# Weathering and Soil

*Differential weathering is responsible for much of the spectacular scenery in Utah's Arches National Park. (Photo by Carr Clifton)*

E   arth's surface is constantly changing. Rock is disintegrated and decomposed, moved to lower elevations by gravity, and carried away by water, wind, or ice. In this manner Earth's physical landscape is sculptured. This chapter focuses on the first step of this never-ending process—weathering. What causes solid rock to crumble, and why does the type and rate of weathering vary from place to place? Soil, an important product of the weathering process and a vital resource, is also examined.

## Earth's External Processes

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Weathering and Soil
▸ Earth's External Processes

Weathering, mass wasting, and erosion are called **external processes** because they occur at or near Earth's surface and are powered by energy from the Sun. External processes are a basic part of the rock cycle because they are responsible for transforming solid rock into sediment.

To the casual observer, the face of Earth may appear to be without change, unaffected by time. In fact, 200 years ago most people believed that mountains, lakes, and deserts were permanent features of an Earth that was thought to be no more than a few thousand years old. Today we know that Earth is 4.5 billion years old and that mountains eventually succumb to weathering and erosion, lakes fill with sediment or are drained by streams, and deserts come and go with changes in climate.

Earth is a dynamic body. Some parts of Earth's surface are gradually elevated by mountain building and volcanic activity. These **internal processes** derive their energy from Earth's interior. Meanwhile, opposing external processes are continually breaking rock apart and moving the debris to lower elevations. The latter processes include:

1. **Weathering**—the physical breakdown (disintegration) and chemical alteration (decomposition) of rock at or near Earth's surface.
2. **Mass wasting**—the transfer of rock and soil downslope under the influence of gravity.
3. **Erosion**—the physical removal of material by mobile agents such as water, wind, or ice.

In this chapter we will focus on rock weathering and the products generated by this activity. However, weathering cannot be easily separated from mass wasting and erosion because as weathering breaks rocks apart, erosion and mass wasting remove the rock debris. This transport of material by erosion and mass wasting further disintegrates and decomposes the rock.
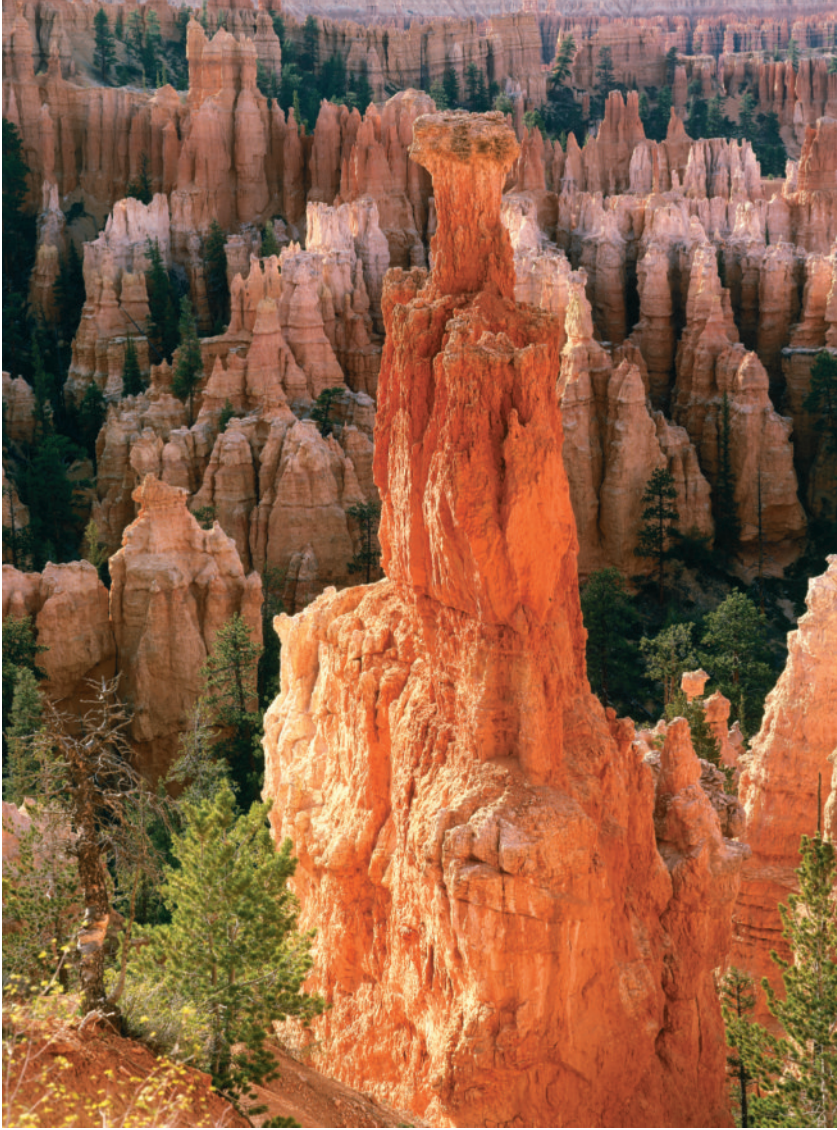
## Weathering

GEODe
Weathering and Soil
▸ Types of Weathering

Weathering goes on all around us, but it seems like such a slow and subtle process that it is easy to underestimate its importance. Yet it is worth remembering that weathering is a basic part of the rock cycle and thus a key process in the Earth system. Weathering is also important to humans— even to those of us who are not studying geology. For example, many of the life-sustaining minerals and elements found in soil, and ultimately in the food we eat, were freed from solid rock by weathering processes. As the chapter-opening photo, Figure 6.1, and many other images in this book illustrate, weathering also contributes to the formation of some of Earth's most spectacular scenery. Of course these same processes are also responsible for causing the deterioration of many of the structures we build (Figure 6.2).

All materials are susceptible to weathering. Consider, for example, the fabricated product concrete, which closely resembles a sedimentary rock called conglomerate. A newly poured concrete sidewalk has a smooth, fresh, unweathered look. However, not many years later the same sidewalk will appear chipped, cracked, and rough, with pebbles exposed at the surface. If a tree is nearby, its roots may heave and buckle the concrete as well. The same natural processes that eventually break apart a concrete sidewalk also act to disintegrate rock.

Weathering occurs when rock is mechanically fragmented (disintegrated) and/or chemically altered (decomposed). **Mechanical weathering** is accomplished by physical forces that break rock into smaller and smaller pieces without changing the rock's mineral composition. **Chemical weathering** involves a chemical transformation of rock into one or more new compounds. These two concepts can be illustrated with a piece of paper. The paper can be disintegrated by tearing it into smaller and smaller pieces, whereas decomposition occurs when the paper is set afire and burned.

