3 Rocks: Materials of the Solid Earth

FOCUS ON CONCEPTS

Each statement represents the primary **LEARNING OBJECTIVE** for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

3.1 Sketch, label, and explain the rock cycle.

3.2 Describe the two criteria used to classify igneous rocks and explain how cooling influences the crystal size of minerals.

3.3 List and describe the different categories of sedimentary rocks and discuss the processes that change sediment into sedimentary rock.

3.4 Define *metamorphism*, explain how metamorphic rocks form, and describe the agents of metamorphism.

3.5 Distinguish between metallic and nonmetallic mineral resources and list at least two examples of each. Compare and contrast the three traditional fossil fuels.

Sedimentary strata in Canyonlands National Park, Utah with the La Sal. (SeBuKi/Alamy)

Why study rocks? You have already learned that some rocks and minerals have great economic value. In addition, all Earth processes depend in some way on the properties of these basic Earth materials. Events such as volcanic eruptions, mountain building, weathering, erosion, and even earthquakes involve rocks and minerals. Consequently, a basic knowledge of Earth materials is essential to understanding most geologic phenomena.

Every rock contains clues about the environment in which it formed. For example, some rocks are composed entirely of small shell fragments. This tells Earth scientists that the rock likely originated in a shallow marine environment. Other rocks contain clues which indicate that they formed from a volcanic eruption or deep in the Earth during mountain building. Thus, rocks contain a wealth of information about events that have occurred over Earth's long history.

3.1 EARTH AS A SYSTEM: THE ROCK CYCLE

Sketch, label, and explain the rock cycle.

Earth as a system is illustrated most vividly when we examine the rock cycle. The **rock cycle** allows us to see many of the interactions among the numerous components and processes of the Earth system (**FIGURE 3.1**). It helps us understand the origins of igneous, sedimentary, and metamorphic rocks and how they are connected. In addition, the rock cycle demonstrates that any rock type, under the right circumstances, can be transformed into any other type.

The Basic Cycle

We begin our discussion of the rock cycle with molten rock, called *magma*, which forms by melting that occurs primarily within Earth's crust and upper mantle (see Figure 3.1). Once formed, a magma body often rises toward the surface because it is less dense than the surrounding rock. Occasionally, magma reaches Earth's surface, where it erupts as *lava*. Eventually, molten rock cools and solidifies, a process called *crystallization* or *solidification*. Molten rock may solidify either beneath the surface or, following a volcanic eruption, at the surface. In either situation, the resulting rocks are called *igneous rocks*.

If igneous rocks are exposed at the surface, they undergo *weathering*, in which the daily influences of the atmosphere slowly disintegrate and decompose rocks. The loose materials that result are often moved downslope by gravity and then picked up and transported by one or more erosional agents—running water, glaciers, wind, or waves. Eventually, these particles and dissolved substances, called *sediment*, are deposited. Although most sediment ultimately comes to rest in the ocean, other sites of deposition include river floodplains, desert basins, lakes, inland seas, and sand dunes.

Next, the sediments undergo *lithification*, a term meaning "conversion into rock." Sediment is usually lithified into *sedimentary rock* when compacted by the weight of overlying materials or when cemented as percolating groundwater fills the pores with mineral matter.

If the resulting sedimentary rock becomes deeply buried or is involved in the dynamics of mountain building, it will be subjected to great pressures and intense heat. The sedimentary rock may react to the changing environment by turning into the third rock type, *metamorphic rock*. If metamorphic rock is subjected to still higher temperatures, it may melt, creating magma, and the cycle begins again.

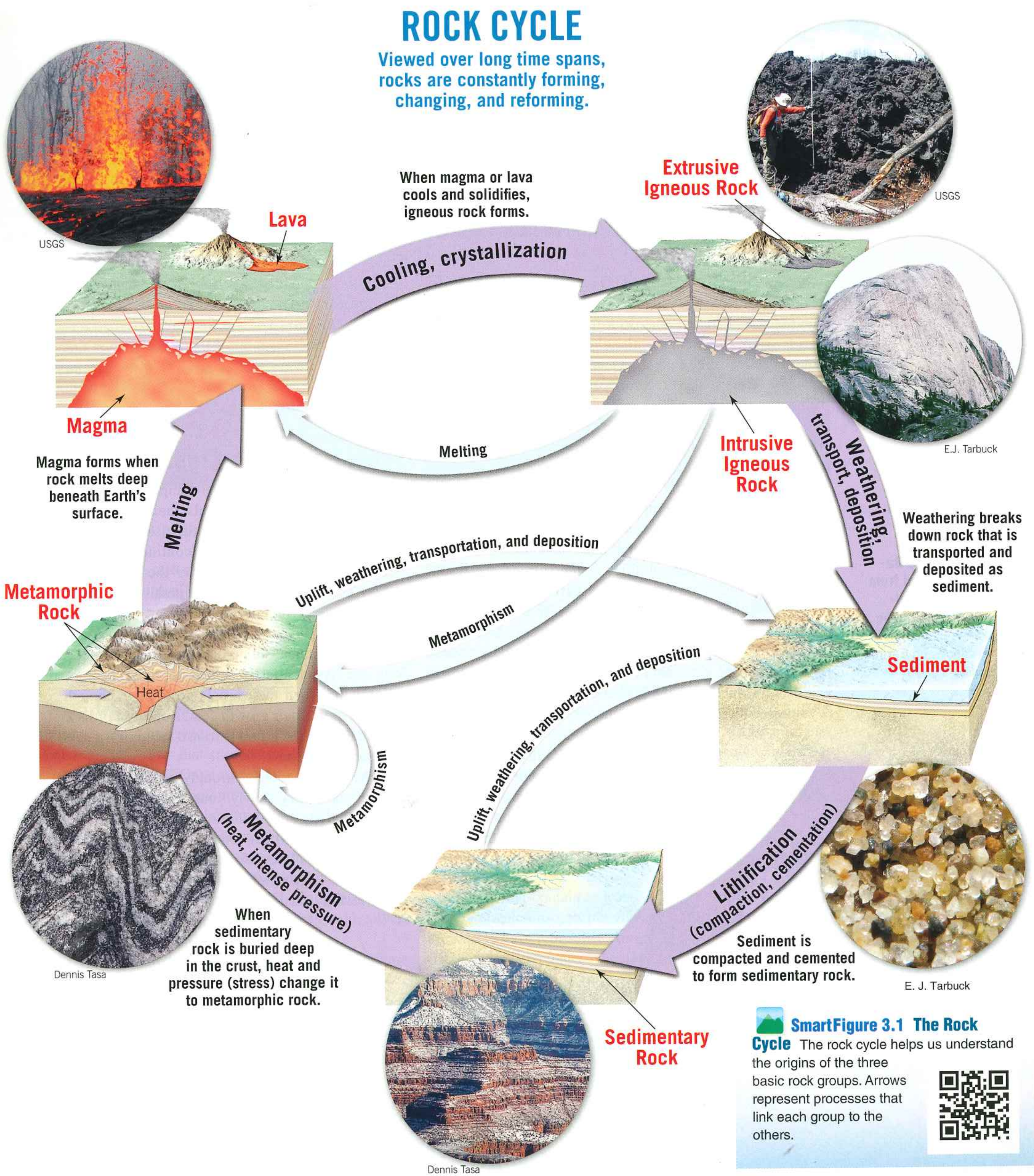
Although rocks may appear to be stable, unchanging masses, the rock cycle shows that they are not. The changes, however, take time—sometimes millions or even billions of years. In addition, the rock cycle operates continuously around the globe, but in different stages, depending on the location. Today, new magma is forming under the island of Hawaii, whereas the rocks that comprise the Colorado Rockies are slowly being worn down by weathering and erosion. Some of this weathered debris will eventually be carried to the Gulf of Mexico, where it will add to the already substantial mass of sediment that has accumulated there.

Alternative Paths

Rocks do not necessarily go through the cycle in the order just described. Other paths are also possible. For example, rather than being exposed to weathering and erosion at Earth's surface, igneous rocks may remain deeply buried (see Figure 3.1). Eventually, these masses may be subjected to the strong compressional forces and high temperatures associated with mountain building. When this occurs, they are transformed directly into metamorphic rocks.

Metamorphic and sedimentary rocks, as well as sediment, do not always remain buried. Rather, overlying layers may be eroded away, exposing the once-buried rock. When this happens, the material is attacked by weathering processes and turned into new raw materials for sedimentary rocks.

In a similar manner, igneous rocks that formed at depth can be uplifted, weathered, and turned into sedimentary rocks. Alternatively, igneous rocks may remain at depth, where the high temperatures and forces associated with mountain building may metamorphose or even melt them. Over time, rocks may be transformed into any other rock type, or even into a different form of the original type. Rocks may take many paths through the rock cycle.



SmartFigure 3.1 The Rock Cycle The rock cycle helps us understand the origins of the three basic rock groups. Arrows represent processes that link each group to the others.

What drives the rock cycle? Earth's internal heat is responsible for the processes that form igneous and metamorphic rocks. Weathering and the transport of weathered material are external processes, powered by energy from the Sun. External processes produce sedimentary rocks.

3.1 CONCEPT CHECKS

1. Sketch and label the rock cycle. Make sure your sketch includes alternative paths.
2. Use the rock cycle to explain the statement "One rock is the raw material for another."

3.2 IGNEOUS ROCKS: "FORMED BY FIRE"

Describe the two criteria used to classify igneous rocks and explain how the rate of cooling influences the crystal size of minerals.

In the discussion of the rock cycle, we pointed out that **igneous rocks** form as *magma* or *lava* cools and crystallizes. **Magma** is molten rock that is most often generated by melting of rocks in Earth's mantle, although melting of crustal rock generates some magma. Once formed, a magma body buoyantly rises toward the surface because it is less dense than the surrounding rocks.

When magma reaches the surface, it is called **lava** (**FIGURE 3.2**). Sometimes, lava is emitted as fountains produced when escaping gases propel molten rock skyward. On other occasions, magma is explosively ejected from vents, producing a spectacular eruption such as the 1980 eruption of Mount St. Helens. However, most eruptions are not violent; rather, volcanoes most often emit quiet outpourings of lava.

When molten rock solidifies *at the surface*, the resulting igneous rocks are classified as **extrusive**, or **volcanic** (after the Roman fire god, Vulcan). Extrusive igneous rocks are abundant in western portions of the Americas, including the volcanic cones of the Cascade Range and the extensive lava flows of the Columbia Plateau. In addition, many oceanic islands, including the Hawaiian islands, are composed almost entirely of volcanic igneous rocks.

As we will see later, most magma loses its mobility before reaching Earth's surface and eventually crystallizes deep below the surface. Igneous rocks that *form at depth* are termed **intrusive**, or **plutonic** (after Pluto, the god of the underworld in classical mythology). Intrusive igneous rocks remain at depth unless portions of the crust are uplifted and the overlying rocks are stripped away by erosion. Exposures of intrusive igneous rocks occur in many places, including Mount Washington, New Hampshire; Stone Mountain, Georgia; Mount Rushmore in the Black Hills of South Dakota; and Yosemite National Park, California (**FIGURE 3.3**).

FIGURE 3.2 Fluid Basaltic Lava Emitted from Hawaii's Kilauea Volcano Kilauea, on the Big Island, is one of the most active volcanoes on Earth. (Photo courtesy of USGS)

From Magma to Crystalline Rock

Magma is molten rock (*melt*) composed of ions of the elements found in silicate minerals, mainly silicon and oxygen that move about freely. Magma also contains gases, particularly water vapor, that are confined within the magma body by the weight (pressure) of the overlying rocks, and it may contain some solids (mineral crystals). As magma cools, the once-mobile ions begin to arrange themselves into orderly patterns—a process called *crystallization*. As cooling continues, numerous small crystals develop, and ions are systematically added to these centers of crystal growth. When the crystals grow large enough for their edges to meet, their growth ceases because of lack of space. Eventually, all the liquid is transformed into a solid mass of interlocking crystals.

The rate of cooling strongly influences crystal size. If magma cools very slowly, ions can migrate over great distances. Consequently, *slow cooling results in the formation of fewer, larger crystals*. On the other hand, if cooling occurs rapidly, the ions lose their motion and quickly combine. This results in a large number of tiny crystals all competing for the available ions. Therefore, *rapid cooling results in the formation of a solid mass of small intergrown crystals.*

If the molten material is cooled almost instantly, there is insufficient time for the ions to arrange themselves into a crystalline network. Solids produced in this manner consist of randomly distributed atoms. Such rocks are called *glass* and are quite similar to ordinary manufactured glass. "Instant" quenching sometimes occurs during violent

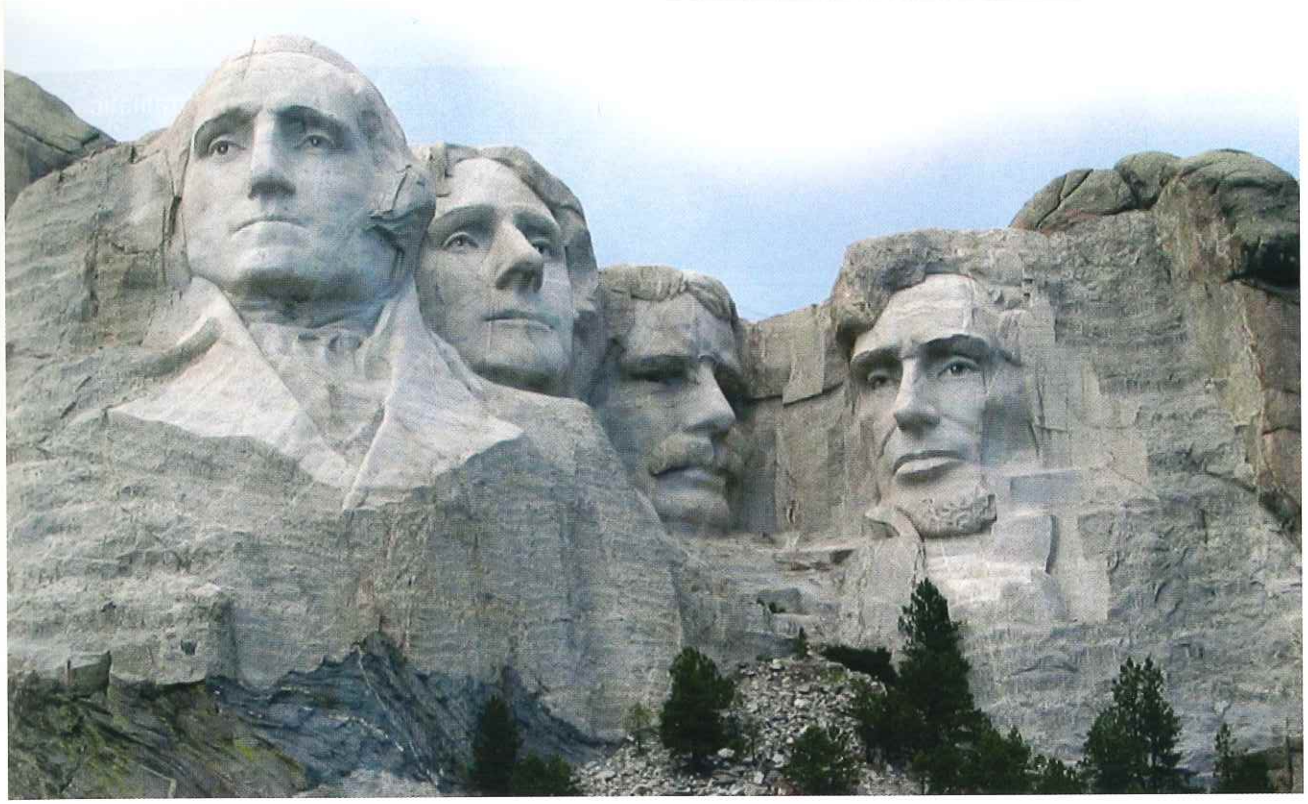


FIGURE 3.3 Mount Rushmore National Memorial, Black Hills of South Dakota This memorial is carved from the intrusive igneous rock granite. This massive igneous body cooled very slowly at depth and has since been uplifted, with the overlying rocks stripped away by erosion. (Photo by Barbara A. Harvey/Shutterstock)

volcanic eruptions that produce tiny shards of glass called *volcanic ash.*

In addition to the rate of cooling, the composition of a magma and the amount of dissolved gases influence crystallization. Because magmas differ in each of these aspects, the physical appearance and mineral composition of igneous rocks vary widely.

Igneous Compositions

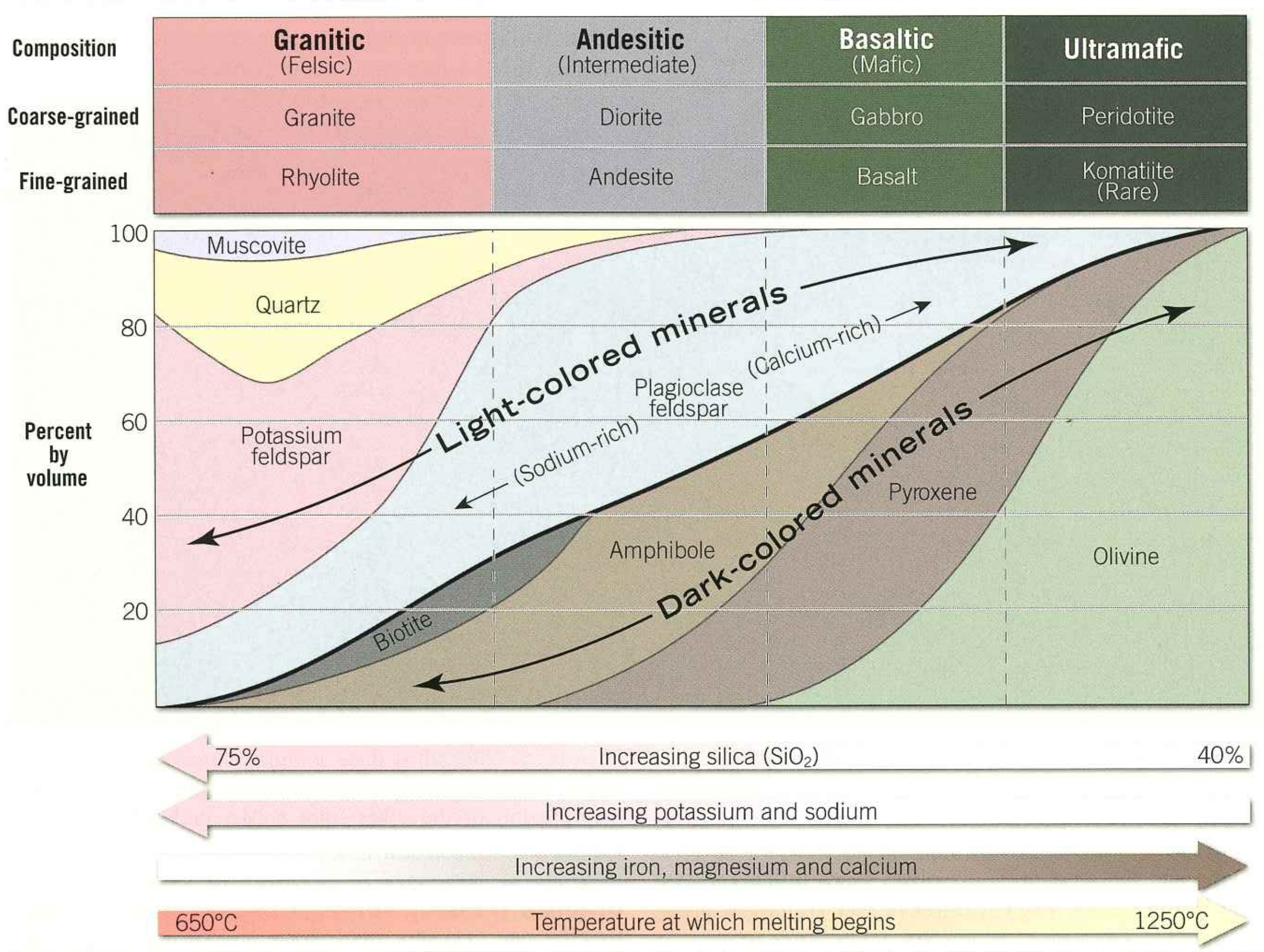
Igneous rocks are composed mainly of silicate minerals. Chemical analysis shows that silicon and oxygen—usually expressed as the silica (SiO_2) content of a magma—are by far the most abundant constituents of igneous rocks. These two elements, plus ions of aluminum (Al), calcium (Ca), sodium (Na), potassium (K), magnesium (Mg), and iron (Fe), make up roughly 98 percent by weight of most magmas. In addition, magma contains small amounts of many other elements, including titanium and manganese, and trace amounts of much rarer elements, such as gold, silver, and uranium.

