clear connection between abundant exposure to erionite dust and mesothelioma?*

The adverse health effects of erionite were documented in the central Anatolian Plateau called Cappadocia, in Turkey.

6. *This erionite was formed as an alteration product of what volcanic material?*

The erionite in Cappadocia is the alteration product of volcanic ash (tuff).

7. *What is meant by the adjective asbestiform?*

Asbestiform describes highly fibrous minerals in which the fibers readily separate into thin, strong fibers that are flexible.

8. *What six minerals are part of the federally mandated definition of asbestos?*

Six minerals that are included in the federally mandated definition of asbestos are chrysotile, crocidolite, amosite, anthophyllite, tremolite, and actinolite.

9. *What is meant by aspect ratio?*

The aspect ratio is obtained by dividing the length of a fibrous mineral grain by its width.

10. *What are the structural differences between chrysotile and members of the amphibole group?*

Chrysotile and amphibole asbestos have fundamentally different structures. Chrysotile, a layer silicate, has layers of *t-o* sheets curled like drinking straws, with a central hole (see Fig. 14.27). Amphibole asbestos, such as crocidolite, has a typical amphibole structure (a chain silicate) in which infinitely extending tetrahedral chains (known as double chains) are coordinated to cations in octahedral sites.

11. *How do the chemical compositions of chrysotile and crocidolite differ?*

Chrysotile has the formula $Mg_3Si_2O_5(OH)_4$, whereas crocidolite (the fibrous variety of riebeckite) has the formula $Na_2Fe^{2+}_3Fe^{3+}_2Si_8O_{22}(OH)_2$.

12. *Which of the six minerals in the definition of asbestos is the most carcinogenic?*

Crocidolite is by far the most carcinogenic of the six.

13. *What asbestos mineral made up about 95% of all asbestos insulation inside buildings*?

Chrysotile made up about 95% of all asbestos used in commercial applications.

14. *In what country is chrysotile asbestos still being mined?*

Chrysotile is still being mined in Canada, in the Eastern Townships of the Province of Quebec, in open pit mines.

15. *Long-term occupational exposure to quartz dust leads to what pulmonary disease?*

Long-term exposure to silica dust leads to silicosis.

16. *Arsenic, even in very small concentrations in the soil, can cause serious health problems. Why is arsenic causing widespread poisoning in Southeast Asia?*

New, deeper water wells, which were installed in Southeast Asia to provide bacteria-free drinking water, unfortunately are tapping water supplies where anoxic conditions make arsenic soluble. Widespread arsenic poisoning has been the result. Unless the arsenic is removed from the drinking water by oxidizing the water while passing it through filters made of activated alumina, or iron and manganese hydroxides, arsenic poisoning will continue to be a problem in this area.

17. *What steps could you take to avoid the hazards posed by radon gas in your house?*

Radon is a dense radioactive gas that can accumulate in the basement of houses. The presence of radon in a house can be determined by radon gas detectors. If a problem is discovered, ventilation of the affected area is normally all that is necessary to eliminate the problem.

18. *What is the most serious problem associated with the use of nuclear power, and how might it be solved?*

The most serious problem associated with the use of nuclear power is the disposal of the high-level radioactive waste that is generated as spent nuclear fuel. At present, most of this material is stored at the power plant where it is generated. This material remains highly radioactive for thousands of years and its long-term storage presents major geologic and engineering problems. A long-term storage site should be geologically stable, so that it will not be affected by earthquakes. The rocks surrounding the storage facility should provide a tight seal from circulating groundwater. Reducing conditions are desirable to prevent uranium from being mobilized in solution in groundwater. The spent nuclear fuel can be fused into glass or incorporated into the mineral perovskite to help isolate it from groundwater. Predicting what will happen to these materials over periods of thousands of years, however, is difficult.

19. *The burning of fossil fuels increases the CO_2 content of the atmosphere. Describe ways to remove this greenhouse gas from the atmosphere.*

Sequestration of CO_2 is one method that may prevent the buildup of this greenhouse gas in the atmosphere. Carbon dioxide that is separated from the atmosphere or from the exhalations of smokestacks at fossil-fuel-burning power plants can be pumped into large underground reservoirs in the Earth such as the traps from which oil or natural gas may have been previously removed. Carbon dioxide could also be sequestered by being pumped into rocks where it could react with primary igneous minerals to form carbonates. Another possible means of sequestering CO_2 is to pump it into the deep ocean where it can dissolve in the water or form solid CO_2 hydrates.

20. *What types of volcanoes pose the greatest hazard? Which are more dangerous, ash falls or ash flows?*

The higher the silica content of a volcano the more dangerous it is, because of the increased possibility of explosive activity. Steep-sided volcanoes, especially in regions of heavy rainfall, can be the source of mudflows (lahars). Ash falls and ash flows both pose serious problems, but ash flows are far more hazardous because of the speed with which they travel. Ash ejected high into the air can cause trouble for air traffic and for respiration, but usually there is sufficient time to take precautionary steps. Ash flows, by contrast, travel so rapidly that there is rarely chance to escape.

21. *How can you recognize an ancient lahar?*

A lahar is a mudflow that descends the flanks of a volcano. It is poorly sorted and has particles ranging in size from boulders to clay. It resembles glacial till, but because it forms on the flank of a volcano, all of its particles are of volcanic origin.

22. *How is interferometric synthetic aperture radar (InSAR) used to monitor volcanoes from satellites?*

Changes in the elevation of a dormant volcano can be collected from satellite radar images over a period of time and converted to interference patterns (interferograms). The changes in elevation can then be used to predict the movement of magma beneath the volcano and warn of impending eruptions.

23. *How might you recognize an ancient tsunami deposit?*

Tsunami deposits are formed rapidly by a powerful wave that can transport material of a wide range of sizes to significant heights above shorelines. Because of the speed with which material is transported, little if any sorting takes place. The result is a poorly sorted sediment that may contain large grains of a wide variety of rock types.

24. *What evidence found on the Cretaceous-Tertiary boundary indicates that the mass extinction at this boundary may be related to meteorite impact?*

The most convincing evidence for meteorite impact at the time of the mass extinction at the end of the Cretaceous Period is the presence of an iridium anomaly in the sediment on the K-T boundary. On Earth, most iridium sank to the core during core formation early in Earth's history, and iridium is therefore only a trace element in crustal rocks. Meteorites, however, contain significant amounts of iridium. The explosion of a large meteorite would therefore have produced an iridium spike in sediments that accumulated at this time. Small glassy spheres are also found on the K-T boundary, which were probably formed from the flash fusion of crustal rocks when the meteorite exploded.