Why does rock weather? Simply, weathering is the response of Earth materials to a changing environment. For instance, after millions of years of uplift and erosion, the

**FIGURE 6.1** Bryce Canyon, National Park, Utah. When weathering accentuates differences in rocks, spectacular landforms are sometimes created. As the rock gradually disintegrates and decomposes, mass wasting and erosion remove the products of weathering. (Photo by Tom Bean)

rocks overlying a large, intrusive igneous body may be removed, exposing it at the surface. This mass of crystalline rock—formed deep below ground where temperatures and pressures are high—is now subjected to a very different and comparatively hostile surface environment. In response, this rock mass will gradually change. This transformation of rock is what we call weathering.

In the following sections we will discuss the various modes of mechanical and chemical weathering. Although we will consider these two categories separately, keep in mind that mechanical and chemical weathering processes usually work simultaneously in nature and reinforce each other.

# Mechanical Weathering

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▶ Mechanical Weathering

When a rock undergoes *mechanical weathering*, it is broken into smaller and smaller pieces, each retaining the characteristics of the original material. The end result is many small

pieces from a single large one. Figure 6.3 shows that breaking a rock into smaller pieces increases the surface area available for chemical attack. An analogous situation occurs when sugar is added to a liquid. In this situation, a cube of sugar will dissolve much slower than an equal volume of sugar granules because the cube has much less surface area available for dissolution. Hence, by breaking rocks into smaller pieces, mechanical weathering increases the amount of surface area available for chemical weathering.

In nature, four important physical processes lead to the fragmentation of rock: frost wedging, expansion resulting from unloading, thermal expansion, and biological activity. In addition, although the work of erosional agents such as wind, glacial ice, and running water is usually considered separately from mechanical weathering, it is nevertheless important. As these mobile agents move rock debris, they relentlessly disintegrate these materials.
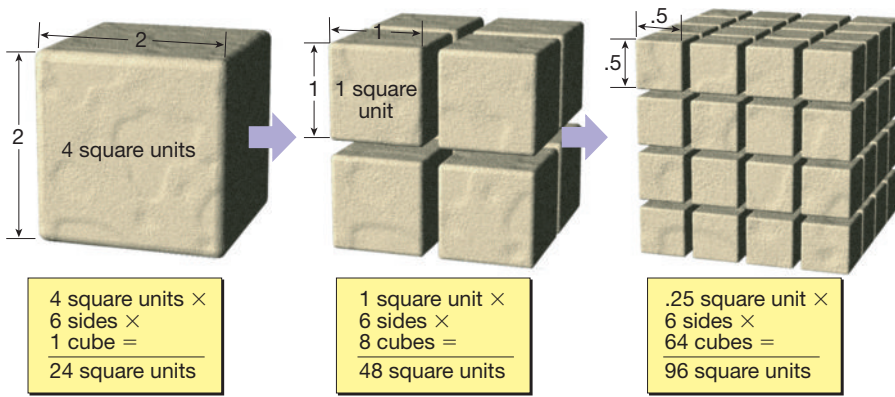
## Frost Wedging

Repeated cycles of freezing and thawing represent an important process of mechanical weathering. Liquid water has the unique property of expanding about 9 percent upon freezing, because water molecules in the regular crystalline structure of ice are farther apart than they are in liquid water near the freezing point. As a result, water freezing in a confined space exerts tremendous outward pressure on the walls of its container. To verify this, consider a tightly sealed glass jar filled with water. As the water freezes, the container cracks.

In nature, water works its way into cracks in rock and, upon freezing, expands and enlarges these openings. After many freeze–thaw cycles, the rock is broken into angular fragments. This process is appropriately called **frost wedging** (Figure 6.4). Frost wedging is most pronounced in mountainous regions where a daily freeze–thaw cycle often exists (see Box 6.1). Here, sections of rock are wedged loose and may tumble into large piles called **talus slopes** that often form at the base of steep rock outcrops (Figure 6.4).

**FIGURE 6.2** Even the most "solid" monuments that people erect eventually yield to the day in and day out attack of weathering processes. Temple of Olympian Zeus, Athens, Greece. (Photo by CORBIS)

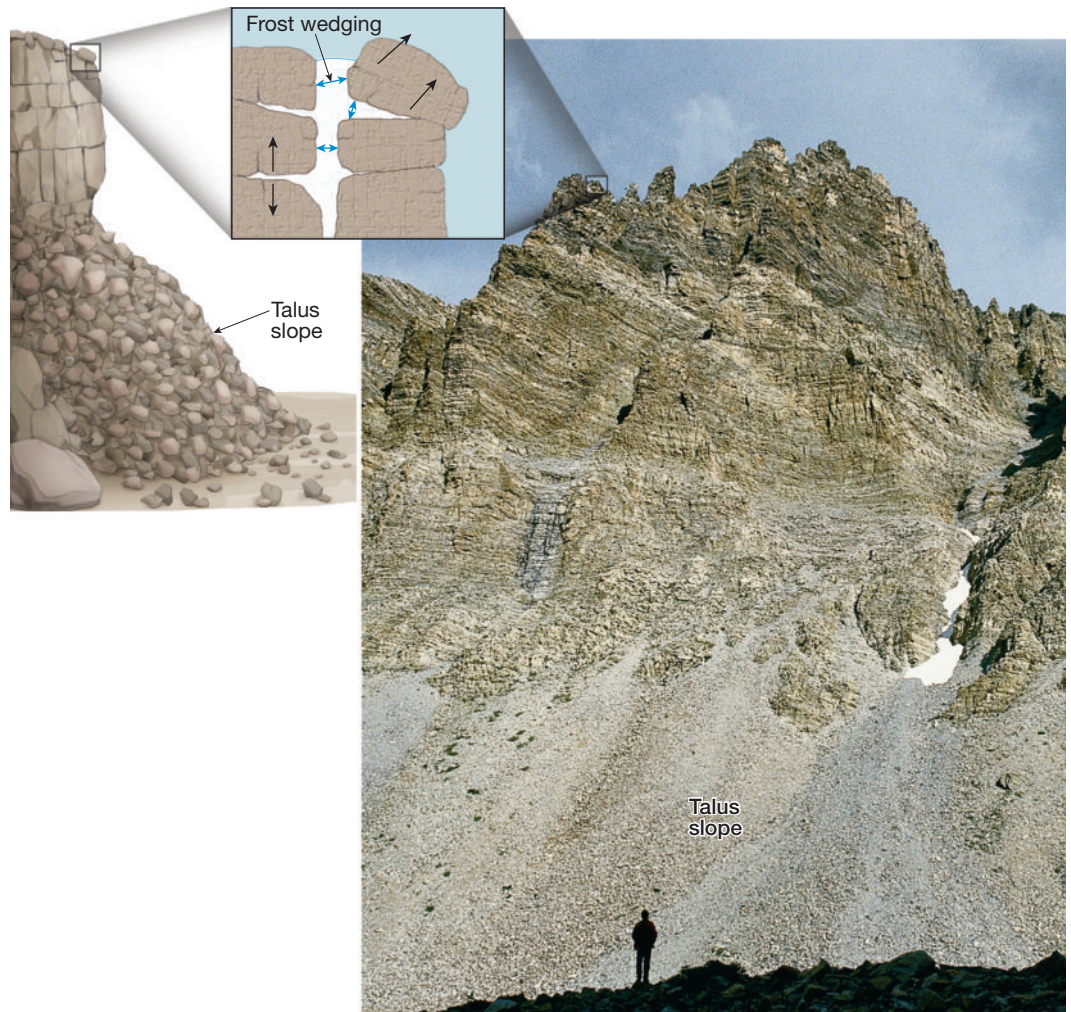| 4 square units × | 1 square unit × | .25 square unit × |
|---|---|---|
| 6 sides × | 6 sides × | 6 sides × |
| 1 cube = | 8 cubes = | 64 cubes = |
| 24 square units | 48 square units | 96 square units |