As magma cools and solidifies, these elements combine to form two major groups of silicate minerals. The *dark silicates* are rich in iron and/or magnesium and are comparatively low in silica (SiO_2). *Olivine*, *pyroxene*, *amphibole*, and *biotite mica* are the common dark silicate minerals of Earth's crust. By contrast, the *light silicates* contain greater amounts of potassium, sodium, and calcium and are richer in silica than dark silicates. Light silicates include *quartz*, *muscovite mica*, and the most abundant mineral group, the *feldspars.* Feldspars make up at least 40 percent of most igneous rocks. Thus, in addition to feldspar, igneous rocks contain some combination of the other light and/or dark silicates listed earlier.

Granitic (Felsic) Versus Basaltic (Mafic) Compositions Despite their great compositional diversity, igneous rocks (and the magmas from which they form) can be divided into broad groups according to their proportions of light and dark minerals (**FIGURE 3.4**). Near one end of the continuum are rocks composed almost entirely of light-colored silicates—quartz and potassium feldspar. Igneous rocks in which these are the dominant minerals have a **granitic composition**. Geologists refer to granitic rocks as being **felsic**, a term derived from *feld*spar and *si*lica (quartz). In addition to quartz and feldspar, most granitic rocks contain about 10 percent dark silicate minerals, usually biotite mica and amphibole. Granitic rocks are major constituents of the continental crust.

Rocks that contain at least 45 percent dark silicate minerals and calcium-rich plagioclase feldspar (but no quartz) are said to have a **basaltic composition**. Basaltic rocks contain a high percentage of dark silicate minerals, so geologists refer to them as **mafic** (from *ma*gnesium and *fe*rrum, the Latin word for iron). Because of their iron content, mafic rocks are typically darker and denser than granitic rocks. Basaltic rocks make up the ocean floor as well as many of the volcanic islands located within the ocean basins.

Other Compositional Groups As you can see in Figure 3.4, rocks with a composition between granitic and basaltic rocks are said to have an **andesitic composition**, or



SmartFigure 3.4 Composition of Common Igneous Rocks (After Dietrich, Daily, and Larsen)

intermediate composition, after the common volcanic rock *andesite*. Intermediate rocks contain at least 25 percent dark silicate minerals, mainly amphibole, pyroxene, and biotite mica, with the other dominant mineral being plagioclase feldspar. This important category of igneous rocks is associated with volcanic activity that is typically confined to the seaward margins of the continents and on volcanic island arcs such as the Aleutian chain.

Another important igneous rock, *peridotite*, contains mostly olivine and pyroxene and thus falls on the opposite side of the compositional spectrum from granitic rocks (see Figure 3.4). Because peridotite is composed almost entirely of ferromagnesian minerals, its chemical composition is referred to as **ultramafic**. Although ultramafic rocks are rare at Earth's surface, peridotite is the main constituent of the upper mantle.

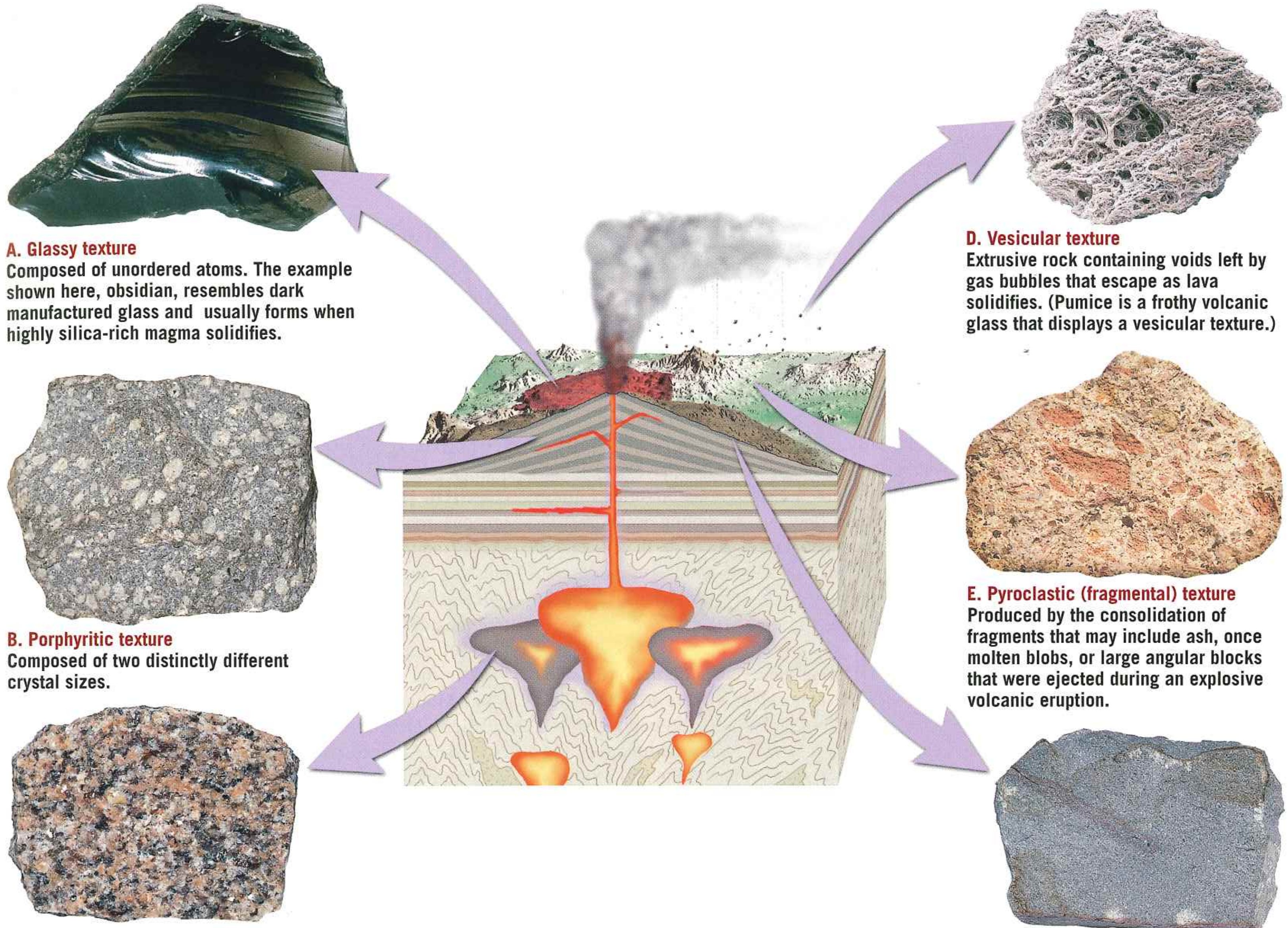
Silica Content as an Indicator of Composition

An important aspect of the chemical composition of igneous rocks is silica (SiO_2) content. Typically, the silica content of crustal rocks ranges from a low of about 40 percent in ultramafic rocks to a high of more than 70 percent in felsic rocks (see Figure 3.4). The percentage of silica in igneous rocks varies in a systematic manner that parallels the abundance of other elements. For example, rocks that are relatively low in silica contain large amounts of iron, magnesium, and calcium. By contrast, rocks high in silica contain very little iron, magnesium, or calcium but are enriched with sodium and potassium. Consequently, the chemical makeup of an igneous rock can be inferred directly from its silica content.

Further, the amount of silica present in magma strongly influences the magma's behavior. Granitic magma, which has a high silica content, is quite viscous ("thick") and may erupt at temperatures as low as 650°C (1200°F). On the other hand, basaltic magmas are low in silica and are generally more fluid. Basaltic magmas also erupt at higher temperatures than granitic magmas—usually at temperatures between 1050° and 1250°C (1920° and 2280°F).

What Can Igneous Textures Tell Us?

Geologists describe the overall appearance of a rock, based on the *size*, *shape*, and *arrangement* of its mineral grains, as its **texture**. Texture is an important property because it allows geologists to make inferences about a rock's origin, based on



A. Glassy texture
Composed of unordered atoms. The example shown here, obsidian, resembles dark manufactured glass and usually forms when highly silica-rich magma solidifies.

B. Porphyritic texture
Composed of two distinctly different crystal sizes.

C. Coarse-grained texture Composed of mineral grains that are large enough to be identified without a microscope.

D. Vesicular texture
Extrusive rock containing voids left by gas bubbles that escape as lava solidifies. (Pumice is a frothy volcanic glass that displays a vesicular texture.)

E. Pyroclastic (fragmental) texture
Produced by the consolidation of fragments that may include ash, once molten blobs, or large angular blocks that were ejected during an explosive volcanic eruption.

F. Fine-grained texture
Composed of crystals that are too small for the individual minerals to be identified without a microscope.

SmartFigure 3.5
Igneous Rock Textures
(Photos courtesy of E. J. Tarbuck and Dennis Tasa)

careful observations of crystal size and other characteristics (**FIGURE 3.5**). Rapid cooling produces small crystals, whereas very slow cooling produces much larger crystals. As you might expect, the rate of cooling is slow in magma chambers that lie deep within the crust, whereas a thin layer of lava extruded upon Earth's surface may chill to form solid rock in a matter of hours. Small molten blobs ejected from a volcano during a violent eruption can solidify in mid-air.

Fine-Grained Texture

Igneous rocks that form at Earth's surface or as small intrusive masses within the upper crust, where cooling is relatively rapid, exhibit a **fine-grained texture** (see Figure 3.5F). By definition, the crystals that make up fine-grained igneous rocks are so small that individual minerals can be distinguished only with the aid of a polarizing microscope or other sophisticated techniques. Therefore, we commonly characterize fine-grained rocks as being light, intermediate, or dark in color.

Coarse-Grained Texture

When large masses of magma slowly crystallize at great depth, they form igneous rocks that exhibit a **coarse-grained texture**. Coarse-grained rocks consist of a mass of intergrown crystals that are roughly equal in size and large enough so that the individual minerals can be identified without the aid of a microscope (see Figure 3.5C). Geologists often use a small magnifying lens to aid in identifying minerals in coarse-grained igneous rocks.

Porphyritic Texture A large mass of magma may require thousands or even millions of years to solidify. Because different minerals crystallize under different environmental conditions (temperatures and pressure), it is possible for crystals of one mineral to become quite large before others even begin to form. If molten rock containing some large crystals moves to a different environment—for example, by erupting at the surface—the remaining liquid portion of the lava cools more quickly. The resulting rock, which has large crystals embedded in a matrix of smaller crystals, is said to have a **porphyritic texture** (see Figure 3.5B). The large crystals in porphyritic rocks are referred to as **phenocrysts** (*pheno* = show, *cryst* = crystal), whereas the matrix of smaller crystals is called **groundmass**.

Vesicular Texture Common features of many extrusive rocks are the voids left by gas bubbles that escape as lava solidifies. These nearly spherical openings are called *vesicles*, and the rocks that contain them are said to have a **vesicular texture**. Rocks that exhibit a vesicular texture often form in the upper zone of a lava flow, where cooling occurs rapidly enough to preserve the openings produced by the expanding gas bubbles (**FIGURE 3.6**). Another common vesicular rock, called *pumice*, forms when silica-rich lava is ejected during an explosive eruption (see Figure 3.5D).

Glassy Texture During some volcanic eruptions, molten rock is ejected into the atmosphere, where it is quenched and cools quickly to become a solid. Rapid cooling of this type may generate rocks having a **glassy texture** (see Figure 3.5A). Glass results when unordered ions are "frozen in place" before they are able to unite into an orderly crystalline structure. *Obsidian*, a common type of natural glass, is similar in appearance to dark chunks of manufactured glass.

Pyroclastic (Fragmental) Texture Another group of igneous rocks is formed from the consolidation of individual rock fragments ejected during explosive volcanic eruptions. The ejected particles might be very fine ash, molten blobs, or large angular blocks torn from the walls of a vent during an eruption. Igneous rocks composed of these rock fragments are said to have a **pyroclastic texture**, or **fragmental texture** (see Figure 3.5E). A common type of pyroclastic rock, called *welded tuff*, is composed of fine fragments of glass that remained hot enough to eventually fuse together.

Common Igneous Rocks

Igneous rocks are classified by their texture and mineral composition. The texture of an igneous rock is mainly a result of its cooling history, whereas its mineral composition is largely a result of the chemical makeup of the parent magma (**FIGURE 3.7**). Because igneous rocks are classified on the basis of both mineral composition and texture, some rocks having similar mineral constituents but exhibiting different textures are given different names.

Granitic (Felsic) Rocks *Granite* is a coarse-grained igneous rock that forms where large masses of magma slowly solidify at depth. During episodes of mountain building, granite and related crystalline rocks may be uplifted, with the processes of weathering and erosion stripping away the overlying crust. Areas where large quantities of granite are exposed at the surface include Pikes Peak in the Rockies, Mount Rushmore in the Black Hills, Stone Mountain in Georgia, and Yosemite National Park in the Sierra Nevada (**FIGURE 3.8**).

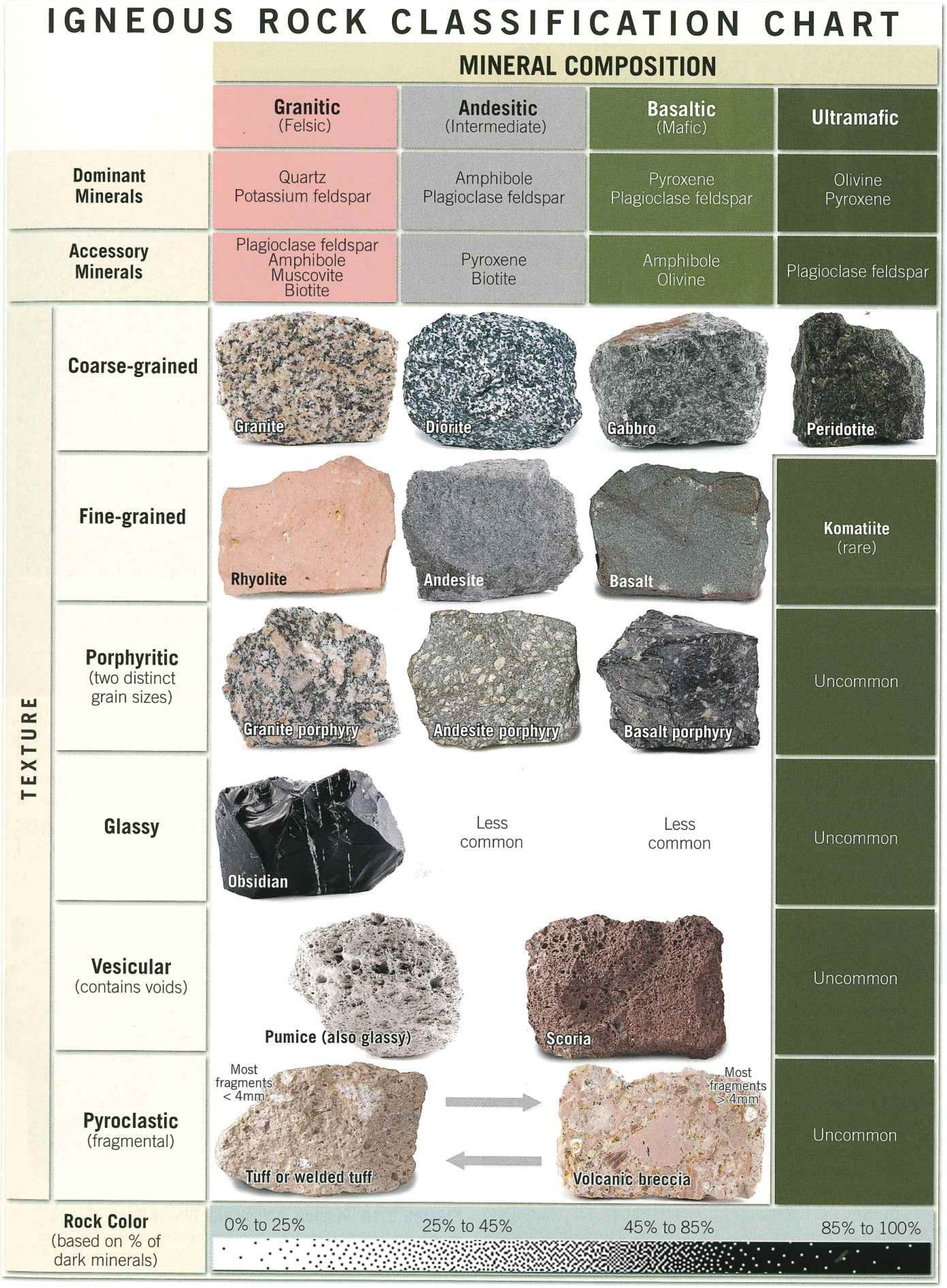
Granite is perhaps the best-known igneous rock, in part because of its natural beauty, which is enhanced when polished, and partly because of its abundance. Slabs of polished granite are commonly used for tombstones, monuments, and countertops.

Rhyolite is the extrusive equivalent of granite (same chemical composition but different texture) and, likewise, is composed essentially of light-colored silicates (see Figure 3.7). This fact accounts for its color, which is usually buff to pink or light gray. Rhyolite is fine grained and frequently contains glass fragments and voids, indicating rapid cooling in a surface environment. In contrast to granite, which is widely distributed as large intrusive masses, rhyolite deposits are less common and generally less voluminous. Yellowstone Park is one well-known exception where extensive lava flows and thick ash deposits of rhyolitic composition are found.

Obsidian is a common type of natural glass that is similar in appearance to a dark chunk of manufactured glass. Although dark in color, obsidian usually has a higher silica content and a chemical composition similar to that of light-colored igneous rocks.

FIGURE 3.6 Vesicular Texture Vesicles form as gas bubbles escape near the top of a lava flow.

Scoria, a volcanic rock with a vesicular texture.



SmartFigure 3.7 Classification of Igneous Rocks, Based on Their Mineral Composition and Texture Coarse-grained rocks are plutonic, solidifying deep underground. Fine-grained rocks are volcanic, or solidify as shallow, thin plutons. Ultramafic rocks are dark, dense rocks, composed almost entirely of minerals containing iron and magnesium. Although relatively rare on Earth's surface, these rocks are major constituents of the upper mantle. (Photos by E. J. Tarbuck and Dennis Tasa)

Corey Rich/
Getty Images

Henrik Lehneren/
Glow Images

FIGURE 3.8 Granitic Rock Exposed in California's Yosemite National Park This rock formed from magma that crystallized deep beneath the surface. (Granite inset photo by E. J. Tarbuck)

FIGURE 3.9 Obsidian, a Natural Glass Native Americans used obsidian to make arrowheads and cutting tools. (Photo by Mark Thiessen/Getty Images)

Obsidian's dark color results from small amounts of metallic ions in an otherwise clear, glassy substance. Because of its excellent conchoidal fracture and ability to hold a sharp, hard edge, obsidian was a prized material from which Native Americans chipped arrowheads and cutting tools (**FIGURE 3.9**).

Another silica-rich volcanic rock that exhibits a glassy and also vesicular texture is *pumice.* Often found with obsidian, pumice forms when large amounts of gas escape from molten rock to generate a gray, frothy mass (**FIGURE 3.10**). In some samples, the vesicles are quite noticeable, whereas in others, the pumice resembles fine shards of intertwined glass. Because of the large volume of air-filled voids, many samples of pumice float in water (see Figure 3.10).

Andesitic (Intermediate) Rocks *Andesite* is a medium-gray, fine-grained rock, typically of volcanic origin. Its name comes from South America's Andes Mountains, where numerous volcanoes are composed of this rock type. In addition, the volcanoes of the Cascade Range and many of the volcanic structures occupying the continental margins that surround the Pacific Ocean have an andesitic composition. Andesite commonly exhibits a porphyritic texture (see Figure 3.7) consisting of phenocrysts that are often light, rectangular crystals of plagioclase feldspar or black, elongated amphibole crystals.

Diorite, the intrusive equivalent of andesite, is a coarse-grained rock that resembles gray granite. However, it can be distinguished from granite because it contains little or no visible quartz crystals and has a higher percentage of dark silicate minerals.

Basaltic (Mafic) Rocks *Basalt*, the most common extrusive igneous rock, is a very dark green to black, fine-grained volcanic rock composed primarily of pyroxene, olivine, and plagioclase feldspar. Many volcanic islands, such as the Hawaiian islands and Iceland, are composed mainly of basalt (**FIGURE 3.11**). Furthermore, the upper layers of the oceanic crust consist of basalt. In the United States, large portions of central Oregon and Washington were the sites of extensive basaltic outpourings.

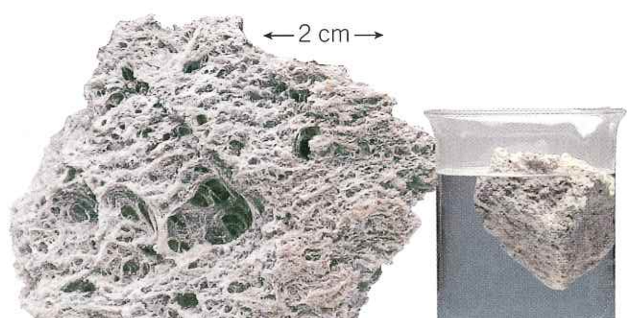


FIGURE 3.10 Pumice, a Vesicular Glassy Rock Pumice is very lightweight because it contains numerous vesicles. (Photo by E. J. Tarbuck; inset photo by Chip Clark)

FIGURE 3.11 Basaltic Lava Flowing from Kilauea Volcano, Hawaii (Photo by David Reggie/Getty Images)

The coarse-grained, intrusive equivalent of basalt is *gabbro* (see Figure 3.7). Although gabbro is not commonly exposed at the surface, it makes up a significant percentage of the oceanic crust.

How Different Igneous Rocks Form

Because a large variety of igneous rocks exist, it is logical to assume that an equally large variety of magmas also exist. However, geologists have observed that a single volcano may extrude lavas exhibiting quite different compositions. Data of this type led them to examine the possibility that magma might change (evolve) and thus become the parent to a variety of igneous rocks. To explore this idea, a pioneering investigation into the crystallization of magma was carried out by N. L. Bowen in the first quarter of the twentieth century.

Bowen's Reaction Series In a laboratory setting, Bowen demonstrated that magma, with its diverse chemistry, crystallizes over a temperature range of at least 200°C, unlike simple compounds (such as water), which solidify at specific temperatures. As magma cools, certain minerals crystallize first at relatively high temperatures. At successively lower temperatures, other minerals begin to crystallize. This arrangement of minerals, shown in **FIGURE 3.12**, became known as **Bowen's reaction series**.

Bowen discovered that the first mineral to crystallize from a body of magma is *olivine.* Further cooling results in the formation of *pyroxene*, as well as *plagioclase feldspar.* At intermediate temperatures, the minerals *amphibole* and *biotite* begin to crystallize.

During the last stage of crystallization, after most of the magma has solidified, the minerals *muscovite* and *potassium feldspar* may form (see Figure 3.12). Finally, *quartz* crystallizes from any remaining liquid. Olivine and quartz are seldom found in the same igneous rock because quartz crystallizes at much lower temperatures than olivine.

Analysis of igneous rocks provides evidence that this crystallization model approximates what can happen in nature. In particular, we find that minerals that form in the same general range on Bowen's reaction series are found together in the same igneous rocks. For example, notice in Figure 3.12 that the minerals quartz, potassium feldspar, and muscovite, located in the same region of Bowen's

EYE ON EARTH

These two types of hardened lava, called Pele's hair and Pele's tears, are commonly generated during lava fountaining that occurs at Kilauea Volcano. They are named after Pele, the Hawaiian goddess of fire and volcanoes. Pele's hair consists of goldish strands that are created when tiny blobs of lava are stretched by strong winds. When lava droplets cool quickly, they form Pele's tears, which are sometimes connected to strands of Pele's hair.

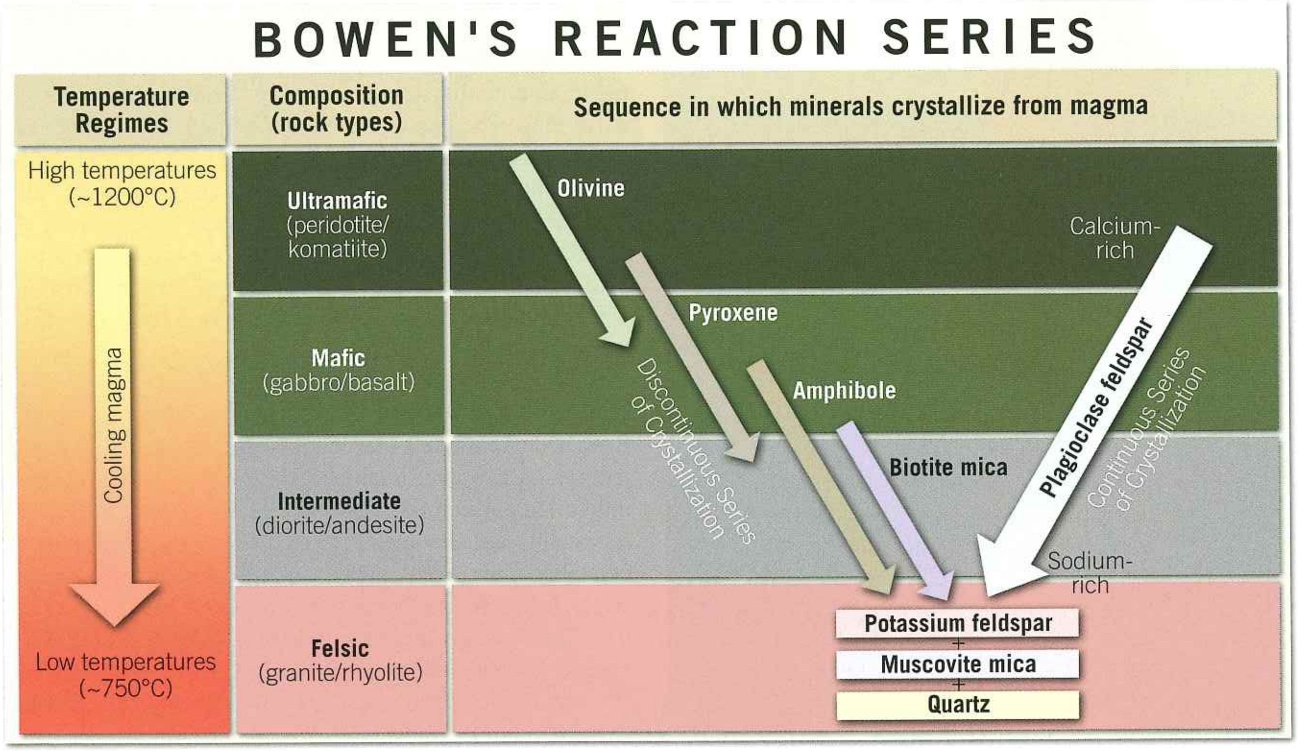
QUESTION 1 *What is the texture of Pele's hair and Pele's tears?*

QUESTION 2 *What is the igneous rock name for Pele's tears?*

1. Pele's hair Marli Miller

2. Pele's tears USGS

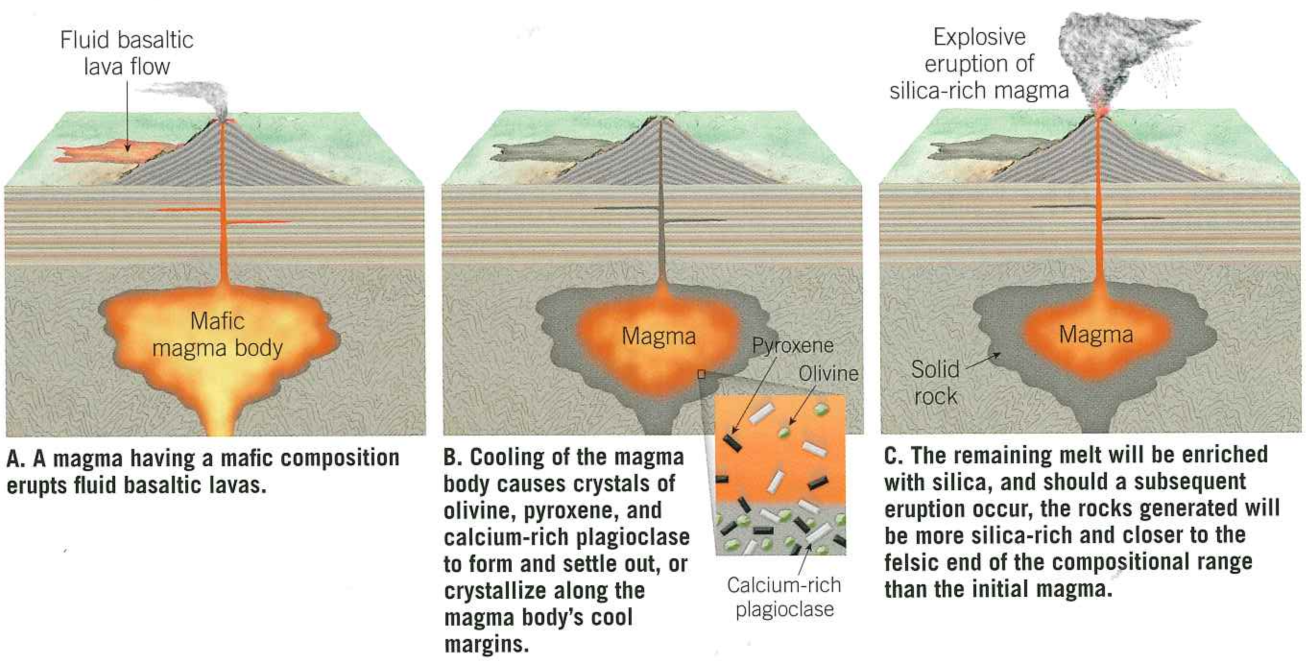
FIGURE 3.12 Bowen's Reaction Series This diagram shows the sequence in which minerals crystallize from a magma. Compare this figure to the mineral composition of the rock groups in Figure 3.7. Note that each rock group consists of minerals that crystallize in the same temperature range.



diagram, are typically found together as major constituents of the igneous rock *granite*.

Magmatic Differentiation Bowen demonstrated that different minerals crystallize from magma according to a predictable pattern. But how do Bowen's findings account for the great diversity of igneous rocks? During the crystallization process, the composition of magma continually changes. This occurs because as crystals form, they selectively remove certain elements from the magma, which leaves the remaining liquid portion (melt) depleted in these elements. Occasionally, separation of the solid and liquid components of magma occurs during crystallization, which creates different sets of minerals and, thus, different types of igneous rocks. One such scenario, called **crystal settling**, occurs when the earlier formed minerals are more dense (heavier) than the liquid portion and sink toward the bottom of the magma chamber, as shown in **FIGURE 3.13**. When the remaining molten material solidifies—either in place or in another location, if it migrates

FIGURE 3.13 Magmatic Differentiation and Crystal Settling Illustration of how a magma evolves as the earliest-formed minerals (those richer in iron, magnesium, and calcium) crystallize and settle to the bottom of the magma chamber, leaving the remaining melt richer in sodium, potassium, and silica (SiO_2).



A. A magma having a mafic composition erupts fluid basaltic lavas.

B. Cooling of the magma body causes crystals of olivine, pyroxene, and calcium-rich plagioclase to form and settle out, or crystallize along the magma body's cool margins.

C. The remaining melt will be enriched with silica, and should a subsequent eruption occur, the rocks generated will be more silica-rich and closer to the felsic end of the compositional range than the initial magma.

into fractures in the surrounding rocks—it will form a rock with a chemical composition much different from the parent magma (see Figure 3.13). The formation of one or more secondary magmas from a single parent magma is called **magmatic differentiation**.

At any stage in the evolution of a magma, the solid and liquid components can separate into two chemically distinct units. Furthermore, magmatic differentiation within the secondary magma can generate other chemically distinct masses of molten rock. Consequently, magmatic differentiation and separation of the solid and liquid components at various stages of crystallization can produce several chemically diverse magmas and, ultimately, a variety of igneous rocks.

3.2 CONCEPT CHECKS

1 What is magma? How does magma differ from lava?
2 In what basic settings do intrusive and extrusive igneous rocks originate?
3 How does the rate of cooling influence crystal size? What other factors influence the texture of igneous rocks?
4 What does a porphyritic texture indicate about the history of an igneous rock?
5 List and distinguish among the four basic compositional groups of igneous rocks.
6 How are granite and rhyolite different? In what way are they similar?
7 What is magmatic differentiation? How might this process lead to the formation of several different igneous rocks from a single magma?

3.3 SEDIMENTARY ROCKS: COMPACTED AND CEMENTED SEDIMENT

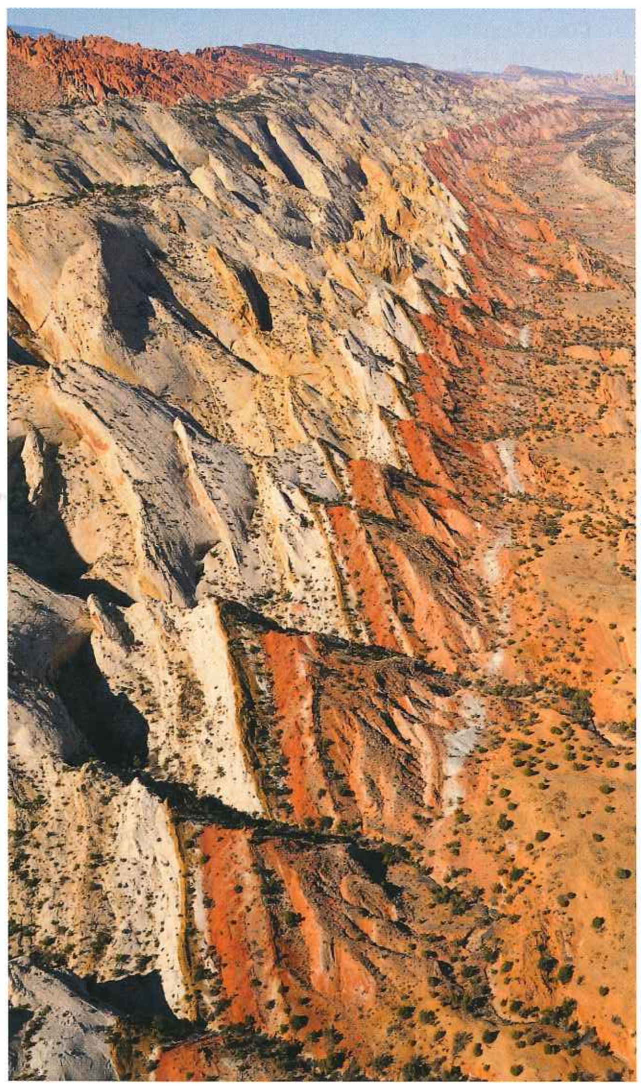
List and describe the different categories of sedimentary rocks and discuss the processes that change sediment into sedimentary rock.

Recall the rock cycle, which shows the origin of **sedimentary rocks**. Weathering begins the process. Next, gravity and erosional agents (running water, wind, waves, and glacial ice) remove the products of weathering and carry them to a new location, where they are deposited. Usually, the particles are broken down further during this transport phase. Following deposition, this **sediment** may become lithified, or "turned to rock." Commonly, *compaction* and *cementation* transform the sediment into solid sedimentary rock.

The word *sedimentary* indicates the nature of these rocks, for it is derived from the Latin *sedimentum*, which means "settling," a reference to a solid material settling out of a fluid. Most sediment is deposited in this fashion. Weathered debris is constantly being swept from bedrock and carried away by water, ice, or wind. Eventually, the material is deposited in lakes, river valleys, seas, and countless other places. The particles in a desert sand dune, the mud on the floor of a swamp, the gravels in a streambed, and even household dust are examples of sediment produced by this never-ending process.

The weathering of bedrock and the transport and deposition of the weathering products are continuous. Therefore, sediment is found almost everywhere. As piles of sediment accumulate, the materials near the bottom are compacted by the weight of the overlying layers. Over long periods, these sediments are cemented together by mineral matter deposited from water in the spaces between particles. This forms solid sedimentary rock.

Geologists estimate that sedimentary rocks account for only about 5 percent (by volume) of Earth's outer 16 kilometers (10 miles). However, the importance of this group of rocks is far greater than this percentage implies. If you sampled the rocks exposed at Earth's surface, you would find that the great majority are sedimentary (**FIGURE 3.14**).



Mobile Field Trip 3.14 Sedimentary Rocks Exposed in Capitol Reef National Park, Utah
About 75 percent of all rock exposures on continents are sedimentary rocks.
(Photo by Michael Collier)

Indeed, about 75 percent of all rock outcrops on the continents are sedimentary. Therefore, we can think of sedimentary rocks as comprising a relatively thin and somewhat discontinuous layer in the uppermost portion of the crust. This makes sense because sediment accumulates at the surface.

It is from sedimentary rocks that geologists reconstruct many details of Earth's history. Because sediments are deposited in a variety of different settings at the surface, the rock layers that they eventually form hold many clues to past surface environments. They may also exhibit characteristics that allow geologists to decipher information about the method and distance of sediment transport. Furthermore, sedimentary rocks contain fossils, which are vital evidence in the study of the geologic past.

Finally, many sedimentary rocks are important economically. Coal, which is burned to provide a significant portion of U.S. electrical energy, is classified as a sedimentary rock. Other major energy resources (such as petroleum and natural gas) occur in pores within sedimentary rocks. Other sedimentary rocks are major sources of iron, aluminum, manganese, and fertilizer, plus numerous materials essential to the construction industry.