**FIGURE 6.3**  Chemical weathering can occur only to those portions of a rock that are exposed to the elements. Mechanical weathering breaks rock into smaller and smaller pieces, thereby increasing the surface area available for chemical attack.

Frost wedging also causes great destruction to highways in the northern United States, particularly in the early spring when the freeze–thaw cycle is well established. Roadways acquire numerous potholes and are occasionally heaved and buckled by this destructive force.

## Salt Crystal Growth

Another expansive force that can split rocks is created by the growth of salt crystals. Rocky shorelines and arid regions are common settings for this process. It begins when sea spray from breaking waves or salty groundwater penetrates crevices and pore spaces in rock. As this water evaporates, salt crystals form. As these crystals gradually grow larger, they weaken the rock by pushing apart the surrounding grains or enlarging tiny cracks.

This same process can also contribute to crumbling roadways where salt is spread to melt snow and ice in winter. The salt dissolves in water and seeps into cracks that quite likely originated from frost action. When the water evaporates, the growth of salt crystals further breaks the pavement.

## Unloading

When large masses of igneous rock, particularly granite, are exposed by erosion, concentric slabs begin to break loose. The process generating these onionlike layers is called

**FIGURE 6.4**  Frost wedging. As water freezes, it expands, exerting a force great enough to break rock. When frost wedging occurs in a setting such as this, the broken rock fragments fall to the base of the cliff and create a cone-shaped accumulation known as talus. (Photo by Tom & Susan Bean, Inc.)

# The Old Man of the Mountain

The Old Man of the Mountain, also known as The Great Stone Face or simply The Profile, was one of New Hampshire's (*The Granite State*) best-known and most enduring symbols. Beginning in 1945, it appeared at the center of the official state emblem. It was a natural rock formation sculpted from Conway Red Granite that, when viewed from the proper location, gave the appearance of an old man (Figure 6.A, left). Each year hundreds of thousands of people traveled to view the Old Man, which protruded from high on Cannon Mountain, 360 meters (1200 feet) above Profile Lake in northern New Hampshire's Franconia Notch State Park.

On Saturday morning, May 3, 2003, the people of New Hampshire learned that the famous landmark had succumbed to nature and collapsed (Figure 6.A, right). The collapse ended decades of efforts to protect the state symbol from the same natural processes that created it in the first place. Ultimately, frost wedging and other weathering processes prevailed.



**FIGURE 6.A**    (**left**) The Old Man of the Mountain, high above Franconia Notch in New Hampshire's White Mountains, as it appeared prior to May 3, 2003. (Associated Press Photo) The inset shows the state emblem of New Hampshire. (**right**) The famous granite outcrop after it collapsed on May 3, 2003. The natural processes that sculpted the Old Man ultimately destroyed it. (Associated Press Photo)

**sheeting.** It is thought that this occurs, at least in part, because of the great reduction in pressure when the overlying rock is eroded away, a process called *unloading.* Accompanying this unloading, the outer layers expand more than the rock below and thus separate from the rock body (Figure 6.5). Continued weathering eventually causes the slabs to separate and spall off, creating **exfoliation domes** (*ex* = off, *folium* = leaf).Excellent examples of exfoliation domes are Stone Mountain, Georgia, and Half Dome and Liberty Cap in Yosemite National Park (Figure 6.5).

Deep underground mining provides us with another example of how rocks behave once the confining pressure is removed. Large rock slabs have been known to explode off the walls of newly cut mine tunnels because of the abruptly reduced pressure. Evidence of this type, plus the fact that fracturing occurs parallel to the floor of a quarry when large blocks of rock are removed, strongly supports the process of unloading as the cause of sheeting.

Although many fractures are created by expansion, others are produced by contraction during the crystallization of magma (see Figure 5.35 p. 152), and still others by tectonic forces during mountain building. Fractures produced by these activities generally form a definite pattern and are called *joints* (Figure 6.6). Joints are important rock structures that allow water to penetrate to depth and start the process of weathering long before the rock is exposed.

## Thermal Expansion

The daily cycle of temperature may weaken rocks, particularly in hot deserts where daily variations may exceed 30°C. Heating a rock causes expansion, and cooling causes contraction. Repeated swelling and shrinking of minerals with different expansion rates should logically exert some stress on the rock's outer shell.

Although this process was once thought to be of major importance in the disintegration of rock, laboratory experiments have not substantiated this. In one test, unweathered rocks were heated to temperatures much higher than those normally experienced on Earth's surface and then cooled. This procedure was repeated many times to simulate hundreds of years of weathering, but the rocks showed little apparent change.