Classifying Sedimentary Rocks

Materials that accumulate as sediment have two principal sources. First, sediments may originate as solid particles from weathered rocks, such as the igneous rocks described earlier. These particles are called *detritus*, and the sedimentary rocks they form are called **detrital sedimentary rocks** (**FIGURE 3.15**).

Detrital Sedimentary Rocks Though a wide variety of minerals and rock fragments may be found in detrital rocks, clay minerals and quartz dominate. As you learned earlier, clay minerals are the most abundant product of the chemical weathering of silicate minerals, especially the feldspars. Quartz, on the other hand, is abundant because it is extremely durable and very resistant to chemical weathering. Thus, when igneous rocks such as granite are weathered, individual quartz grains are set free.

Geologists use particle size to distinguish among detrital sedimentary rocks. Figure 3.15 presents the four size categories for particles making up detrital rocks. When gravel-size particles predominate, the rock is called *conglomerate* if the sediment is rounded and *breccia* if the pieces are angular (see Figure 3.15). Angular fragments indicate that the particles were not transported very far from their source prior to deposition and so have not had corners and rough edges abraded. *Sandstone* is the name given to rocks when sand-size grains prevail. *Shale*, the most common sedimentary rock, is made of very fine-grained sediment and composed mainly of clay minerals (see Figure 3.15). *Siltstone*, another rather fine-grained rock, is composed of clay-sized sediment intermixed with slightly larger silt-sized grains.

Using particle size is not only a convenient method of dividing detrital rocks; the sizes of the component grains

FIGURE 3.15 Detrital Sedimentary Rocks (Photos by E. J. Tarbuck and Dennis Tasa)

Detrital Sedimentary Rocks

Clastic Texture (particle size)	Sediment Name	Rock Name
Coarse (over 2 mm)	Gravel (Rounded particles)	**Conglomerate** 
	Gravel (Angular particles)	**Breccia** 
Medium (1/16 to 2 mm)	Sand	**Sandstone** 
		Arkose* 
Fine (1/16 to 1/256 mm)	Silt	**Siltstone** 
Very fine (less than 1/256 mm)	Clay	**Shale or Mudstone** 

*If abundant feldspar is present the rock is called arkose.

also provide useful information about the environment in which the sediment was deposited. Currents of water or air sort the particles by size. The stronger the current, the larger the particle size carried. Gravels, for example, are moved by swiftly flowing rivers, rockslides, and glaciers. Less energy is required to transport sand; thus, it is common in wind-blown dunes, river deposits, and beaches. Because silts and clays settle very slowly, accumulations of these materials are generally associated with the quiet waters of a lake, lagoon, swamp, or marine environment.

Although detrital sedimentary rocks are classified by particle size, in certain cases, the mineral composition is also part of naming a rock. For example, most sandstones are predominantly quartz rich, and they are often referred to as quartz sandstone. In addition, rocks consisting of detrital sediments are rarely composed of grains of just one size. Consequently, a rock containing quantities of both sand and silt can be correctly classified as sandy siltstone or silty sandstone, depending on which particle size dominates.

Chemical and Biochemical Sedimentary Rocks

In contrast to detrital rocks, which form from the solid products of weathering, **chemical sedimentary rocks** and **biochemical sedimentary rocks** are derived from material (ions) that is carried in solution to lakes and seas (**FIGURE 3.16**). This material does not remain dissolved in water indefinitely. Under certain conditions, it precipitates (settles out) to form *chemical sediments* as a result of physical processes. An example of chemical sediments resulting from physical processes is the salt left behind as a body of saltwater evaporates.

Precipitation may also occur indirectly through life processes of water-dwelling organisms that form materials called *biochemical sediments*. Many water-dwelling animals and plants extract dissolved mineral matter to form shells and other hard parts. After the organisms die, their skeletons may accumulate on the floor of a lake or an ocean.

Limestone, an abundant sedimentary rock, is composed chiefly of the mineral calcite ($CaCO_3$). Nearly 90 percent of limestone is formed from biochemical sediments secreted by marine organisms, and the remaining amount consists of chemical sediments that precipitated directly from seawater.

One easily identified biochemical limestone is *coquina*, a coarse rock composed of loosely cemented shells and shell fragments (**FIGURE 3.17**). Another less obvious but familiar example is *chalk*, a soft, porous rock made up almost entirely of the hard parts of microscopic organisms that are no larger than the head of a pin. Among the most famous chalk deposits are the White Chalk Cliffs exposed along the southeast coast of England (**FIGURE 3.18**).

Inorganic limestone forms when chemical changes or high water temperatures increase the concentration of calcium carbonate to the point that it precipitates. *Travertine*, the type of limestone that decorates caverns, is one example.

Chemical, Biochemical, and Organic Sedimentary Rocks

Composition		Texture	Rock Name
Calcite, $CaCO_3$		Nonclastic: Fine to coarse crystalline	**Crystalline Limestone** 
Calcite, $CaCO_3$		Nonclastic: Microcrystalline calcite	**Microcrystalline Limestone** 
Calcite, $CaCO_3$		Nonclastic: Fine to coarse crystalline	**Travertine** 
Calcite, $CaCO_3$	Biochemical Limestone	Clastic: Visible shells and shell fragments loosely cemented	**Coquina** 
Calcite, $CaCO_3$	Biochemical Limestone	Clastic: Various size shells and shell fragments cemented with calcite cement	**Fossiliferous Limestone** 
Calcite, $CaCO_3$	Biochemical Limestone	Clastic: Microscopic shells and clay	**Chalk** 
Quartz, SiO_2		Nonclastic: Very fine crystalline	**Chert (light colored)** 
Gypsum $CaSO_4 \bullet 2H_2O$		Nonclastic: Fine to coarse crystalline	**Rock Gypsum** 
Halite, NaCl		Nonclastic: Fine to coarse crystalline	**Rock Salt** 
Altered plant fragments (organic)		Nonclastic: Fine-grained organic matter	**Bituminous Coal** 

FIGURE 3.16 Chemical, Biochemical, and Organic Sedimentary Rocks. (Photos by E. J. Tarbuck and Dennis Tasa)

Groundwater is the source of travertine that is deposited in caves. As water drops reach the air in a cavern, some of the carbon dioxide dissolved in the water escapes, causing calcium carbonate to precipitate.

Dissolved silica (SiO_2) precipitates to form varieties of microcrystalline quartz (**FIGURE 3.19**). Sedimentary rocks composed of microcrystalline quartz include chert (light color), flint (dark), jasper (red), and agate (banded). These chemical sedimentary rocks may have either an inorganic or biochemical origin, but the mode of origin is usually difficult to determine.

Very often, evaporation causes minerals to precipitate from water. Such minerals include halite, the chief component of *rock salt*, and gypsum, the main ingredient of *rock gypsum*. Both materials have significant commercial importance. Halite is familiar to everyone as the common salt used in cooking and seasoning foods. Of course, it has many other uses and has been considered important enough that people have sought, traded, and fought over it for much of human history. Gypsum is the basic ingredient of plaster of Paris. This material is used most extensively in the construction industry for "drywall" and plaster.

In the geologic past, many areas that are now dry land were covered by shallow arms of the sea that had only narrow connections to the open ocean. Under these conditions, water continually moved into the bay to replace

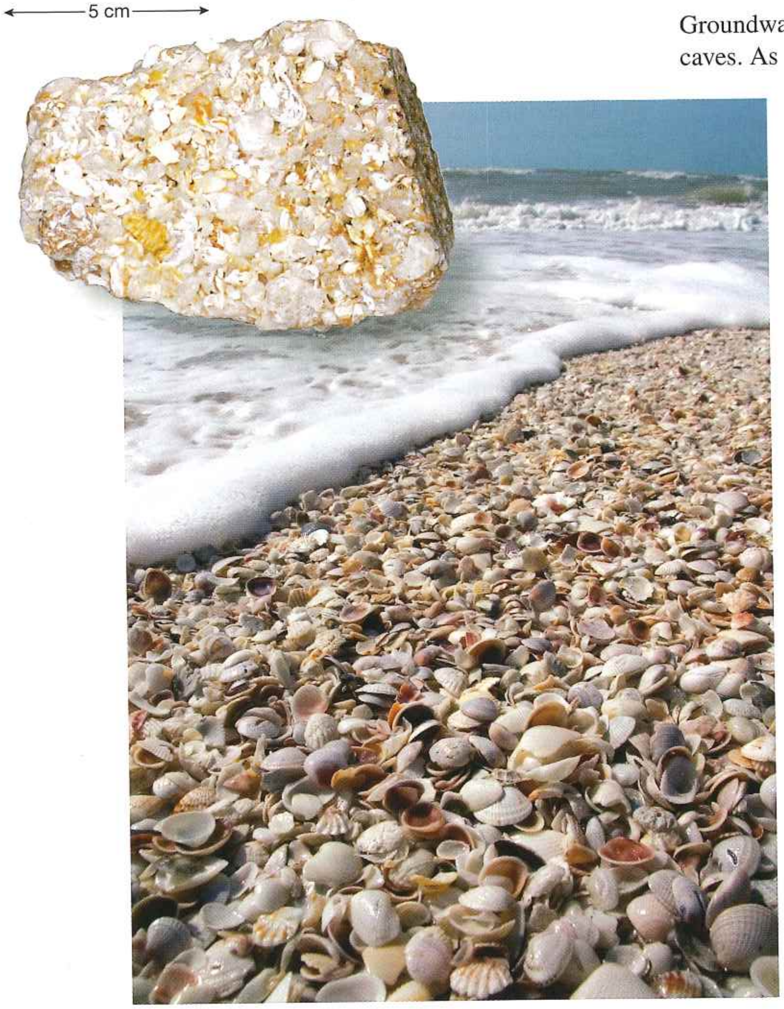
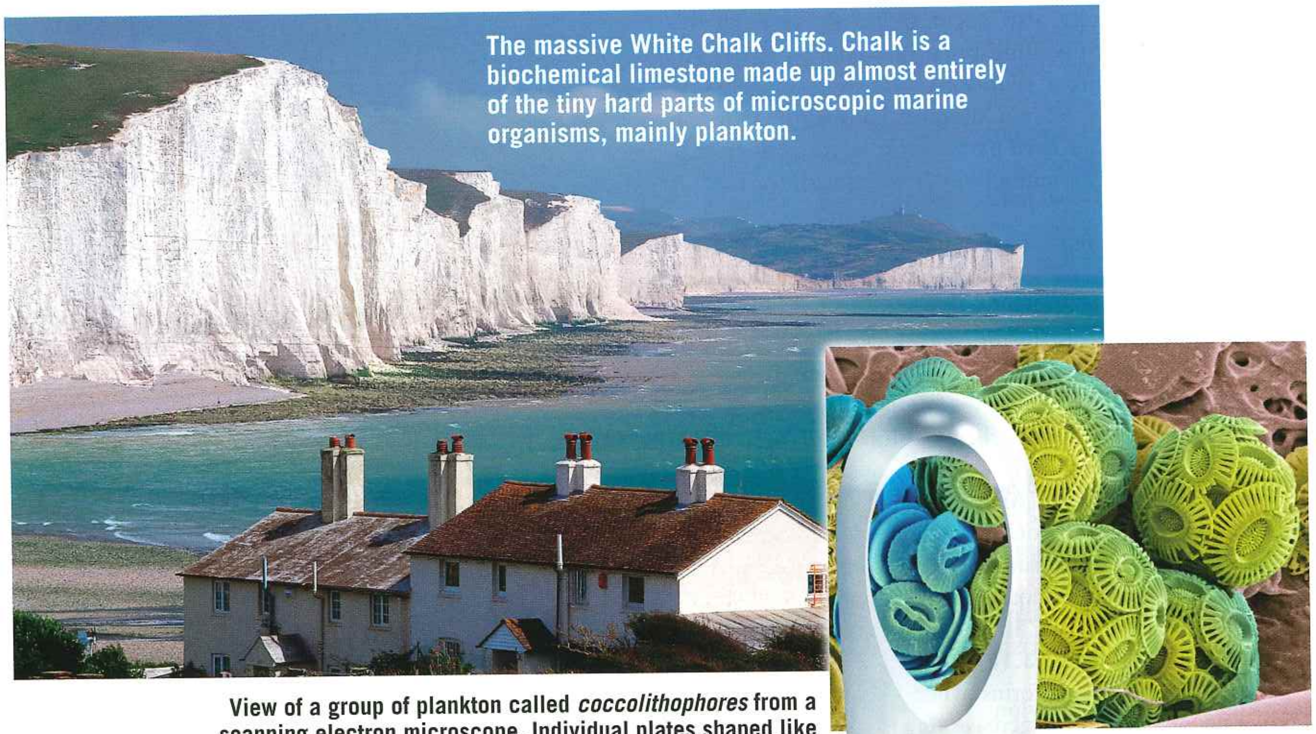


FIGURE 3.17 Coquina This variety of limestone consists of shell fragments; therefore, it has a biochemical origin. (Rock photo by E. J. Tarbuck; beach photo by Donald R. Frazier Photolibrary, Inc./Alamy)



View of a group of plankton called *coccolithophores* from a scanning electron microscope. Individual plates shaped like hubcaps are only three one-thousandths of a millimeter in diameter; so tiny they could pass through the eye of a needle.

FIGURE 3.18 The White Chalk Cliffs This prominent deposit underlies large portions of southern England as well as parts of northern France. (White Chalk Cliffs photo by BL Images Ltd/Alamy; Coccolithophores photo by Science Photo Library/Alamy Images)

FIGURE 3.19 Varieties of Chert Chert is the name applied to a number of dense, hard chemical sedimentary rocks made of microcrystalline quartz. (Agate photo by The Natural History Museum/Alamy Images; petrified wood photo by gracious_tiger/Shutterstock; flint and jasper photos by E. J. Tarbuck; arrowhead photo by Daniel Sambraus/Science Source)

water lost by evaporation. Eventually, the waters of the bay became saturated, and salt deposition began. Today, these arms of the sea are gone, and the remaining deposits are called **evaporite deposits**.

On a smaller scale, evaporite deposits can be seen in such places as Death Valley, California. Here, following rains or periods of snowmelt in the mountains, streams flow from surrounding mountains into an enclosed basin. As the water evaporates, dissolved materials left behind as a white crust on the ground form *salt flats* (**FIGURE 3.20**).

Coal—An Organic Sedimentary Rock

Coal, in contrast to sedimentary rocks that are rich in calcite or silica, consists mostly of **organic matter**. Close examination of a piece of coal under a microscope or magnifying glass often reveals plant structures such as leaves, bark, and wood that have been chemically altered but remain identifiable. This supports the conclusion that coal is the end product of the burial of large amounts of plant material over extended periods (**FIGURE 3.21**).

The initial stage in coal formation is the accumulation of large quantities of plant remains. However, special conditions are required for such accumulations because dead plants normally decompose when exposed to the atmosphere. An ideal environment that allows for the accumulation of plant material is a swamp. Because stagnant swamp water is oxygen deficient, complete decay (oxidation) of the plant material is not possible. At various times during Earth history, such environments have been common. Coal undergoes successive stages of formation. With each successive stage, higher temperatures and pressures drive off impurities and volatiles, as shown in Figure 3.21.

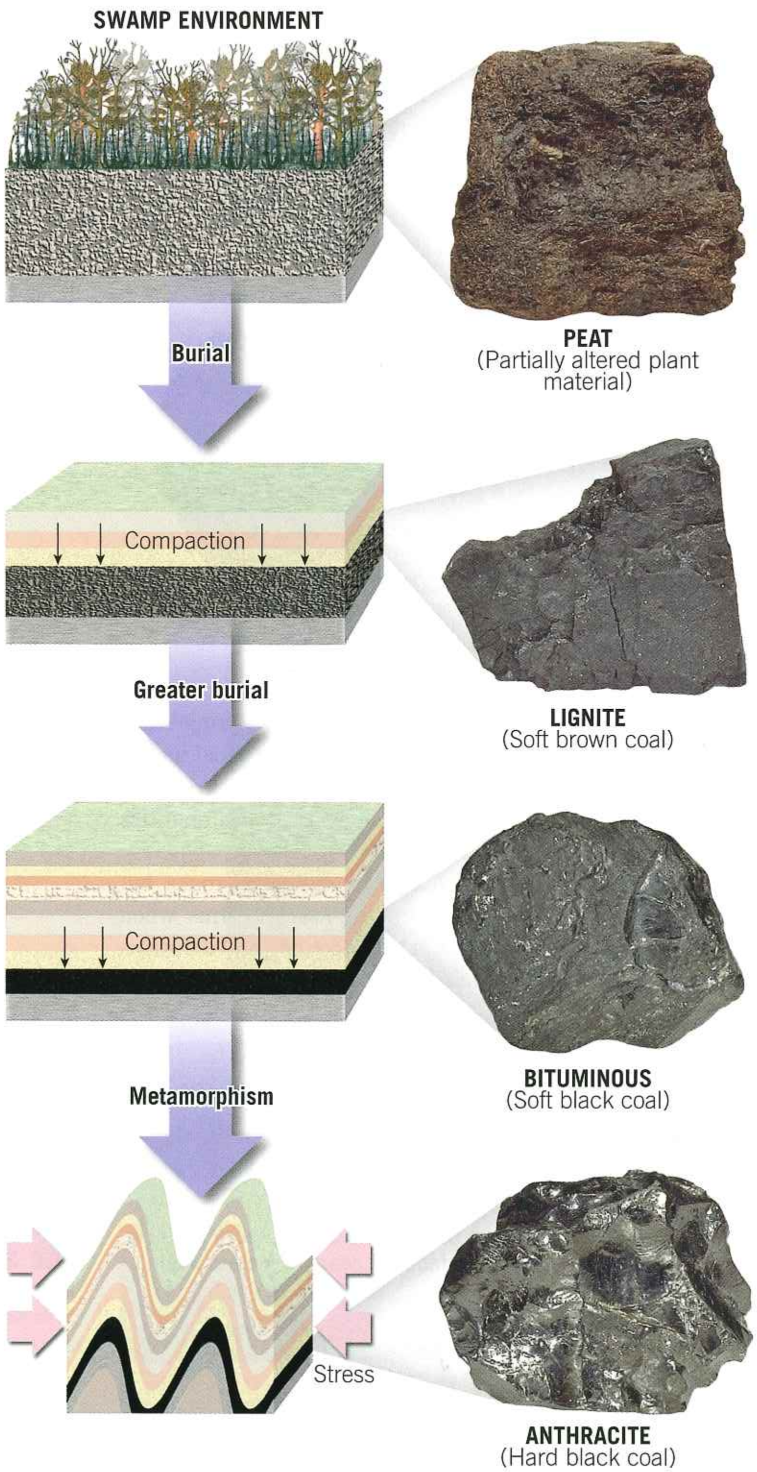
Lignite and bituminous coals are sedimentary rocks, but anthracite is a metamorphic rock. Anthracite forms when sedimentary layers are subjected to the folding and deformation associated with mountain building.

Lithification of Sediment

Lithification refers to the processes by which sediments are transformed into solid sedimentary rocks. One of the most common processes is **compaction** (**FIGURE 3.22**). As

This extensive evaporite deposit is a 30,000-acre expanse of hard white salt that in places is nearly 2 meters thick.