Nevertheless, pebbles in desert areas do show evidence of shattering that may have been caused by temperature changes (Figure 6.7). A proposed solution to this dilemma suggests that rocks must first be weakened by chemical weathering before they can be broken down by thermal activity. Further, this process may be aided by the rapid cooling of a desert rainstorm. Additional data are needed before a definite conclusion can be reached as to the impact of temperature variation on rock disintegration.
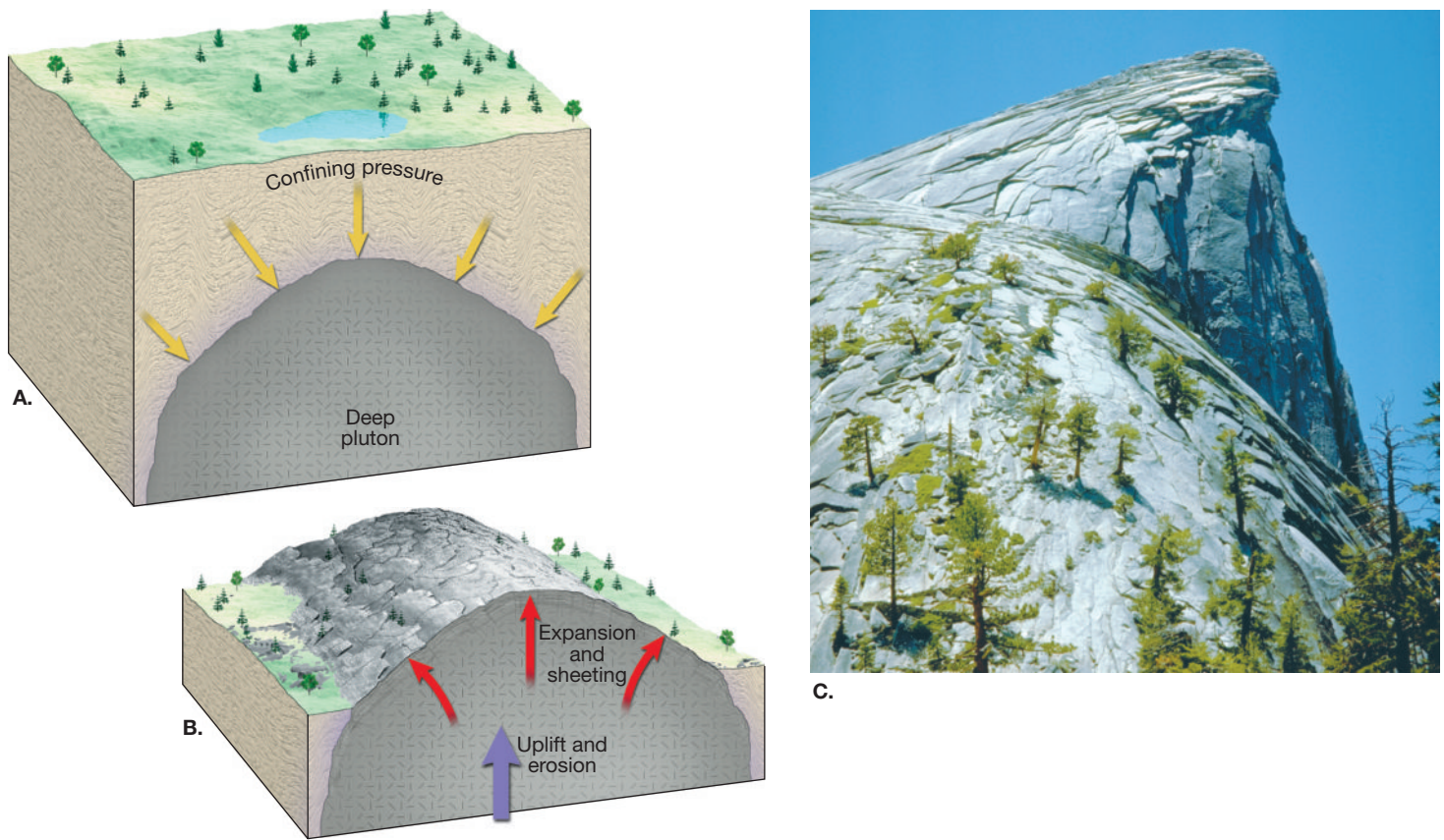
**FIGURE 6.5**    Sheeting is caused by the expansion of crystalline rock as erosion removes the overlying material. When the deeply buried pluton in **A** is exposed at the surface following uplift and erosion in **B,** the igneous mass fractures into thin slabs. The photo in **C** is of the summit of Half Dome in Yosemite National Park, California. It is an exfoliation dome and illustrates the onionlike layers created by sheeting. (Photo by Breck P. Kent)

**FIGURE 6.6**    Aerial view of nearly parallel joints near Moab, Utah. (Photo by Michael Collier)

**FIGURE 6.7** These stones were once rounded stream gravels; however, long exposure in a hot desert climate disintegrated them. (Photo by C. B. Hunt, U.S. Geological Survey)

## Biological Activity

Weathering is also accomplished by the activities of organisms, including plants, burrowing animals, and humans. Plant roots in search of nutrients and water grow into fractures, and as the roots grow, they wedge the rock apart (Figure 6.8). Burrowing animals further break down rock by moving fresh material to the surface, where physical and chemical processes can more effectively attack it. Decaying organisms also produce acids that contribute to chemical weathering. Where rock has been blasted in search of minerals or for road construction, the impact of humans is particularly noticeable.

## Chemical Weathering

**GEODe**
**Weathering and Soil**
▸ Chemical Weathering

In the preceding discussion of mechanical weathering, you learned that breaking rock into smaller pieces aids chemical weathering by increasing the surface area available for chemical attack. It should also be pointed out that chemical weathering contributes to mechanical weathering. It does so by weakening the outer portions of some rocks, which, in turn, makes them more susceptible to being broken by mechanical weathering processes.

*Chemical weathering* involves the complex processes that break down rock components and internal structures of minerals. Such processes convert the constituents to new minerals or release them to the surrounding environment. During this transformation, the original rock decomposes into substances that are stable in the surface environment. Consequently, the products of chemical weathering will remain essentially unchanged as long as they remain in an environment similar to the one in which they formed.

Water is by far the most important agent of chemical weathering. Pure water alone is a good solvent, and small

amounts of dissolved materials result in increased chemical activity for weathering solutions. The major processes of chemical weathering are dissolution, oxidation, and hydrolysis. Water plays a leading role in each.

## Dissolution

Perhaps the easiest type of decomposition to envision is the process of **dissolution.** Just as sugar dissolves in water, so too do certain minerals. One of the most water-soluble minerals is halite (common salt), which as you may recall, is composed of sodium and chloride ions. Halite readily dissolves in water because, although this compound maintains overall electrical neutrality, the individual ions retain their respective charges.

Moreover, the surrounding water molecules are polar—that is, the oxygen end of the molecule has a small residual negative charge; the end with hydrogen has a small positive charge. As the water molecules come in contact with halite, their negative ends approach sodium ions and their positive ends cluster about chloride ions. This disrupts the attractive forces in the halite crystal and releases the ions to the water solution (Figure 6.9).