SmartFigure 3.20 Bonneville Salt Flats This well-known Utah site was once a large salt lake. (Photo by Jupiterimages/Glow Images)



SmartFigure 3.21 From Plants to Coal Successive stages in the formation of coal. (Photos by E. J. Tarbuck)

sediments accumulate through time, the weight of overlying material compresses the deeper sediments. As the grains are pressed closer and closer, pore space is greatly reduced. For example, when clays are buried beneath

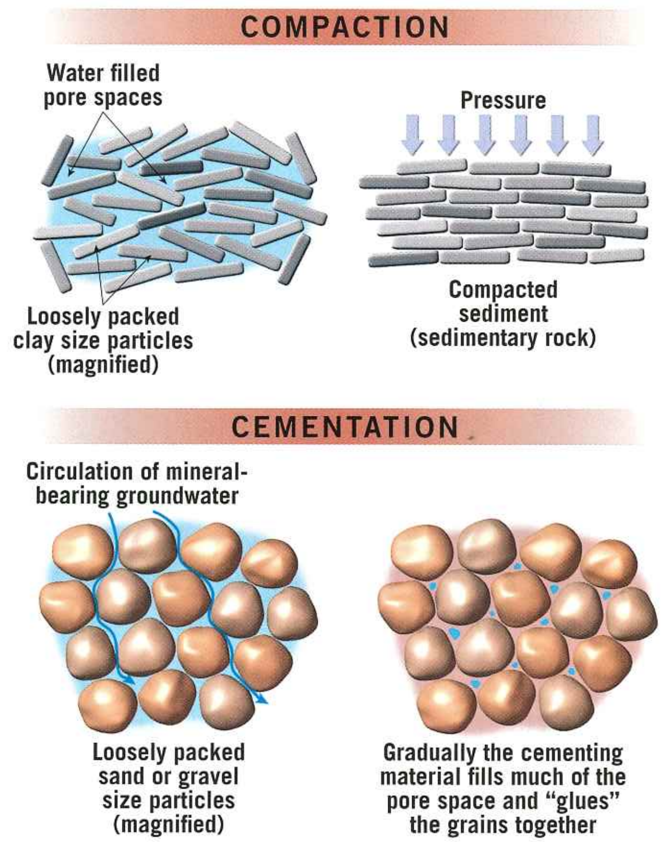


FIGURE 3.22 Compaction and Cementation

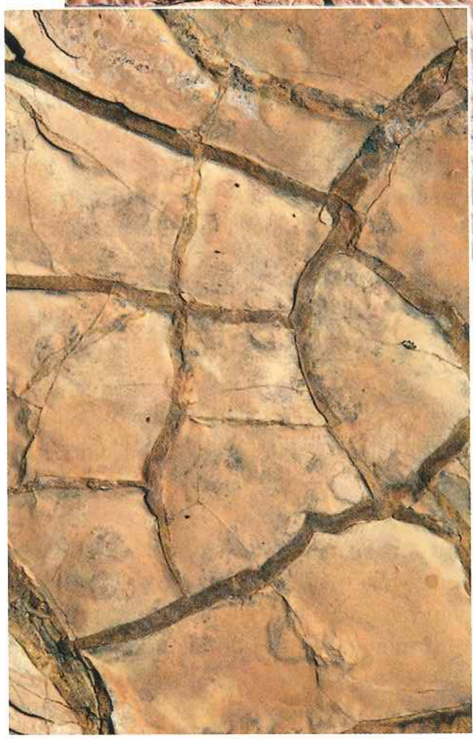
several thousand meters of material, the volume of the clay may be reduced as much as 40 percent. Compaction is most effective in converting very fine-grained sediments, such as clay-size particles, into sedimentary rocks.

Because sand and coarse sediments (gravel) are not easily compressed, they are generally transformed into sedimentary rocks by the process of **cementation** (see Figure 3.22). The cementing materials are carried in a water-rich solution that percolates through the pore spaces between particles. Over time, the cement precipitates onto the sediment grains, fills the open spaces, and acts like a "glue" to join the particles together. Calcite, silica, and iron oxide are the most common cements. Identification of the cementing material is simple. Calcite cement will effervesce (fizz) with dilute hydrochloric acid. Silica is the hardest cement and thus produces the hardest sedimentary rocks. When a sedimentary rock has an orange or red color, this usually means iron oxide is present.

Features of Sedimentary Rocks

Sedimentary rocks are particularly important in the study of Earth history. These rocks form at Earth's surface, and as layer upon layer of sediment accumulates, each records the nature of the environment at the time the sediment was deposited. These layers, called **strata**, or **beds**, are the *single most characteristic feature of sedimentary rocks* (see Figure 3.14).

A.



B.

FIGURE 3.23 Sedimentary Environments **A.** Ripple marks preserved in sedimentary rocks may indicate a beach or stream channel environment. (Photo by Tim Graham/Alamy Images) **B.** Mud cracks form when wet mud or clay dries and shrinks, perhaps signifying a tidal flat or desert basin. (Photo by Marli Miller)

The thickness of beds ranges from microscopically thin to tens of meters thick. Separating the strata are *bedding planes*, flat surfaces along which rocks tend to separate or break. Generally, each bedding plane marks the end of one episode of sedimentation and the beginning of another.

Sedimentary rocks provide geologists with evidence for deciphering past environments. A conglomerate, for example, indicates a high-energy environment, such as a rushing stream, where only the coarse materials can settle out. By contrast, black shale and coal are associated with a low-energy, organic-rich environment, such as a swamp or lagoon. Other features found in some sedimentary rocks also give clues to past environments (**FIGURE 3.23**).

Fossils, the traces or remains of prehistoric life, are perhaps the most important inclusions found in some sedimentary rock (**FIGURE 3.24**). Knowing the nature of the life-forms that existed at a particular time may help answer many questions about the environment. Was it land or ocean, lake or swamp? Was the climate hot or cold, rainy or dry? Was the ocean water shallow or deep, turbid or clear? Furthermore, fossils are important time indicators and play a key role in matching up rocks from different places that are the same age. Fossils are important tools used in interpreting the geologic past and will be examined in some detail in Chapter 11.

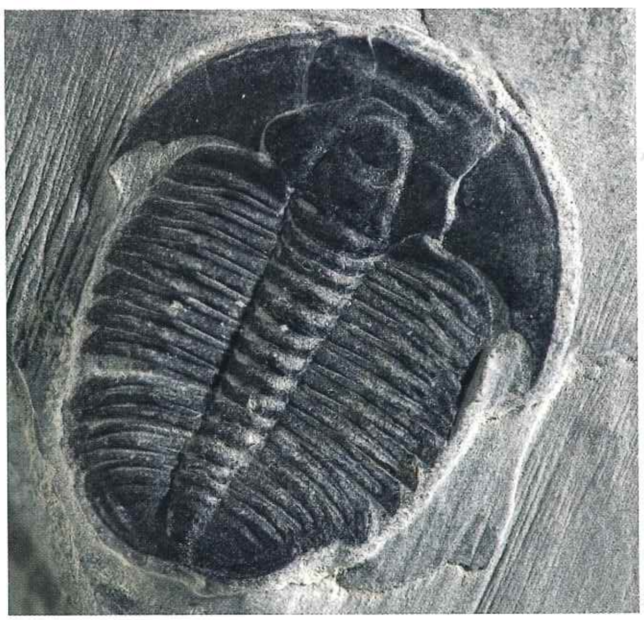


FIGURE 3.24 Fossils—Clues to the Past Fossils, the remains or traces of prehistoric life, are primarily associated with sediments and sedimentary rocks. A large variety of trilobites are associated with the Paleozoic era. (Photo by Russell Shively/Shutterstock)

3.3 CONCEPT CHECKS

1. Why are sedimentary rocks important?
2. What minerals are most abundant in detrital sedimentary rocks? In which rocks do these sediments predominate?
3. Distinguish between conglomerate and breccia.
4. What are the two categories of chemical sedimentary rock? Give an example of a rock that belongs to each category.
5. How do evaporites form? Give an example.
6. Describe the two processes by which sediments are transformed into sedimentary rocks. Which is the most effective process in the lithification of sand- and gravel-sized sediments?
7. List three common cements. How might each be identified?
8. What is the most characteristic feature of sedimentary rocks?

3.4 METAMORPHIC ROCKS: NEW ROCK FROM OLD Define *metamorphism*, explain how metamorphic rocks form, and describe the agents of metamorphism.

Recall from the discussion of the rock cycle that metamorphism is the transformation of one rock type into another. **Metamorphic rocks** are produced from preexisting igneous, sedimentary, or even other metamorphic rocks (**FIGURE 3.25**). Thus, every metamorphic rock has a *parent rock*—the rock from which it was formed.

Metamorphism, which means "to change form," is a process that leads to changes in the mineralogy, texture (for example, grain size), and sometimes chemical composition of rocks. Metamorphism takes place when preexisting rock is subjected to a physical or chemical environment that is significantly different from that in which it initially formed. In response to these new conditions, the rock gradually changes until a state of equilibrium with the new environment is reached. Most metamorphic changes occur at the elevated temperatures and pressures that exist in the zone beginning a few kilometers below Earth's surface and extending into the mantle.

Metamorphism often progresses incrementally, from slight changes (*low-grade metamorphism*) to substantial changes (*high-grade metamorphism*) (**FIGURE 3.26**). For example, under low-grade metamorphism, the common sedimentary rock *shale* becomes the more compact metamorphic rock called *slate* (see Figure 3.26A). Hand samples of these rocks are sometimes difficult to distinguish, illustrating that the transition from sedimentary to metamorphic rock is often gradual, and the changes can be subtle.

In more extreme environments, metamorphism causes a transformation so complete that the identity of the parent rock cannot be determined. In high-grade metamorphism, such features as bedding planes, fossils, and vesicles that may have existed in the parent rock are obliterated. Furthermore, when rocks deep in the crust (where temperatures are high) are subjected to directed pressure, the entire mass may deform, producing large-scale structures such as folds (see Figure 3.26B).

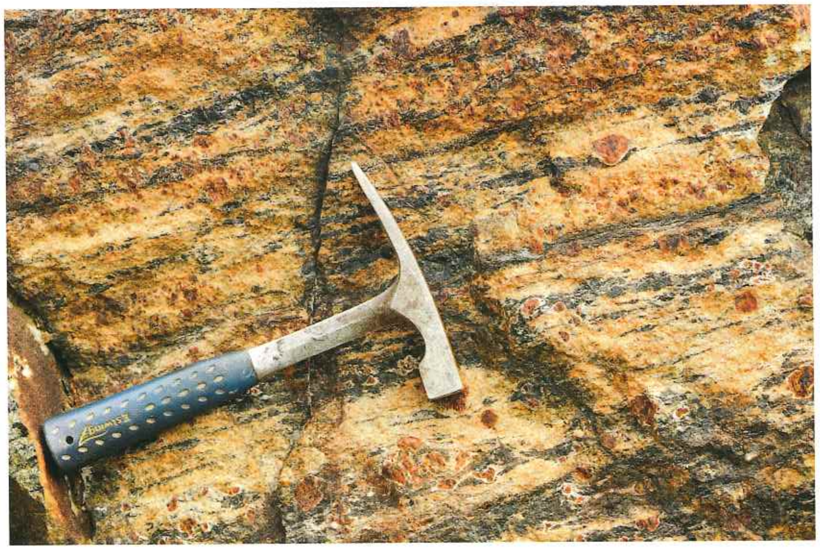
In the most extreme metamorphic environments, the temperatures approach those at which rocks melt. However, *during metamorphism, the rock must remain essentially solid*, for if complete melting occurs, we have entered the realm of igneous activity.

Most metamorphism occurs in one of two settings:

1. When rock is intruded by magma, **contact metamorphism**, or **thermal metamorphism**, may take place. In such a situation, change is caused by the rise in temperature within the rock surrounding the mass of molten material.
2. During mountain building, great quantities of rock are subjected to pressures and high temperatures associated with large-scale deformation called **regional metamorphism**.

Extensive areas of metamorphic rocks are exposed on every continent. Metamorphic rocks are an important component of many mountain belts, where they make up a large portion of a mountain's crystalline core. Even the stable continental interiors, which are generally covered by sedimentary rocks, are underlain by metamorphic basement rocks. In each of these settings, the metamorphic rocks are usually highly deformed and intruded by igneous masses. Consequently, significant parts of Earth's continental crust are composed of metamorphic and associated igneous rocks.

Mobile Field Trip FIGURE 3.25 Metamorphic Rocks in the Adirondacks, New York. (Photo by Michael Collier)



What Drives Metamorphism?

The agents of metamorphism include *heat*, *confining pressure*, *differential stress*, and *chemically active fluids*. During metamorphism, rocks are often subjected to all four metamorphic agents simultaneously. However, the degree of metamorphism and the contribution of each agent vary greatly from one environment to another.

Heat as a Metamorphic Agent

Thermal energy (*heat*) is the most important factor driving metamorphism. It triggers chemical reactions that result in the recrystallization of existing minerals and the formation of new minerals. Thermal energy for metamorphism comes mainly from two sources. Rocks experience a rise in temperature when they are intruded by magma rising from below. This is called *contact*, or *thermal*, *metamorphism*. In this situation, the adjacent host rock is "baked" by the emplaced magma.

By contrast, rocks that formed at Earth's surface will experience a gradual increase in temperature and pressure as they are taken to greater depths. In the upper crust, this increase in temperature averages about 25°C per kilometer. When buried to a depth of about 8 kilometers (5 miles), where temperatures are between 150° and 200°C, clay minerals tend to become unstable and begin to recrystallize into other minerals, such as chlorite and muscovite, that are stable in this environment. (Chlorite is a mica-like mineral formed by the metamorphism of iron- and magnesium-rich silicates.) However, many silicate minerals, particularly those found in crystalline igneous rocks—quartz and feldspar, for example—remain stable at these temperatures. Thus, metamorphic changes in these minerals require much higher temperatures in order to recrystallize.

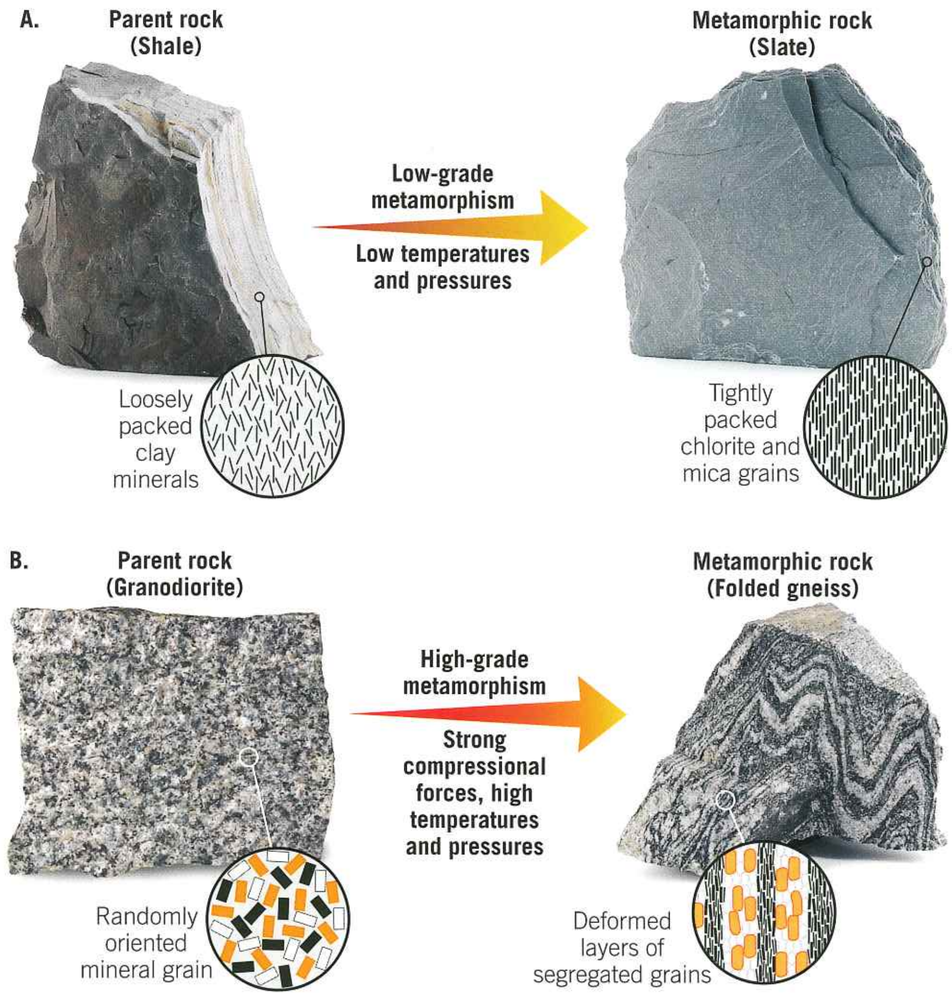


FIGURE 3.26 Metamorphic Grade **A.** Low-grade metamorphism illustrated by the transformation of the common sedimentary rock shale to the more compact metamorphic rock slate. **B.** High-grade metamorphic environments obliterate the existing texture and often change the mineralogy of the parent rock. High-grade metamorphism occurs at temperatures that approach those at which rocks melt. (Photos by Dennis Tasa)

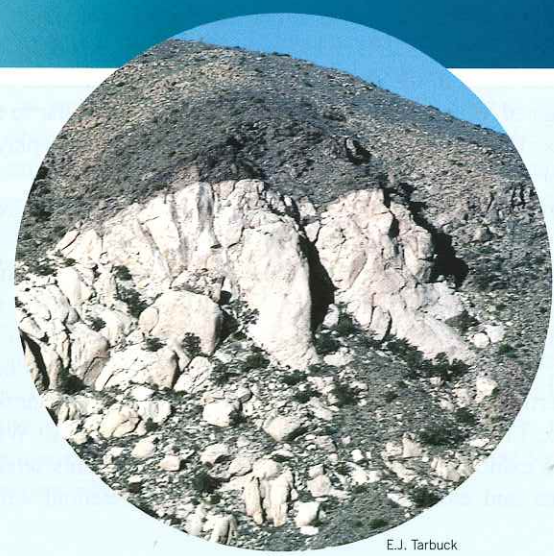
Confining Pressure and Differential Stress as Metamorphic Agents Pressure, like temperature, increases with depth as the thickness of the overlying rock increases. Buried rocks are subjected to *confining pressure*—similar to water pressure in that the forces are equally applied in all directions (**FIGURE 3.27A**). The deeper you go in the ocean, the greater the confining pressure. The same is true for buried rock. Confining pressure causes the spaces between mineral grains to close, producing a more compact rock that has greater density. Further, at great depths,

EYE ON EARTH

This rock outcrop, located in Joshua Tree National Park, consists of dark-colored metamorphic rocks that overlie light-colored igneous rocks.

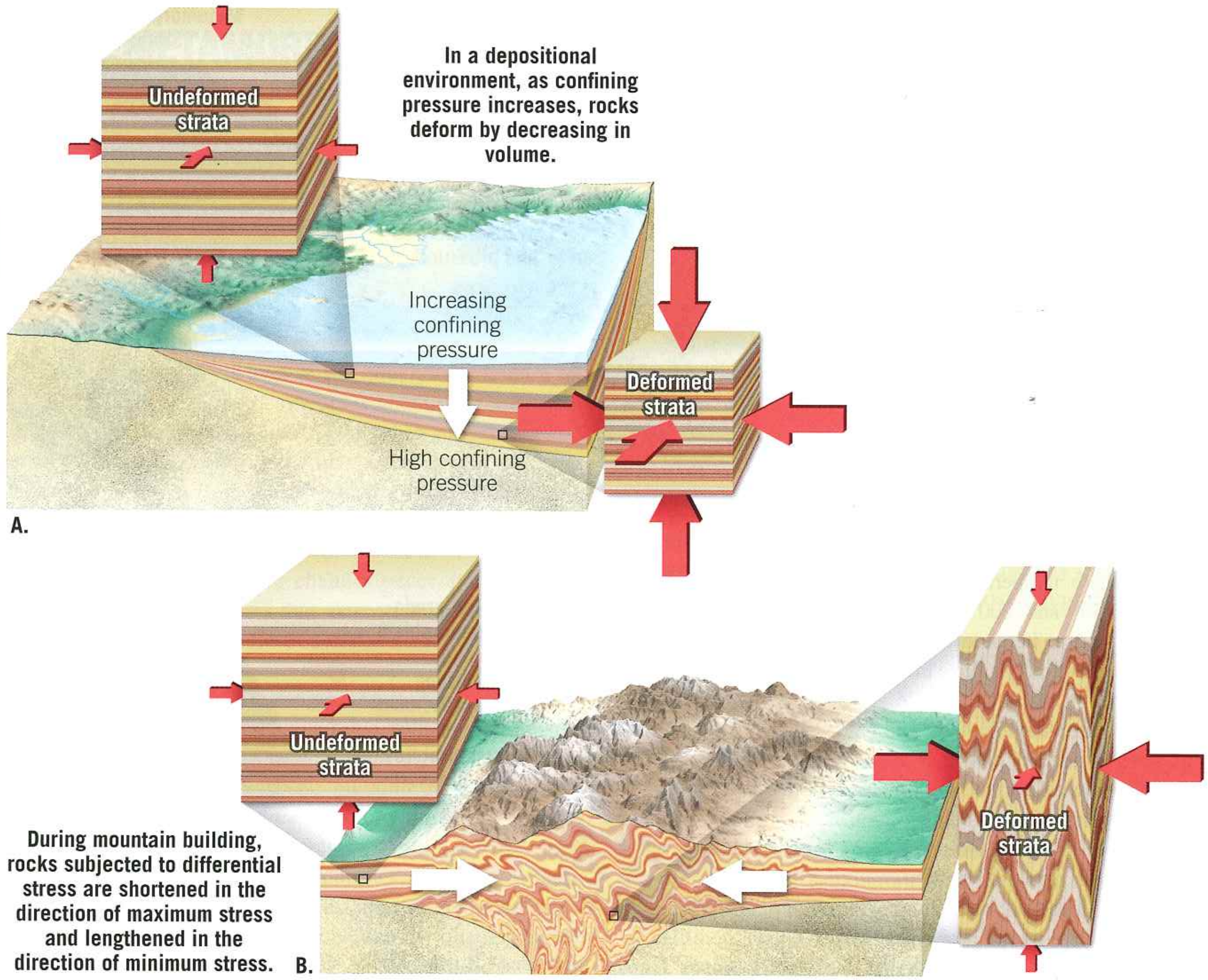
QUESTION 1 *Name the type of metamorphism—contact (thermal), or regional metamorphism—that likely produced these metamorphic rocks.*

QUESTION 2 *Write a brief statement that describes the geologic history of this area, based on what you observe in this image.*



E.J. Tarbuck

SmartFigure 3.27
Confining Pressure and Differential Stress



confining pressure may cause minerals to recrystallize into new minerals that display more compact crystalline forms.

During episodes of mountain building, large rock bodies become highly crumpled and metamorphosed (**FIGURE 3.27B**). The forces that generate mountains are unequal in different directions and are called *differential stress.* Unlike confining pressure, which "squeezes" rock equally in all directions, differential stresses are greater in one direction than in others. As shown in Figure 3.27B, rocks subjected to differential stress are shortened in the direction of greatest stress, and they are elongated, or lengthened, in the direction perpendicular to that stress. The deformation caused by differential stresses plays a major role in developing metamorphic textures.

In surface environments where temperatures are relatively low, rocks are *brittle* and tend to fracture when subjected to differential stress. (Think of a heavy boot crushing a piece of fine crystal.) Continued deformation grinds and pulverizes the mineral grains into small fragments. By contrast, in high-temperature, high-pressure environments deep in Earth's crust, rocks are *ductile* and tend to flow rather than break. (Think of a heavy boot crushing a soda can.) When rocks exhibit ductile behavior, their mineral grains tend to flatten and elongate when subjected to differential stress. This accounts for their ability to deform by flowing (rather than fracturing) to generate intricate folds.

Chemically Active Fluids Ion-rich fluids composed mainly of water and other volatiles (materials that readily change to gases at surface conditions) are believed to play an important role in some types of metamorphism. Fluids that surround mineral grains act as catalysts to promote recrystallization by enhancing ion migration. In progressively hotter environments, these ion-rich fluids become correspondingly more reactive. Chemically active fluids can produce two types of metamorphism, explained below. The first type changes the arrangement and shape of mineral grains within a rock; the second type changes the rock's chemical composition.

When two mineral grains are squeezed together, the parts of their crystalline structures that touch are the most highly stressed. Atoms at these sites are readily dissolved by the hot fluids and move to the voids between individual grains. Thus, hot fluids aid in the recrystallization of mineral grains by dissolving material from regions of high stress and then precipitating (depositing) this material in areas of low stress. As a result, *minerals tend to recrystallize and grow longer in a direction perpendicular to compressional stresses.*

When hot fluids circulate freely through rocks, ionic exchange may occur between adjacent rock layers, or ions may migrate great distances before they are finally deposited. The latter situation is particularly common when we consider hot fluids that escape during the crystallization of an intrusive mass of magma. If the rocks surrounding the magma differ markedly in composition from the invading fluids, there may be a substantial exchange of ions between the fluids and host rocks. When this occurs, the overall composition of the surrounding rock changes.

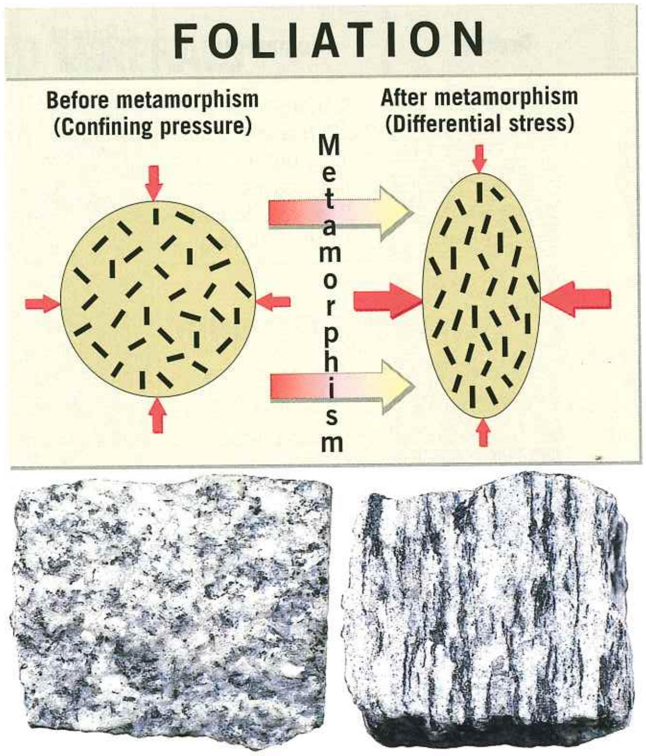


FIGURE 3.28 Rotation of Platy and Elongated Mineral Grains to Produce a Foliated Texture Under the pressures of metamorphism, some mineral grains become reoriented and aligned at right angles to the stress. The resulting orientation of mineral grains gives the rock a foliated (layered) texture. If the coarse-grained igneous rock (granite) on the left underwent intense metamorphism, it could end up closely resembling the metamorphic rock on the right (gneiss). (Photos by E. J. Tarbuck)

Metamorphic Textures

The degree of metamorphism is reflected in a rock's *texture* and *mineralogy.* (Recall that the term *texture* is used to describe the size, shape, and arrangement of grains within a rock.) When rocks are subjected to low-grade metamorphism, they become more compact and thus denser. A common example is the metamorphic rock slate, which forms when shale is subjected to temperatures and pressures only slightly greater than those associated with the compaction that lithifies sediment. In this case, differential stress causes the microscopic clay minerals in shale to align into the more compact arrangement found in slate.

Under more extreme conditions, stress causes certain minerals to recrystallize. In general, recrystallization encourages the growth of larger crystals. Consequently, many metamorphic rocks consist of visible crystals, much like coarse-grained igneous rocks.

Foliation The term **foliation** refers to any nearly flat arrangement of mineral grains or structural features within a rock. Although foliation may occur in some sedimentary and even a few types of igneous rocks, it is a fundamental characteristic of regionally metamorphosed rocks—that is, rock units that have been strongly deformed, mainly during folding. In metamorphic environments, foliation is ultimately driven by compressional stresses that shorten rock units, causing mineral grains in preexisting rocks to develop parallel, or nearly parallel, alignments (**FIGURE 3.28**). Examples of foliation include the *parallel alignment of platy (flat and disk-like) minerals* such as the micas; the *parallel alignment of flattened pebbles*; *compositional banding*, in which dark and light minerals separate generating a layered appearance; and *rock cleavage*, in which rocks can be easily split into tabular slabs.

Nonfoliated Textures Not all metamorphic rocks exhibit a foliated texture. Those that do not are referred to as **nonfoliated** and typically develop in environments where deformation is minimal and the parent rocks are composed of minerals that have a relatively simple chemical composition, such as quartz or calcite. For example, when a fine-grained limestone (made of calcite) is metamorphosed by the intrusion of a hot magma body (contact metamorphism), the small calcite grains recrystallize and form larger interlocking crystals. The resulting rock, *marble*, exhibits large, equidimensional grains that are randomly oriented, similar to those in a coarse-grained igneous rock.

Common Metamorphic Rocks

A chart depicting the common rocks produced by metamorphic processes is found in **FIGURE 3.29**, and a description of each follows.

Foliated Rocks *Slate* is a very fine-grained foliated rock composed of minute mica flakes that are too small to be visible (see Figure 3.29). A noteworthy characteristic of slate is its excellent rock cleavage, or tendency to break into flat slabs. This property has made slate a useful rock for roof and floor tile, as well as billiard tables (**FIGURE 3.30**). Slate is usually generated by the low-grade metamorphism of shale. Less frequently, it is produced when volcanic ash is metamorphosed. Slate's color is variable. Black slate contains organic material, red slate gets its color from iron oxide, and green slate is usually composed of chlorite, a greenish micalike mineral.

Phyllite represents a degree of metamorphism between slate and schist. Its constituent platy minerals, mainly muscovite and chlorite, are larger than those in slate but not large enough to be readily identifiable with the unaided eye. Although phyllite appears similar to slate, it can be easily distinguished from slate by its glossy sheen and wavy surface (see Figure 3.29).

COMMON METAMORPHIC ROCKS

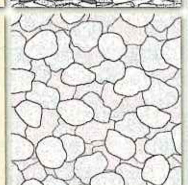
Metamorphic Rock		Texture		Comments	Parent Rock
Slate		Foliated		Composed of tiny chlorite and mica flakes, breaks in flat slabs called slaty cleavage, smooth dull surfaces	Shale, mudstone, or siltstone
Phyllite		Foliated		Fine-grained, glossy sheen, breaks along wavy surfaces	Shale, mudstone, or siltstone
Schist		Foliated		Medium- to coarse-grained, scaly foliation, micas dominate	Shale, mudstone, or siltstone
Gneiss		Foliated		Coarse-grained, compositional banding due to segregation of light and dark colored minerals	Shale, granite, or volcanic rocks
Marble		Nonfoliated		Medium- to coarse-grained, relatively soft (3 on the Mohs scale), interlocking calcite or dolomite grains	Limestone, dolostone
Quartzite		Nonfoliated		Medium- to coarse-grained, very hard, massive, fused quartz grains	Quartz sandstone

FIGURE 3.29 Classification of Common Metamorphic Rocks (Photos by E. J. Tarbuck)

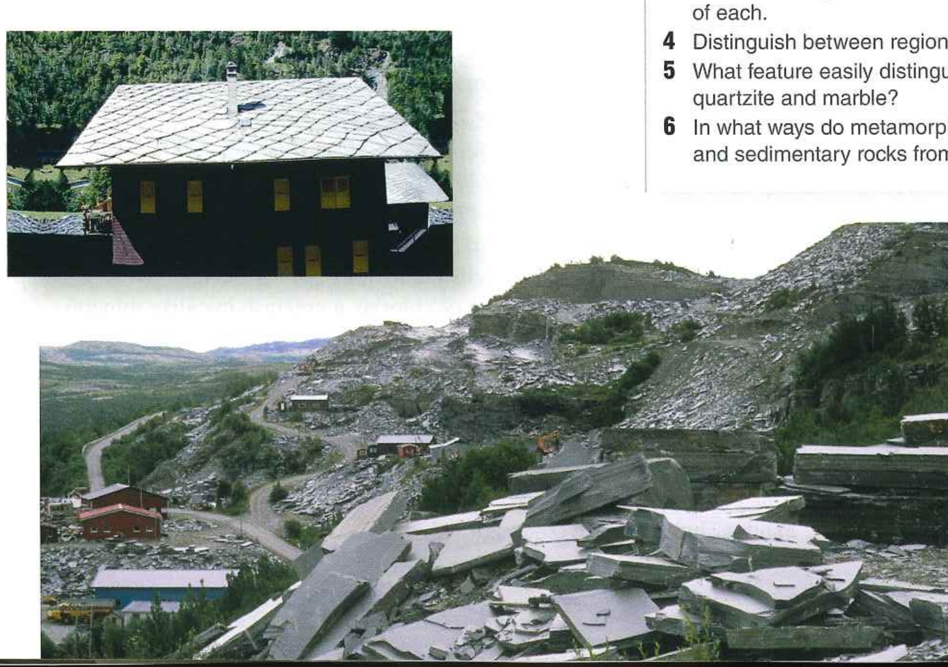


FIGURE 3.30 Slate Exhibits Rock Cleavage Because slate breaks into flat slabs, it has many uses. The larger image shows a quarry near Alta, Norway. (Photo by Fred Bruemmer/Getty Images) In the inset photo, slate is used as a roof on a house in Switzerland. (Photo by E. J. Tarbuck)

Schists are moderately to strongly foliated rocks formed by regional metamorphism (see Figure 3.29). They are platy and can be readily split into thin flakes or slabs. Many schists originate from shale parent rock. The term *schist* describes the *texture* of a rock regardless of composition. For example, schists composed primarily of muscovite and biotite are called *mica schists.*

Gneiss (pronounced "nice") is the term applied to banded metamorphic rocks in which elongated and granular (as opposed to platy) minerals predominate (see Figure 3.29). The most common minerals in gneisses are quartz and feldspar, with lesser amounts of muscovite, biotite, and hornblende. Gneisses exhibit strong segregation of light and dark silicates, giving them a characteristic banded texture. While still deep below the surface where temperatures and pressures are great, banded gneisses can be deformed into intricate folds.

Nonfoliated Rocks *Marble* is a coarse, crystalline rock whose parent rock is limestone. Marble is composed of large interlocking calcite crystals, which form from the recrystallization of smaller grains in the parent rock. Because of its color and relative softness (hardness of only 3 on the Mohs scale), marble is a popular building stone. White marble is particularly prized as a stone from which to carve monuments and statues, such as the Lincoln Memorial in Washington, DC, and the Taj Mahal in India. The parent rocks from which various marbles form contain impurities that color the stone. Thus, marble can be pink, gray, green, or even black.

Quartzite is a very hard metamorphic rock most often formed from quartz sandstone. Under moderate- to high-grade metamorphism, the quartz grains in sandstone fuse. Pure quartzite is white, but iron oxide may produce reddish or pinkish stains, and dark minerals may impart a gray color.

3.4 CONCEPT CHECKS

1. Metamorphism means "change form." Describe how a rock may change during metamorphism.
2. Briefly describe what is meant by the statement "every metamorphic rock has a parent rock."
3. List the four agents of metamorphism and describe the role of each.
4. Distinguish between regional and contact metamorphism.
5. What feature easily distinguishes schist and gneiss from quartzite and marble?
6. In what ways do metamorphic rocks differ from the igneous and sedimentary rocks from which they formed?

3.5 RESOURCES FROM ROCKS AND MINERALS

Distinguish between metallic and nonmetallic mineral resources and list at least two examples of each. Compare and contrast the three traditional fossil fuels.

The outer layer of Earth, which we call the crust, is only as thick when compared to the remainder of the Earth as a peach skin is to a peach, yet it is of supreme importance to us. We depend on it for fossil fuels and as a source of such diverse minerals as the iron for automobiles, salt to flavor food, and gold for world trade. In fact, on occasion, the availability or absence of certain Earth materials has altered the course of history. As the world population grows and the material requirements of modern society increase, the need to locate additional supplies of useful minerals becomes more challenging.

Most of the energy and mineral resources used by humans are nonrenewable. **FIGURE 3.31** shows the annual per capita consumption of several important mineral and energy resources. These data reflect an individually prorated share of the materials required by industry to support the needs of our modern society—including a vast array of homes, cars, electronics, cosmetics, packaging, and other products and services.