Although most minerals are, for all practical purposes, insoluble in pure water, the presence of even a small amount

**FIGURE 6.8** Root wedging widens fractures in rock and aids the process of mechanical weathering. Harriman State Park, New York. (Photo by Carr Clifton)
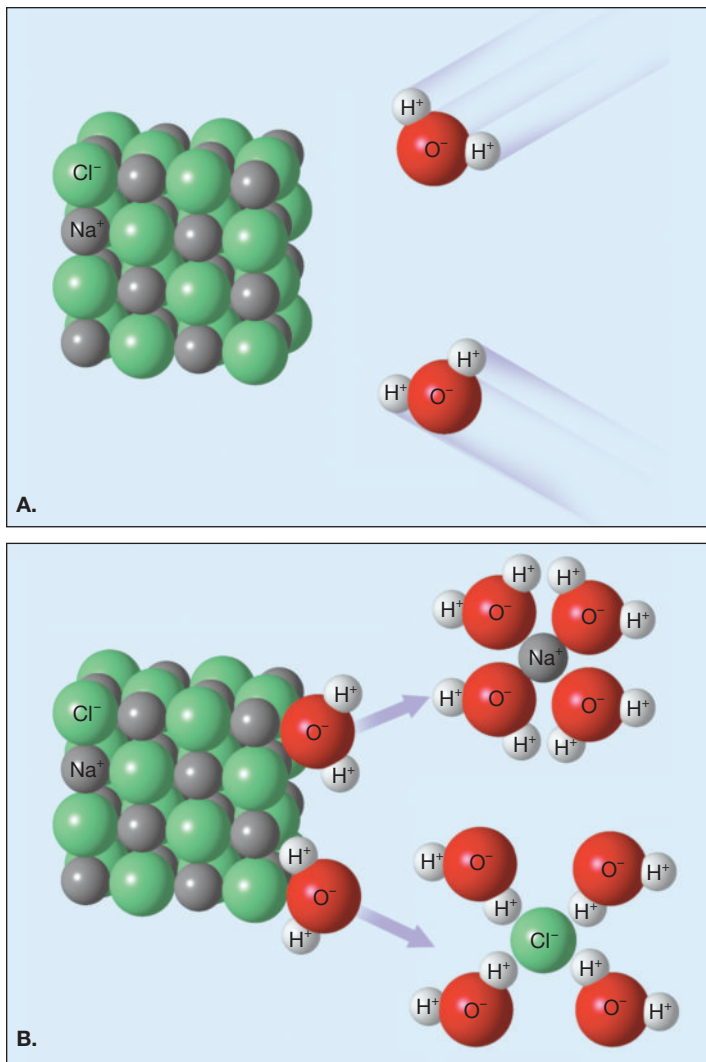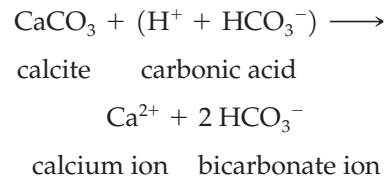
**FIGURE 6.9**    Illustration of halite dissolving in water. **A.** Sodium and chloride ions are attacked by the polar water molecules. **B.** Once removed, these ions are surrounded and held by a number of water molecules as shown.

of acid dramatically increases the corrosive force of water. (An acidic solution contains the reactive hydrogen ion, $H^+$.) In nature, acids are produced by a number of processes. For example, carbonic acid is created when carbon dioxide in the atmosphere dissolves in raindrops. As acidic rainwater soaks into the ground, carbon dioxide in the soil may increase the acidity of the weathering solution. Various organic acids are also released into the soil as organisms decay, and sulfuric acid is produced by the weathering of pyrite and other sulfide minerals.

Regardless of the source of the acid, this highly reactive substance readily decomposes most rocks and produces certain products that are water soluble. For example, the mineral calcite, $CaCO_3$, which composes the common building stones marble and limestone, is easily attacked by even a weakly acidic solution.

The overall reaction by which calcite dissolves in water containing carbon dioxide is:

$$CaCO_3 + (H^+ + HCO_3^-) \longrightarrow$$

calcite    carbonic acid

$$Ca^{2+} + 2\,HCO_3^-$$

calcium ion    bicarbonate ion

During this process, the insoluble calcium carbonate is transformed into soluble products. In nature, over periods of thousands of years, large quantities of limestone are dissolved and carried away by underground water. This activity is clearly evidenced by the large number of subsurface caverns found in every one of the contiguous 48 states (Figure 6.10). Monuments and buildings made of limestone or marble are also subjected to the corrosive work of acids, particularly in industrial areas that have smoggy, polluted air (see Box 6.2).

The soluble ions from reactions of this type are retained in our underground water supply. It is these dissolved ions that are responsible for the so-called hard water found in many locales. Simply, hard water is undesirable because the active ions react with soap to produce an insoluble material that renders soap nearly useless in removing dirt. To solve this problem, a water softener can be used to remove these ions, generally by replacing them with others that do not chemically react with soap.

## Oxidation

Everyone has seen iron and steel objects that rusted when exposed to water (Figure 6.11). The same thing can happen to iron-rich minerals. The process of rusting occurs when oxygen combines with iron to form iron oxide as follows:

$$4\,Fe \quad + \quad 3\,O_2 \quad \longrightarrow \quad 2\,Fe_2O_3$$

iron    oxygen    iron oxide (hematite)
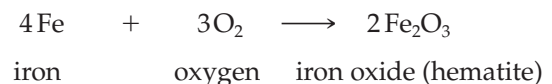
**FIGURE 6.10**    The dissolving power of carbonic acid plays an important part in forming limestone caverns. Carlsbad Caverns National Park, New Mexico. (Photo by Hohle Kalkstein/DRK Photo)

**FIGURE 6.11**  Iron reacts with oxygen to form iron oxide as seen on these rusted barrels. (Photo by Stephen J. Krasemann/DRK Photo)

This type of chemical reaction, called **oxidation,**\* occurs when electrons are lost from one element during the reaction. In this case, we say that iron was oxidized because it lost electrons to oxygen. Although the oxidation of iron progresses very slowly in a dry environment, the addition of water greatly speeds the reaction.

Oxidation is important in decomposing such ferromagnesian minerals as olivine, pyroxene, and hornblende. Oxygen readily combines with the iron in these minerals to form the reddish-brown iron oxide called *hematite* ($Fe_2O_3$) or in other cases a yellowish-colored rust called *limonite* [$FeO(OH)$]. These products are responsible for the rusty color on the surfaces of dark igneous rocks, such as basalt, as they begin to weather. However, oxidation can occur only after iron is freed from the silicate structure by another process, called hydrolysis.

Another important oxidation reaction occurs when sulfide minerals such as pyrite decompose. Sulfide minerals are major constituents in many metallic ores, and pyrite is frequently associated with coal deposits as well. In a moist environment, chemical weathering of pyrite ($FeS_2$) yields sulfuric acid ($H_2SO_4$) and iron oxide [$FeO(OH)$]. In many mining locales this weathering process creates a serious environmental hazard, particularly in humid areas where abundant rainfall infiltrates spoil banks (waste material left after coal or other minerals are removed). This so-called *acid mine drainage* eventually makes its way to streams, killing aquatic organisms and degrading aquatic habitats (Figure 6.12).
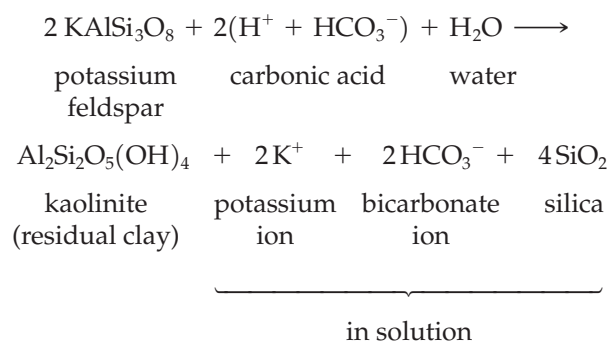
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\*The reader should note that *oxidation* is a term referring to any chemical reaction in which a compound or radical loses electrons. The element oxygen is not necessarily present.

## Hydrolysis

The most common mineral group, the silicates, is decomposed primarily by the process of **hydrolysis** (*hydro* = water, *lysis* = a loosening), which basically is the reaction of any substance with water. Ideally, the hydrolysis of a mineral could take place in pure water as some of the water molecules dissociate to form the very reactive hydrogen ($H^+$) and hydroxyl ($OH^-$) ions. It is the hydrogen ion that attacks and replaces other positive ions found in the crystal lattice. With the introduction of hydrogen ions into the crystalline structure, the original orderly arrangement of atoms is destroyed and the mineral decomposes.

In nature, water usually contains other substances that contribute additional hydrogen ions, thereby greatly accelerating hydrolysis. The most common of these substances is carbon dioxide, $CO_2$, which dissolves in water to form carbonic acid, $H_2CO_3$. Rain dissolves some carbon dioxide in the atmosphere, and additional amounts, released by decaying organic matter, are acquired as the water percolates through the soil.

In water, carbonic acid ionizes to form hydrogen ions ($H^+$) and bicarbonate ions ($HCO_3^-$). To illustrate how a rock undergoes hydrolysis in the presence of carbonic acid, let's examine the chemical weathering of granite, a common continental rock. Recall that granite consists mainly of quartz and potassium feldspar. The weathering of the potassium feldspar component of granite is as follows:

$$2\, KAlSi_3O_8 + 2(H^+ + HCO_3^-) + H_2O \longrightarrow$$

potassium        carbonic acid        water
feldspar

$$Al_2Si_2O_5(OH)_4 \;+\; 2\,K^+ \;+\; 2\,HCO_3^- \;+\; 4\,SiO_2$$

kaolinite        potassium   bicarbonate     silica
(residual clay)      ion          ion

in solution

**FIGURE 6.12**  This water seeping from an abandoned mine in Colorado is an example of *acid mine drainage.* Acid mine drainage is water with a high concentration of sulfuric acid ($H_2SO_4$) produced by the oxidation of sulfide minerals such as pyrite. When such acid-rich water migrates from its source, it may pollute surface waters and groundwater and cause significant ecological damage. (Photo by Tim Haske/Profiles West/Index Stock Photography, Inc.)

## BOX 6.2 ▶ EARTH AS A SYSTEM

# Acid Precipitation—A Human Impact on the Earth System

Humans are part of the complex interacting whole we call the Earth system. As such, our actions cause changes to all the other parts of the system. For example, by going about our normal routine, we humans modify the composition of the atmosphere. These atmospheric modifications in turn cause unintended and unwanted changes to occur in the hydrosphere, biosphere, and solid Earth. Acid precipitation is one small but significant example.

Decomposed stone monuments and structures are common sights in many cities (Figure 6.B). Although we expect rock to gradually decompose, many of these monuments have succumbed prematurely. An important cause for this accelerated chemical weathering is acid precipitation.

Rain is naturally somewhat acidic (Figure 6.C). When carbon dioxide from the atmosphere dissolves in water, the product is weak carbonic acid. However, the term *acid precipitation* refers to precipitation that is much more acidic than natural, unpolluted rain and snow.

As a consequence of burning large quantities of fossil fuels, like coal and petroleum products, about 40 million tons of sulfur and nitrogen oxides are released into the atmosphere each year in the United States. The major sources of these emissions include power-generating plants,



**FIGURE 6.B**    Acid rain accelerates the chemical weathering of stone monuments and structures. (Photo by Adam Hart-Davis/Science Photo Library/Photo Researchers, Inc.)

industrial processes such as ore smelting and petroleum refining, and vehicles of all kinds. Through a series of complex chemical reactions, some of these pollutants are converted into acids that then fall to Earth's surface as rain or snow. Another portion is deposited in dry form and subsequently converted into acid after coming in contact with precipitation, dew, or fog.

Northern Europe and eastern North America have experienced widespread acid rain for some time. Studies have also shown that acid rain occurs in many other regions, including western North America, Japan, China, Russia, and South America. In addition to local pollution sources, a portion of the acidity found in the northeastern United States and eastern Canada originates hundreds of kilometers away in industrialized regions to the south and southwest. This situation occurs because many pollutants remain in the atmosphere as long as five days, during which time they may be transported great distances.

The damaging environmental effects of acid rain are thought to be considerable in some areas and imminent in others (Figure 6.D). The best-known effect is an increased acidity in thousands of lakes in Scandinavia and eastern North America. Accompanying this have been substantial increases in

In this reaction, the hydrogen ions ($H^+$) attack and replace potassium ions ($K^+$) in the feldspar structure, thereby disrupting the crystalline network. Once removed, the potassium is available as a nutrient for plants or becomes the soluble salt potassium bicarbonate ($KHCO_3$), which may be incorporated into other minerals or carried to the ocean.

The most abundant product of the chemical breakdown of potassium feldspar is the clay mineral kaolinite. Clay minerals are the end products of weathering and are very stable under surface conditions. Consequently, clay minerals make up a high percentage of the inorganic material in soils. Moreover, the most abundant sedimentary rock, shale, contains a high proportion of clay minerals.

In addition to the formation of clay minerals during the weathering of potassium feldspar, some silica is removed from the feldspar structure and carried away by groundwater. This dissolved silica will eventually precipitate, producing nodules of chert or flint, or it will fill in the pore spaces between grains of sediment, or it will be carried to the ocean, where microscopic animals will remove it from the water to build hard silica shells.

To summarize, the weathering of potassium feldspar generates a residual clay mineral, a soluble salt (potassium bicarbonate), and some silica, which enters into solution.