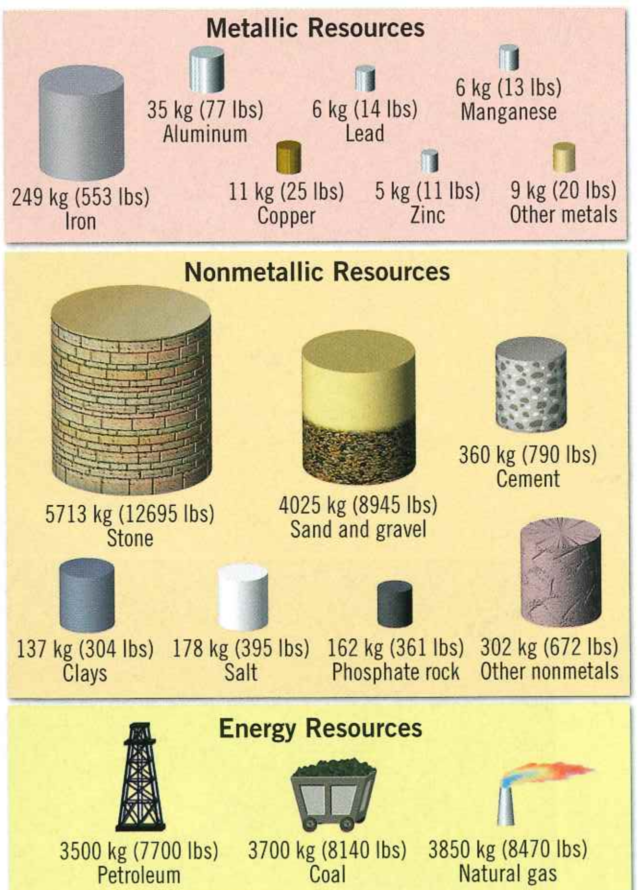


FIGURE 3.31 How Much Do Each of Us Use? The annual per capita consumption of metallic and nonmetallic resources for the United States is about 11,000 kilograms (12 tons). About 97 percent of the materials used are nonmetallic. The per capita use of oil, coal, and natural gas exceeds 11,000 kilograms. (U.S. Geological Survey)

Metallic Mineral Resources

Some of the most important accumulations of metals, including gold, silver, copper, platinum, and nickel, are produced by igneous and metamorphic processes that concentrate desirable materials to the extent that extraction is economically feasible (**TABLE 3.1**). Igneous processes that generate some metal deposits are straightforward. For example, as a large magma body cools, minerals that crystallize early and are heavy tend to settle to the lower portion of the magma chamber. This type of *magmatic differentiation* is particularly important in large

TABLE 3.1 Occurrence of Metallic Minerals

Metal	Principal Ores	Geologic Occurrences
Aluminum	Bauxite	Residual product of weathering
Chromium	Chromite	Magmatic segregation
Copper	Chalcopyrite	Hydrothermal deposits; contact metamorphism; enrichment by weathering processes
	Bornite	
	Chalcocite	
Gold	Native gold	Hydrothermal deposits; placers
Iron	Hematite	Banded sedimentary formations; magmatic segregation
	Magnetite	
	Limonite	
Lead	Galena	Hydrothermal deposits
Magnesium	Magnesite	Hydrothermal deposits
	Dolomite	
Manganese	Pyrolusite	Residual product of weathering
Mercury	Cinnabar	Hydrothermal deposits
Molybdenum	Molybdenite	Hydrothermal deposits
Nickel	Pentlandite	Magmatic segregation
Platinum	Native platinum	Magmatic segregation; placers
Silver	Native silver	Hydrothermal deposits; enrichment by weathering processes
	Argentite	
Tin	Cassiterite	Hydrothermal deposits; placers
Titanium	Ilmenite	Magmatic segregation; placers
	Rutile	
Tungsten	Wolframite	Pegmatites; contact metamorphic deposits; placers
	Scheelite	
Uranium	Uraninite (pitchblende)	Pegmatites; sedimentary deposits
Zinc	Sphalerite	Hydrothermal deposits

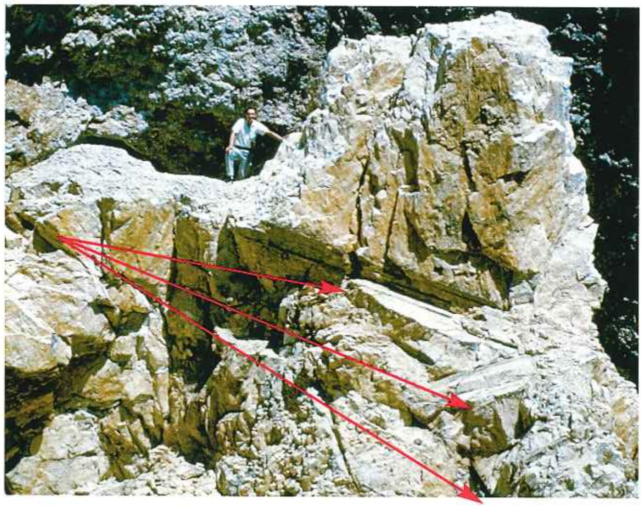


FIGURE 3.32 Pegmatites This pegmatite in the Black Hills of South Dakota was mined for its large crystals of spodumene, a source of lithium which is used in the manufacture of batteries for cell phones and computers. Arrows are pointing to impressions left by crystals. Note the person in the upper center of the photo for scale. (Photo by James G. Kirchner)

basaltic magmas where chromite (ore of chromium), magnetite, and platinum are occasionally generated. Layers of chromite, along with other heavy minerals, are mined from such deposits in the Bushveld Complex in South Africa, which contains over 70 percent of the world's known reserves of platinum.

Igneous processes are also important in generating other types of mineral deposits. For example, as a granitic magma cools and crystallizes, the residual melt becomes enriched in rare elements and heavy metals, including gold and silver. Furthermore, because water and other volatile substances do not crystallize along with the bulk of the magma body, these fluids make up a high percentage of the melt during the final phase of solidification. Crystallization in a fluid-rich environment enhances the migration of ions and results in the formation of crystals several centimeters, or even a few meters, in length. The resulting rocks, called **pegmatites**, are composed of these unusually large crystals (**FIGURE 3.32**).

Most pegmatites are granitic in composition and consist of large crystals of quartz, feldspar, and muscovite. Feldspar is used in the production of ceramics, and muscovite is used for electrical insulation and glitter. In addition to these common silicates, some pegmatites contain semiprecious gems such as beryl, topaz, and tourmaline. Moreover, minerals containing the elements lithium, gold, silver, uranium, and the rare earths are sometimes found. Most pegmatites are located within large igneous masses or as dikes or veins that cut into the host rock surrounding a magma chamber (**FIGURE 3.33**).

Among the most important ore deposits are those generated from hydrothermal (*hydra* = water, *therm* = heat) solutions. Included in this group are the gold deposits of the Homestake Mine in South Dakota; the lead, zinc, and silver ores near Coeur d'Alene, Idaho; the silver deposits of the Comstock Lode in Nevada; and the copper ores of the Keweenaw Peninsula in Michigan.

The majority of hydrothermal deposits originate from hot, metal-rich fluids that are associated with cooling magma bodies. During solidification, liquids plus various metallic ions accumulate near the top of the magma chamber. Because these hot fluids are very mobile, they can migrate great distances through the surrounding host rock before they are eventually deposited. Some of this fluid moves along fractures or bedding planes, where it cools and precipitates the metallic ions to produce **vein deposits** (see Figure 3.33). Many of the most productive deposits of gold, silver, and mercury occur as hydrothermal vein deposits.

Another important type of accumulation generated by hydrothermal activity is called a **disseminated deposit**. Rather than being concentrated in narrow veins and dikes, these ores are distributed as minute masses throughout the entire rock mass (see Figure 3.33). Much of the world's copper is extracted from disseminated deposits, including the huge Bingham Canyon copper mine in Utah (see Figure 2.34). Because these accumulations contain only 0.4 to 0.8 percent copper, between 125 and 250 metric tons of ore must be mined for every ton of metal recovered. The environmental impact of these large excavations, including the problems of waste disposal, is significant.

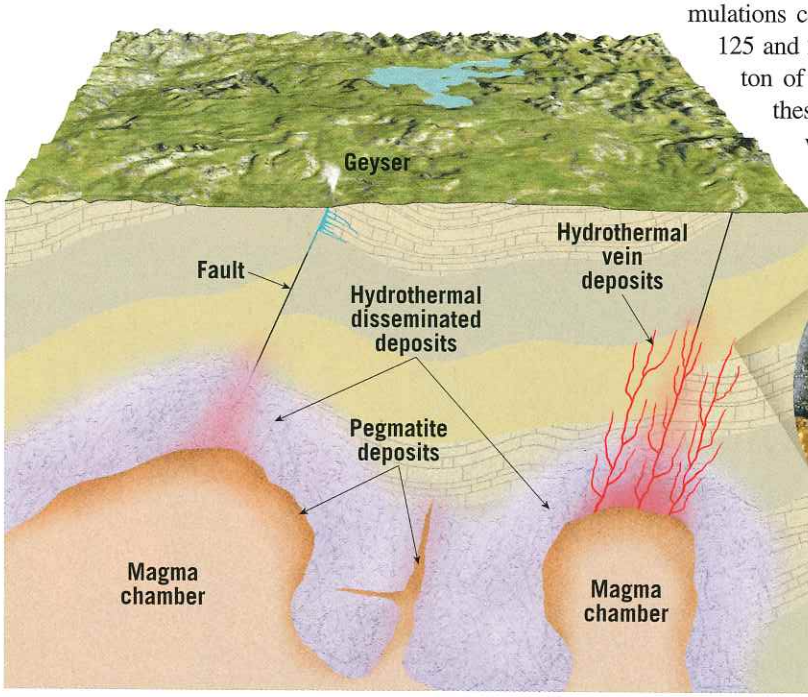


Figure 3.33 Relationship Between An Igneous Body and Associated Pegmatites and Hydrothermal Mineral Deposits (Photo by Greenshoots Communications/ Alamy)

TABLE 3.2 Occurrences and Uses of Nonmetallic Minerals

Mineral	Uses	Geologic Occurrences
Apatite	Phosphorus fertilizers	Sedimentary deposits
Asbestos	Incombustible fibers	Metamorphic alteration (chrysotile)
Calcite	Aggregate; steelmaking; soil conditioning; chemicals; cement; building stone	Sedimentary deposits
Clay minerals	Ceramics; china	Residual product of weathering (kaolinite)
Corundum	Gemstones; abrasives	Metamorphic deposits
Diamond	Gemstones; abrasives	Kimberlite pipes; placers
Fluorite	Steelmaking; aluminum refining; glass; chemicals	Hydrothermal deposits
Garnet	Abrasives; gemstones	Metamorphic deposits
Graphite	Pencil lead; lubricant; refractories	Metamorphic deposits
Gypsum	Plaster of Paris	Evaporite deposits
Halite	Table salt; chemicals; ice control	Evaporite deposits; salt domes
Muscovite	Insulator in electrical applications	Pegmatites
Quartz	Primary ingredient in glass	Igneous intrusions; sedimentary deposits
Sulfur	Chemicals; fertilizer manufacture	Sedimentary deposits; hydrothermal deposits
Sylvite	Potassium fertilizers	Evaporite deposits
Talc	Powder used in paints, cosmetics, etc.	Metamorphic deposits

Nonmetallic Mineral Resources

Mineral resources not used as fuels or processed for the metals they contain are referred to as *nonmetallic mineral resources*. These materials are extracted and processed either to make use of the nonmetallic elements they contain or for the physical and chemical properties they possess (**TABLE 3.2**). Nonmetallic mineral resources are commonly divided into two broad groups: *building materials* and *industrial minerals*. Some substances have many different uses and are found in both categories. Limestone, perhaps the most versatile and widely used rock of all, is perhaps the best example. As a building material, it is used as crushed rock, as building stone, and in the making of cement. Moreover, as an industrial mineral, it is an ingredient in the manufacture of steel and is used in agriculture to neutralize acidic soils.

Besides aggregate (sand, gravel, and crushed rock) and cut stone, the other important building materials include gypsum for plaster and wallboard, clay for tile and bricks, and cement, which is made from limestone and shale. Cement and aggregate are used to make concrete, a material that is essential to construction of roads, bridges, and all large buildings.

Many and various nonmetallic resources are classified as industrial minerals. People often do not realize the importance of industrial minerals because they see only the products that result from their use and not the minerals themselves. That is, many nonmetallics are used up in the process of creating other products. For example, fluorite and limestone are part of the steelmaking process; corundum and garnet are used as abrasives to make machinery parts; and sylvite, a potassium-rich mineral, is used in the production of fertilizers.

Energy Resources: Fossil Fuels

Coal, petroleum, and natural gas are the primary fuels of our modern industrial economy. Currently, about 82 percent of the energy consumed in the United States comes from these basic fossil fuels. Although major shortages of oil and gas will not occur for many years, known global reserves are declining. Unless large new petroleum sources are discovered, a greater share of our future needs will be required from alternative energy sources, such as nuclear, geothermal, solar, wind, tidal, and hydroelectric power. Two fossil-fuel alternatives, oil sands and oil shale, are also promising sources of liquid fuels.

Coal In addition to oil and natural gas, coal is commonly called a **fossil fuel**. This designation is appropriate because when coal is burned, energy from the Sun that was stored by plants many millions of years ago is being used, hence the actual burning of "fossils."

In the United States, coal fields are widespread and contain supplies that should last hundreds of years (**FIGURE 3.34**). Although coal is plentiful, its recovery and utilization present a number of challenges. Surface mining can turn the countryside into a scarred wasteland if careful and costly reclamation is not carried out to restore the land. Although underground mining does not scar the landscape to the same degree, it presents significant risks to human health and safety.

Air pollution is another significant problem associated with the burning of coal. Much coal contains significant quantities of sulfur. Despite efforts to remove sulfur before the coal is burned, some remains; when coal is burned, the sulfur is converted into noxious sulfur dioxide gas. Through

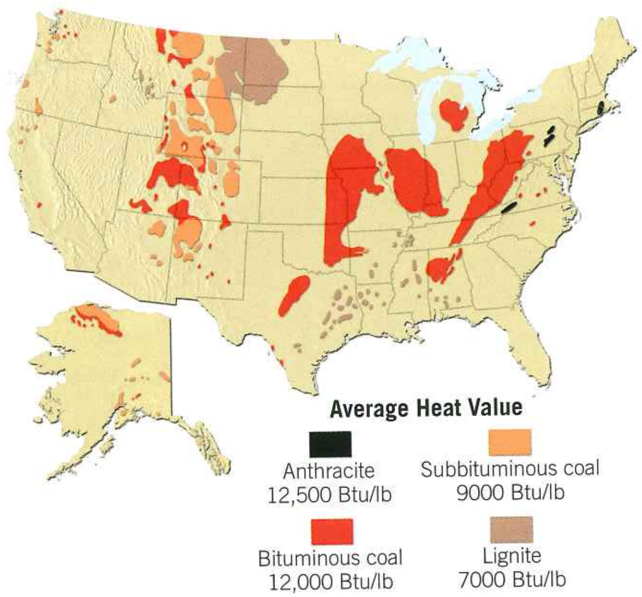


FIGURE 3.34 Coal Fields of the United States Most of the coal mined is subbituminous and bituminous. Wyoming and West Virginia are the leading producers. (Data from the U.S. Geological Survey)

a series of complex chemical reactions in the atmosphere, sulfur dioxide is converted to sulfuric acid, which eventually falls to Earth's surface in rain or snow. This acid precipitation, known as acid rain, can have adverse ecological effects over widespread areas.

As is the case when other fossil fuels are burned, the combustion of coal produces carbon dioxide. This major greenhouse gas plays a significant role in the heating of our atmosphere. Chapter 20 examines this issue in more detail.

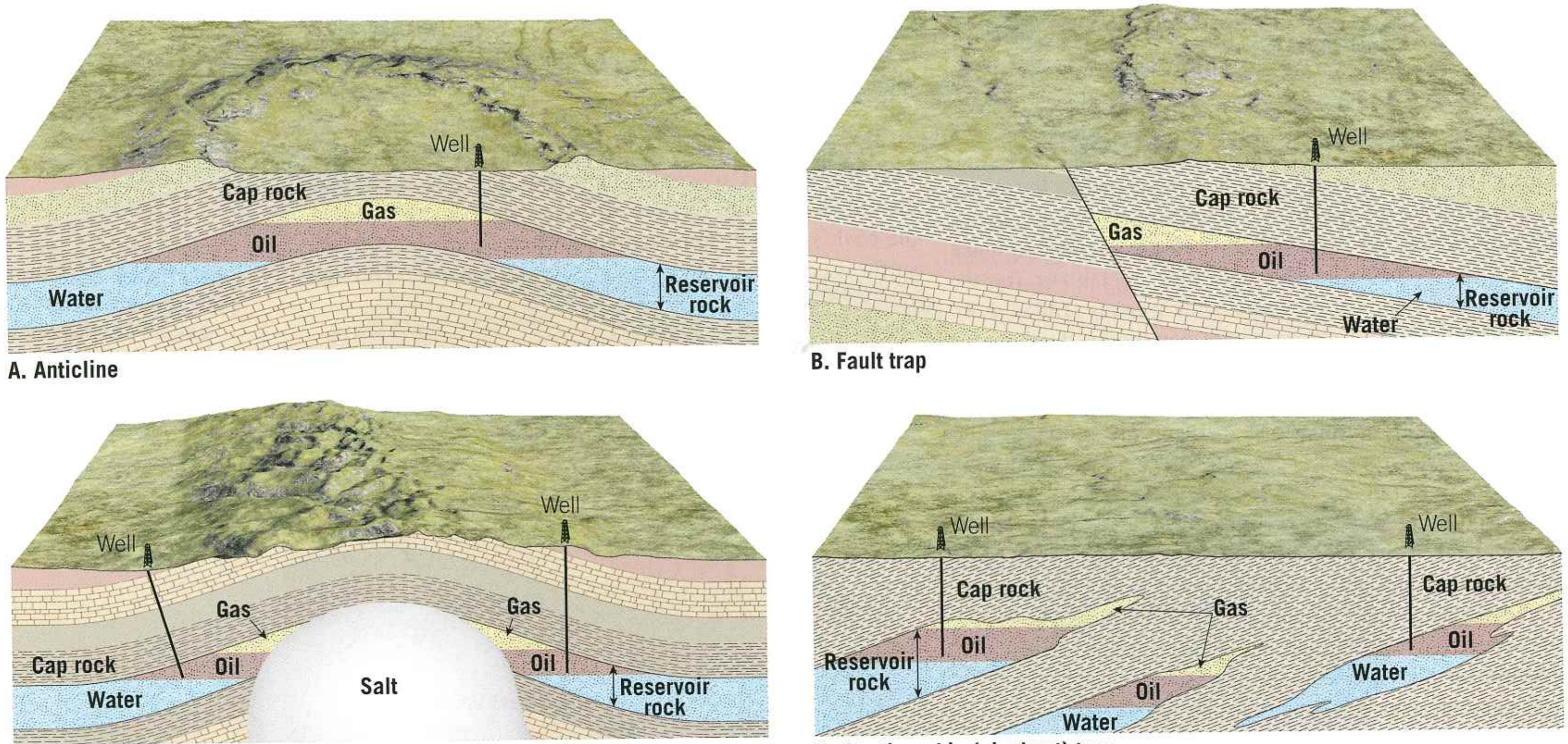
Oil and Natural Gas Together, petroleum and natural gas provided more than 60 percent of the energy consumed in the United States in 2012. Like coal, petroleum and natural gas are biological products derived from the remains of organisms. However, the environments in which they form are very different, as are the organisms. Coal is formed mostly from plant material that accumulated in swampy environments on land, as shown in Figure 3.21.

Oil and natural gas are generated from the remains of marine plants and animals, mainly microscopic plankton, which died in ancient seas millions of years ago. This organic material was deposited in sedimentary basins together with mud, sand, and other sediments that protected it from oxidation. With increased temperature and burial, chemical reactions gradually transform this organic matter into the liquid and gaseous hydrocarbons we call petroleum and natural gas.

Unlike the organic matter from which they formed, the newly created petroleum and natural gas are mobile. These fluids are gradually squeezed from the compacting, mud-rich layers where they originate, called the **source rock**, into adjacent permeable beds such as sandstone, where openings between sediment grains are larger. Because this occurs in a marine environment, the rock layers containing the oil and gas are saturated with water. Oil and gas, being less dense than water, migrate upward through the water-filled pore spaces of the enclosing rocks.

A geologic environment that allows for economically significant amounts of oil and gas to accumulate underground is termed an **oil trap**. Several geologic structures may act as oil traps and all share have two basic features: a porous, permeable **reservoir rock** that will yield petroleum and natural gas in sufficient quantities to make drilling worthwhile and a **cap rock**, such as shale, that is virtually impermeable to oil and gas. The cap rock halts the upwardly mobile oil and gas and keeps the oil and gas from escaping at the surface. **FIGURE 3.35** illustrates some common oil and natural-gas traps, which are described in the following list:

- **Anticline**—One of the simplest traps is an *anticline*, an uparched series of sedimentary strata (see Figure 3.35A). As the strata are bent, the rising oil and gas collect at the apex (top) of the fold. Because of its



SmartFigure 3.35 Common Oil Traps

lower density, the natural gas collects above the oil. Both rest upon the denser water that saturates the reservoir rock.