Quartz, the other main component of granite, is very resistant to chemical weathering; it remains substantially unaltered when attacked by weak acidic solutions. As a result, when granite weathers, the feldspar crystals dull and slowly turn to clay, releasing the once interlocked quartz grains, which still retain their fresh, glassy appearance. Although some of the quartz remains in the soil, much is eventually transported to the sea or to other sites of deposition, where it becomes the main constituent of such features as sandy beaches and sand dunes. In time these quartz grains may be lithified to form the sedimentary rock sandstone.

Table 6.1 lists the weathered products of some of the most common silicate minerals. Remember that silicate minerals make up most of Earth's crust and that these minerals are
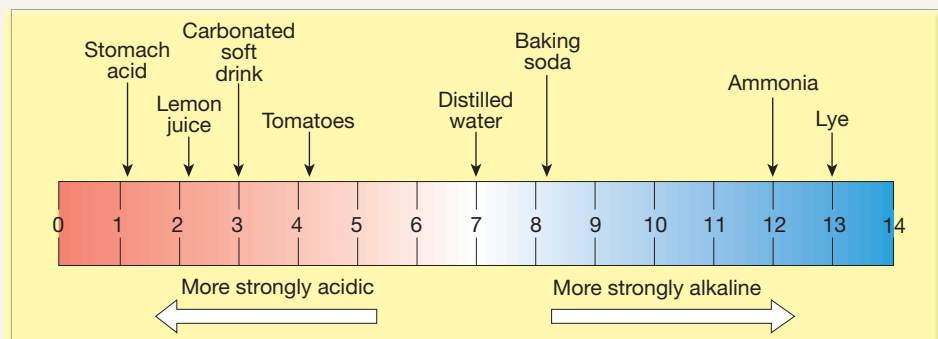
**FIGURE 6.C**   The *pH scale* is a common measure of the degree of acidity or alkalinity of a solution. The scale ranges from 0 to 14, with a value of 7 denoting a solution that is neutral. Values below 7 indicate greater acidity, whereas numbers above 7 indicate greater alkalinity. The pH values of some familiar substances are shown on the diagram. Although distilled water is neutral (pH 7), rainwater is naturally acidic. It is important to note that the pH scale is logarithmic; that is, each whole number increment indicated a tenfold difference. Thus, pH 4 is 10 times more acidic than pH 5 and 100 times (10 × 10) more acidic than pH 6.



**FIGURE 6.D**   Damage to forests by acid precipitation is well documented in Europe and eastern North America. These trees in the Great Smoky Mountains have been injured by acid-laden clouds. (Photo by Doug Locke/Dembinsky Photo Associates)

dissolved aluminum leached from the soil by the acidic water, which is toxic to fish. Consequently, some lakes are virtually devoid of fish, and others are approaching this condition. Ecosystems are characterized by many interactions at many levels of organization, which means that evaluating the effects of acid precipitation on these complex systems is difficult and expensive and far from complete.

In addition to the many lakes that can no longer support fish, research indicates that acid precipitation may also reduce agricultural crop yields and impair the productivity of forests. Acid rain not only harms the foliage but also damages roots and leaches nutrient minerals from the soil. Finally, acid precipitation promotes the corrosion of metals and contributes to the destruction of stone structures.

essentially composed of only eight elements. When chemically weathered, the silicate minerals yield sodium, calcium, potassium, and magnesium ions that form soluble products, which may be removed from groundwater. The element iron combines with oxygen, producing relatively insoluble iron oxides, most notably hematite and limonite, which give soil a reddish-brown or yellowish color. Under most condi-

tions the three remaining elements—aluminum, silicon, and oxygen—join with water to produce residual clay minerals. However, even the highly insoluble clay minerals are very slowly removed by subsurface water.
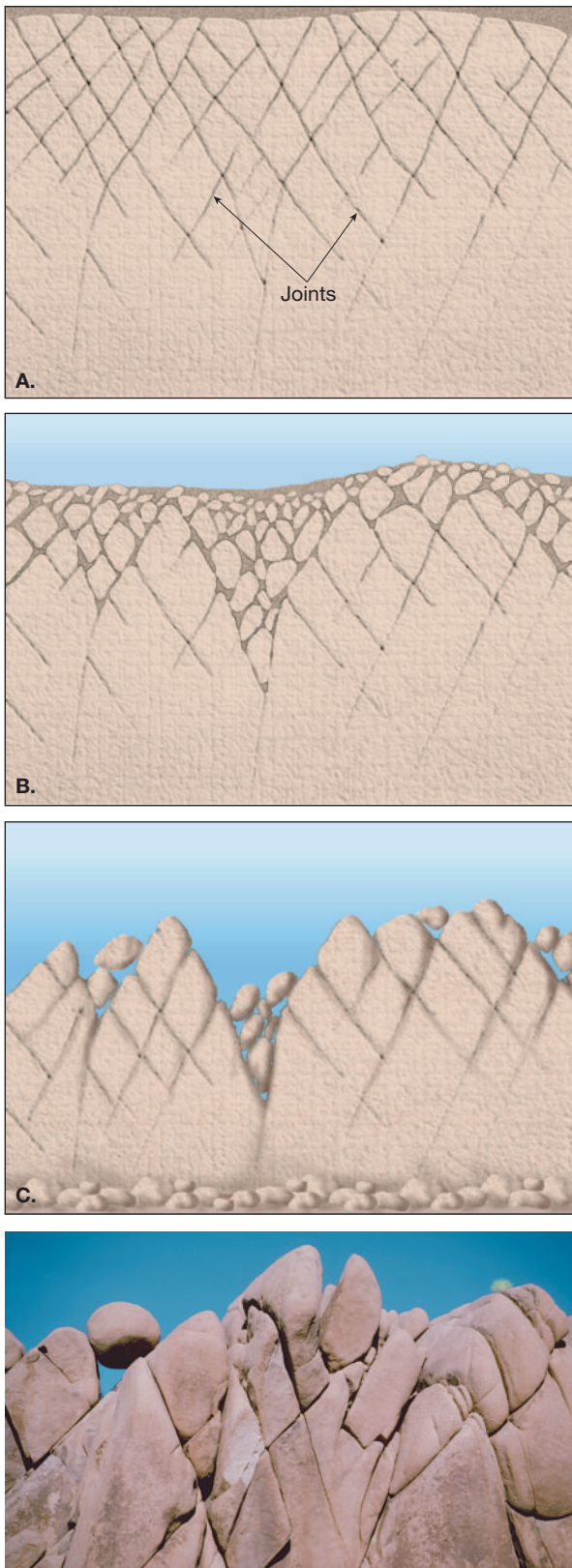
## Alterations Caused by Chemical Weathering

As noted earlier, the most significant result of chemical weathering is the decomposition of unstable minerals and the generation or retention of those materials that are stable at Earth's surface. This accounts for the predominance of certain minerals in the surface material we call soil.