- **Fault trap**—This type of trap forms when strata are displaced in such a manner as to bring a dipping reservoir rock into position opposite an impermeable bed, as shown in Figure 3.35B. In this case, the upward migration of the oil and gas is halted where it encounters the fault.
- **Salt dome**—In the Gulf coastal plain region of the United States, important accumulations of oil occur in association with *salt domes*. Such areas have thick accumulations of sedimentary strata, including layers of rock salt. Salt occurring at great depths has been forced to rise in columns by the pressure of overlying beds. These rising salt columns gradually deform the overlying strata. Because oil and gas migrate to the highest level possible, they accumulate in the upturned sandstone beds adjacent to the salt column (see Figure 3.35C).
- **Stratigraphic (pinchout) trap**—Yet another important geologic circumstance that may lead to significant accumulations of oil and gas is termed a *stratigraphic trap*. These oil-bearing structures result primarily from the original pattern of sedimentation rather than structural deformation. The stratigraphic trap illustrated in Figure 3.35D exists because a sloping bed of sandstone thins to the point of disappearance.

When drilling punctures the lid created by the cap rock, the oil and natural gas, which are under pressure, migrate from the pore spaces of the reservoir rock to the drill pipe. On rare occasions, when fluid pressure is great, it may force oil up the drill hole to the surface, causing a "gusher" at the surface. Usually, however, a pump is required to extract the oil.

Hydraulic Fracturing In some shale deposits, there are significant reserves of natural gas and petroleum that cannot naturally leave because of the rock's low permeability. The practice of **hydraulic fracturing** (often called "fracking") shatters the shale, opening cracks through which these fluids can flow into wells and then be brought to Earth's surface. The fracturing of the shale is initiated by pumping liquids into the rock at very high pressures. The pressurized liquid is mostly water but also includes sand and other chemicals that aid in the fracturing process. Some of these chemicals may be toxic, and there are concerns about fracking fluids leaking into aquifers that supply communities with freshwater. The injection fluid also includes sand, so when fractures open in the shale, the sand grains can keep the fractures propped open and permit the gas to continue to flow. Because of concerns about potential groundwater contamination and induced seismicity, hydraulic fracturing remains a controversial practice. Its environmental effects are a focus of continuing research.

3.5 CONCEPT CHECKS

1. List two general types of hydrothermal deposits.
2. Nonmetallic resources are commonly divided into two broad groups. List the two groups and give some examples of materials that belong to each.
3. Why are coal, oil, and natural gas called *fossil fuels*?
4. What is an oil trap? Sketch two examples.
5. What do all oil traps have in common?

EYE ON EARTH

The image on the left shows an active landfill where tons of trash and garbage are dumped every day. Eventually this site will be reclaimed to resemble the area shown on the right and become a source of energy. (Left photo by NHPA/SuperStock; Right photo by Jim West/Alamy)

QUESTION 1 *Explain how an area filled with trash and waste could become a source of energy. What form of energy will it be? How might it be used?*

QUESTION 2 *Will this energy be considered renewable or nonrenewable? Explain.*

3 CONCEPTS IN REVIEW

Rocks: Materials of the Solid Earth

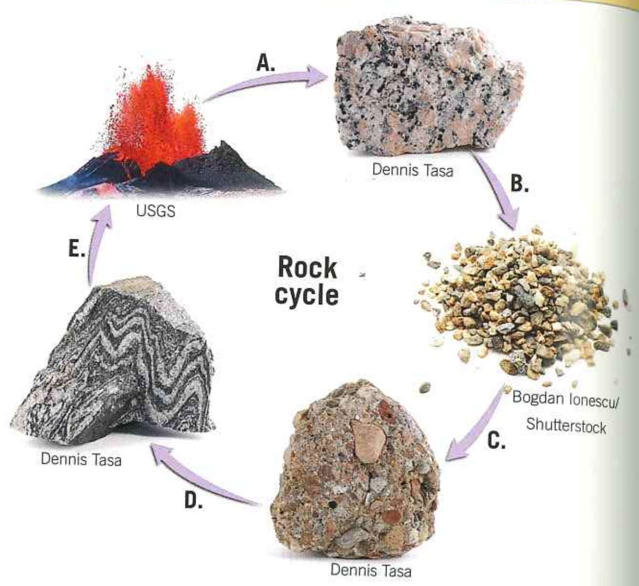
3.1 EARTH AS A SYSTEM: THE ROCK CYCLE

Sketch, label, and explain the rock cycle.

KEY TERM: rock cycle

- The rock cycle is a good model for thinking about the transformation of one rock to another due to Earth processes. All igneous rocks are made from molten rock. All sedimentary rocks are made from weathered products of other rocks. All metamorphic rocks are the products of preexisting rocks that are heated or squeezed at high temperatures and/or pressures. Given the right conditions, any kind of rock can be transformed into any other kind of rock.

Q Name the processes that are represented by each of the letters in this rock cycle diagram.



3.2 IGNEOUS ROCKS: "FORMED BY FIRE"

Describe the two criteria used to classify igneous rocks and explain how the rate of cooling influences the crystal size of minerals.

KEY TERMS: igneous rock, magma, lava, extrusive (volcanic), intrusive (plutonic), granitic (felsic) composition, basaltic (mafic) composition, andesitic (intermediate) composition, ultramafic, texture, fine-grained texture, coarse-grained texture, porphyritic texture, phenocrysts, groundmass, vesicular texture, glassy texture, pyroclastic (fragmental) texture, Bowen's reaction series, crystal settling, magmatic differentiation

- Completely or partly molten rock is called magma if it is below Earth's surface and lava if it has erupted onto the surface. It consists of a liquid melt that contains gases (volatiles) such as water vapor, and it may contain solids (mineral crystals).
- Magmas that cool at depth produce intrusive igneous rocks, whereas those that erupt onto Earth's surface produce extrusive igneous rocks.
- To geologists, texture is a description of the size, shape, and arrangement of mineral grains in a rock. A careful observation of the texture of igneous rocks can lead to insights about the conditions under which they formed. Lava on or near the surface cools rapidly, resulting in a large number of very small crystals that gives it a fine-grained texture. When magma cools at depth, the surrounding rock insulates it, and heat is lost more slowly. This allows sufficient time for the magma's ions to be organized into larger crystals, resulting in a rock with a coarse-grained texture. If crystals begin to form at depth and then the magma moves to a shallow depth or erupts at the surface, it will have a two-stage cooling history. The result is a rock with a porphyritic texture.
- Pioneering experimentation by N. L. Bowen revealed that in a cooling magma, minerals crystallize in a specific order. The dark-colored silicate minerals, such as olivine, crystallize first at the highest temperatures (1250°C [2300°F]), whereas the light silicates, such as quartz, crystallize last at the lowest temperatures (650°C [1200°F]). Separation of minerals by mechanisms such as crystal settling result in igneous rocks having a wide variety of chemical compositions.
- Igneous rocks are divided into broad compositional groups based on the percentage of dark and light silicate minerals they contain. Granitic (or felsic) rocks (such as granite and rhyolite) are composed mostly of the light-colored silicate minerals potassium feldspar and quartz. Rocks of andesitic (or intermediate) composition (rocks such as andesite) contain plagioclase feldspar and amphibole. Basaltic (or mafic) rocks (such as basalt) contain abundant pyroxene and calcium-rich plagioclase feldspar.

3.3 SEDIMENTARY ROCKS: COMPACTED AND CEMENTED SEDIMENT

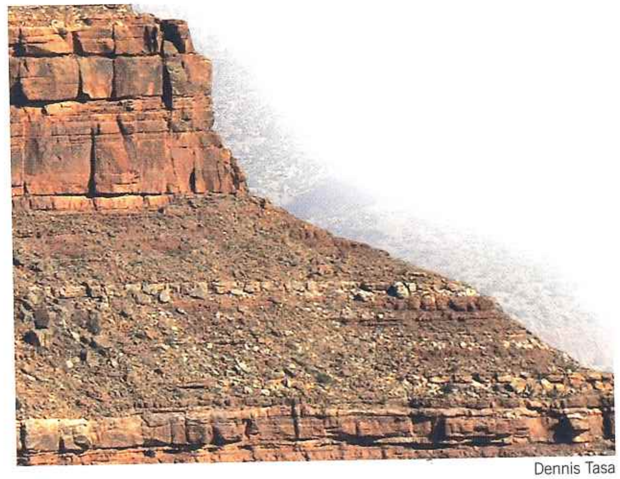
List and describe the different categories of sedimentary rocks and discuss the processes that change sediment into sedimentary rock.

KEY TERMS: sedimentary rock, sediment, detrital sedimentary rock, chemical sedimentary rock, biochemical sedimentary rock, evaporite deposit, organic matter, lithification, compaction, cementation, strata (beds), fossil

- Although igneous and metamorphic rocks make up most of Earth's crust by volume, sediment and sedimentary rocks are concentrated near the surface.
- Detrital sedimentary rocks are made of solid particles, mostly quartz grains and microscopic clay minerals. Common detrital sedimentary rocks include shale (the most abundant sedimentary rock), sandstone, and conglomerate.
- Chemical and biochemical sedimentary rocks are derived from mineral matter (ions) that is carried in solution to lakes and seas. Under certain conditions, ions in solution precipitate (settle out) to form chemical sediments as a result of physical processes, such as evaporation. Precipitation may also occur indirectly through life processes of water-dwelling organisms that form materials called biochemical sediments. Many water-dwelling animals and plants extract dissolved mineral matter to form shells and other hard parts. After the organisms die, their skeletons may accumulate on the floor of a lake or an ocean.

- Limestone, an abundant sedimentary rock, is composed chiefly of the mineral calcite ($CaCO_3$). Rock gypsum and rock salt are chemical rocks that form as water evaporates.
- Coal forms from the burial of large amounts of plant matter in low-oxygen depositional environments such as swamps and bogs.
- The transformation of sediment into sedimentary rock is lithification. The two main processes that contribute to lithification are compaction (a reduction in pore space by packing grains more tightly together) and cementation (a reduction in pore space by adding new mineral material that acts as a "glue" to bind the grains to each other).

Q This photo was taken in the Grand Canyon, Arizona. What name(s) do geologists use for the characteristic features found in the sedimentary rocks shown in this image?



Dennis Tasa

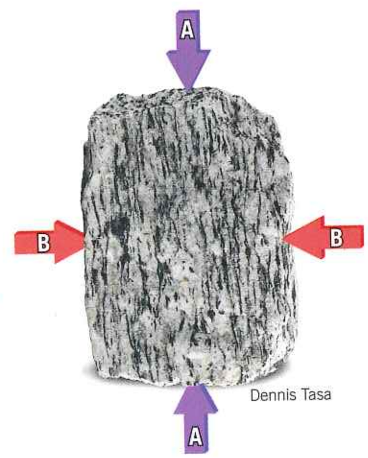
3.4 METAMORPHIC ROCKS: NEW ROCK FROM OLD

Define *metamorphism*, explain how metamorphic rocks form, and describe the agents of metamorphism.

KEY TERMS: metamorphic rock, metamorphism, contact (thermal) metamorphism, regional metamorphism, foliation, nonfoliated

- When rocks are subjected to elevated temperatures and pressures, they can change form, producing metamorphic rocks. Every metamorphic rock has a parent rock—the rock it used to be prior to metamorphism. When the minerals in parent rocks are subjected to heat and pressure, new minerals can form.
- Heat, confining pressure, differential stress, and chemically active fluids are four agents that drive metamorphic reactions. Any one alone may trigger metamorphism, or all four may exert influence simultaneously.
- Confining pressure results from burial. The pressure is of the same magnitude in every direction, like the pressure that a swimmer experiences when diving to the bottom of a swimming pool. An increase in confining pressure causes rocks to compact into more dense configurations.
- Differential stress results from tectonic forces. The pressure is greater in some directions and less in other directions. Rocks subjected to differential stress under ductile conditions deep in the crust tend to shorten in the direction of greatest stress and elongate in the direction(s) of least stress, producing flattened or stretched grains. If the same differential stress is applied to a rock in the shallow crust, it may deform in a brittle fashion instead, breaking into smaller pieces.
- A common kind of texture is foliation, the planar arrangement of mineral grains. Common foliated metamorphic rocks include slate, phyllite, schist, and gneiss. The order listed here is the order of increasing metamorphic grade: Slate is least metamorphosed, and gneiss is the most metamorphosed.
- Common nonfoliated metamorphic rocks include quartzite and marble, recrystallized rocks that form from quartz sandstone and limestone.

Q Examine the photograph. Determine whether this rock is foliated or nonfoliated and then determine whether it formed under confining pressure or differential stress. Which of the pairs of arrows shows the direction of maximum stress?



Dennis Tasa

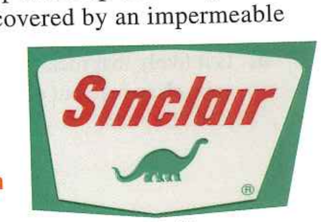
3.5 RESOURCES FROM ROCKS AND MINERALS

Distinguish between metallic and nonmetallic mineral resources and list some examples of each. Compare and contrast the three traditional fossil fuels.

KEY TERMS: pegmatite, vein deposit, disseminated deposit, fossil fuel, source rock, oil trap, reservoir rock, cap rock, hydraulic fracturing

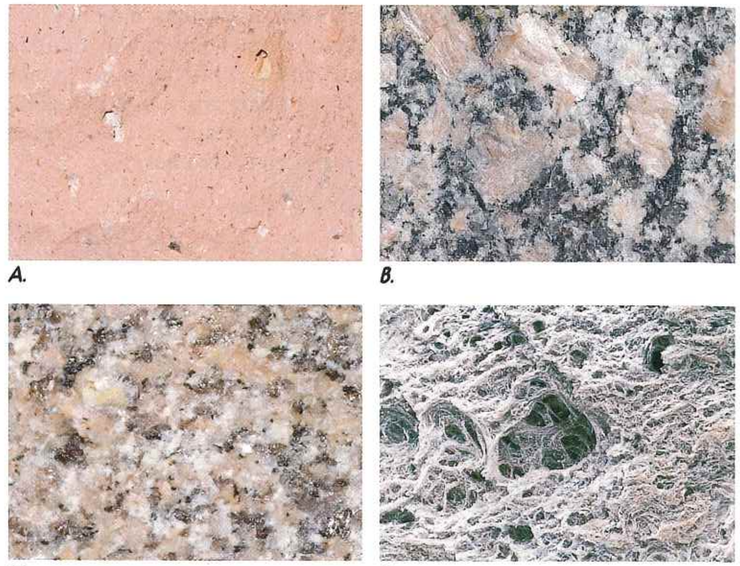
- Igneous processes concentrate some economically important elements through both magmatic differentiation and the emplacement of pegmatites. Magmas may also release hydrothermal (hot-water) solutions that penetrate surrounding rock, carrying dissolved metals in them. The metal ores may be precipitated as fracture-filling deposits (veins) or may "soak" into surrounding strata, producing countless tiny deposits disseminated throughout the host rock.
- Earth materials that are not used as fuels or processed for the metals they contain are referred to as nonmetallic resources. The two broad groups of nonmetallic resources are building materials (such as gypsum, used for plaster) and industrial minerals (including sylvite, a potassium-rich mineral used to make fertilizers).
- Coal, oil, and natural gas are all fossil fuels. In each, the energy of ancient sunlight, captured by photosynthesis, is stored in the hydrocarbons of plants or other living things buried by sediments. Although coal is abundant, coal mining can be dangerous and environmentally harmful, and burning coal generates several kinds of pollution.
- Oil and natural gas are formed from the heated remains of tiny marine plants and animals. Both oil and natural gas leave their source rock (typically shale) and migrate to an oil trap made up of more porous rocks, called reservoir rocks, which are covered by an impermeable cap rock.

Q As you can see here, the Sinclair Oil Company's logo speaks directly to the "fossil" nature of the fuel it sells. However, is it likely that any *dinosaur* carbon has ended up in Sinclair's oil? Explain.



Vespasian/Alamy

GIVE IT SOME **THOUGHT**

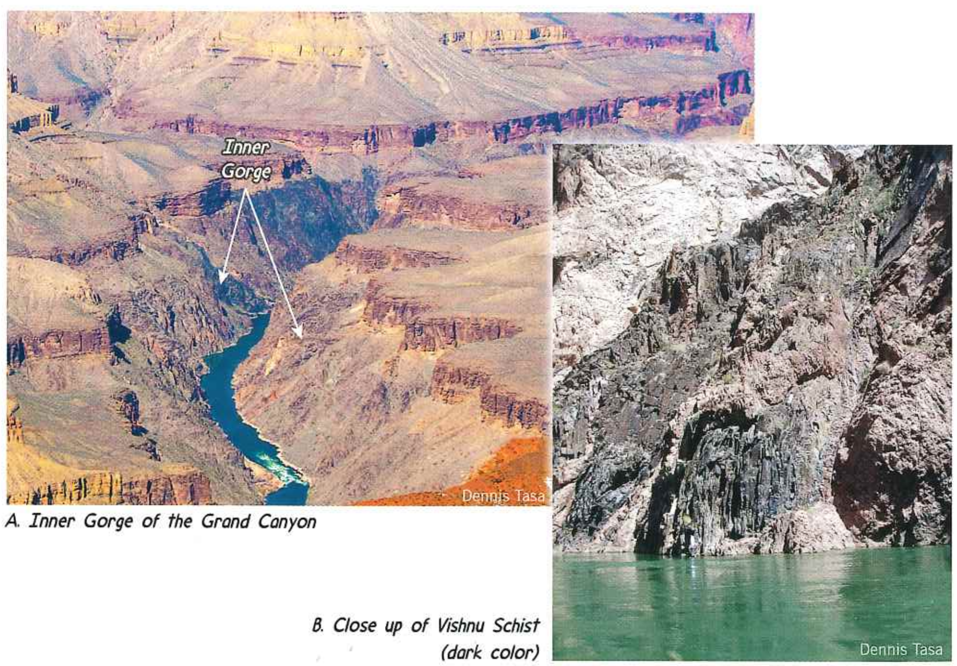


A. B. C. D.

1. Refer to Figure 3.1. How does the rock cycle diagram—in particular, the labeled arrows—support the fact that sedimentary rocks are the most abundant rock type on Earth's surface?
2. Would you expect all the crystals in an intrusive igneous rock to be the same size? Explain why or why not.
3. Apply your understanding of igneous rock textures to describe the cooling history of each of the igneous rocks pictured on the right.
4. Is it possible for two igneous rocks to have the same mineral composition but be different rocks? Support your answer with an example.
5. Use your understanding of magmatic differentiation to explain how magmas of different composition can be generated in a cooling magma chamber.
6. Dust collecting on furniture is an everyday example of a sedimentary process. Provide another example of a sedimentary process that might be observed in or around where you live.
7. Describe two reasons sedimentary rocks are more likely to contain fossils than igneous rocks.
8. If you hiked to a mountain peak and found limestone at the top, what would that indicate about the likely geologic history of the rock there?
9. The accompanying photos each illustrate either a typical igneous, sedimentary, or metamorphic rock body. Which do you think is a metamorphic rock? Explain why you ruled out the other rock bodies. (Photos by E. J. Tarbuck)

A. B. C.

10. Examine the accompanying photos, which show the geology of the Grand Canyon. Notice that most of the canyon consists of layers of sedimentary rocks, but if you were to hike down into the Inner Gorge, you would encounter the Vishnu Schist, which is metamorphic rock.
    - **a.** What process might have been responsible for the formation of the Vishnu Schist? How does this process differ from the processes that formed the sedimentary rocks that are atop the Vishnu Schist?
    - **b.** What does the Vishnu Schist tell you about the history of the Grand Canyon prior to the formation of the canyon itself?
    - **c.** Why is the Vishnu Schist visible at Earth's surface?
    - **d.** Is it likely that rocks similar to the Vishnu Schist exist elsewhere but are not exposed at Earth's surface? Explain.



A. Inner Gorge of the Grand Canyon

B. Close up of Vishnu Schist (dark color)