In addition to altering the internal structure of minerals, chemical weathering causes physical changes as well. For instance, when angular rock masses are chemically weathered as water enters along joints, the boulders take on a spherical shape. The gradual rounding of the corners and edges of angular blocks is illustrated in Figure 6.13. The corners are

| TABLE 6.1 | Products of Weathering | |
|---|---|---|
| **Mineral** | **Residual Products** | **Material in Solution** |
| Quartz | Quartz grains | Silica |
| Feldspars | Clay minerals | Silica, $K^+$, $Na^+$, $Ca^{2+}$ |
| Amphibole (hornblende) | Clay minerals Limonite Hematite | Silica $Ca^{2+}$, $Mg^{2+}$ |
| Olivine | Limonite Hematite | Silica $Mg^{2+}$ |

attacked most readily because of the greater surface area for their volume as compared to the edges and faces. This process, called **spheroidal weathering,** gives the weathered rock a more rounded or spherical shape (Figure 6.13D).

Sometimes during the formation of spheroidal boulders, successive shells separate from the rock's main body (Figure 6.14). Eventually the outer shells break off, allowing the chemical weathering activity to penetrate deeper into the boulder. This spherical scaling results because, as the minerals in the rock weather to clay, they increase in size through the addition of water to their structure. This increased bulk exerts an outward force that causes concentric layers of rock to break loose and fall off.

Hence, chemical weathering does produce forces great enough to cause mechanical weathering. This type of spheroidal weathering in which shells spall off should not be confused with the phenomenon of sheeting discussed earlier. In sheeting, the fracturing occurs as a result of unloading, and the rock layers that separate from the main body are largely unaltered at the time of separation.



A.

B.

C.

**FIGURE 6.13**   Spheroidal weathering of extensively jointed rock. Chemical weathering associated with water moving through the joints enlarges them. Because the rocks are attacked more on the corners and edges, they take on a spherical shape. The photo shows spheroidal weathering in Joshua Tree National Park, California. (Photo by E. J. Tarbuck)

*Students Sometimes Ask . . .*

*Is the clay created by chemical weathering the same clay that's used in making ceramics?*

Yes. Kaolinite, the clay described in the section on hydrolysis, is called *china clay* and is used for high-quality porcelain. However, far greater quantities of this clay are used as a coating in the manufacture of high-quality paper, such as that used in this book.

Weathering actually creates many different clay minerals that have many different uses. Clay minerals are used in making bricks, tiles, sewer pipes, and cement. Clays are used as lubricants in the bore holes of oil-drilling rigs and are a common ingredient in paint. Products as varied as your car's catalytic converter and filters used in beer- and wine-making rely on clay minerals.

**FIGURE 6.14**   Successive shells are loosened as the weathering process continues to penetrate ever deeper into the rock. (Photo by Martin Schmidt, Jr.)

# Rates of Weathering

**GEODe**  Weathering and Soil

▶ Rates of Weathering

Several factors influence the type and rate of rock weathering. We have already seen how mechanical weathering affects the rate of weathering. By breaking rock into smaller pieces, the amount of surface area exposed to chemical weathering increases. Other important factors examined here include the roles of rock characteristics and climate.

## Rock Characteristics

Rock characteristics encompass all of the chemical traits of rocks, including mineral composition and solubility. In addition, any physical features, such as joints (cracks), can be important because they influence the ability of water to penetrate rock.

The variations in weathering rates due to the mineral constituents can be demonstrated by comparing old headstones made from different rock types. Headstones of granite, which is composed of silicate minerals, are relatively resistant to chemical weathering. We can see this by examining the inscriptions on the headstones shown in Figure 6.15. In contrast, the marble headstone shows signs of extensive chemical alteration over a relatively short period. Marble is composed of calcite (calcium carbonate), which readily dissolves even in a weakly acidic solution.

The most abundant mineral group, the silicates, weathers in the order shown in Figure 6.16. This arrangement of minerals is identical to Bowen's reaction series. The order in which the silicate minerals weather is essentially the same as their order of crystallization. The explanation for this is related to the crystalline structure of silicate minerals. The strength of silicon–oxygen bonds is great. Because quartz is composed entirely of these strong bonds, it is very resistant to weathering. By contrast, olivine has far fewer silicon–oxygen bonds and is not nearly as resistant to chemical weathering.

## Climate

Climatic factors, particularly temperature and moisture, are crucial to the rate of rock weathering. One important example from mechanical weathering is that the frequency of freeze–thaw cycles greatly affects the amount of frost wedging. Temperature and moisture also exert a strong influence on rates of chemical weathering and on the kind and amount of vegetation present. Regions with lush vegetation often have a thick mantle of soil rich in decayed organic matter from which chemically active fluids such as carbonic acid and humic acids are derived.

The optimum environment for chemical weathering is a combination of warm temperatures and abundant moisture. In polar regions chemical weathering is ineffective because frigid temperatures keep the available moisture locked up as ice, whereas in arid regions there is insufficient moisture to foster rapid chemical weathering.

Human activities can influence the composition of the atmosphere, which in turn can impact the rate of chemical weathering. Box 6.2 examines one well-known example—acid rain.

## Differential Weathering

Masses of rock do not weather uniformly. Take a moment to look back at the photo of a dike in Figure 5.33 (p. 151). The durable igneous mass stands above the surrounding terrain like a stone wall. A glance at Figure 6.1 shows an additional example of this phenomenon, called **differential weathering.** The results vary in scale from the rough, uneven surface of the marble headstone in Figure 6.15 to the boldly sculpted exposures shown in the chapter-opening photo.

Many factors influence the rate of rock weathering. Among the most important are variations in the composition of the rock. More resistant rock protrudes as ridges (see Figure 14.13, p. 390) or pinnacles, or as steeper cliffs on an irregular hillside (see Figure 7.4, p. 197). The number and spacing of joints can also be a significant factor (see Figures 6.6 and 6.13). Differential weathering and subsequent erosion are responsible for creating many unusual and sometimes spectacular rock formations and landforms.

## Soil

Soil covers most land surfaces. Along with air and water, it is one of our most indispensable resources (Figure 6.17). Also like air and water, soil is taken for granted by many of us. The following quote helps put this vital layer in perspective.

**FIGURE 6.15**  An examination of headstones reveals the rate of chemical weathering on diverse rock types. The granite headstone (left) was erected four years before the marble headstone (right). The inscription date of 1872 on the marble monument is nearly illegible. (Photos by E. J. Tarbuck)

| Environment of Formation | Silicate Minerals | Susceptibility to Chemical Weathering |
|---|---|---|
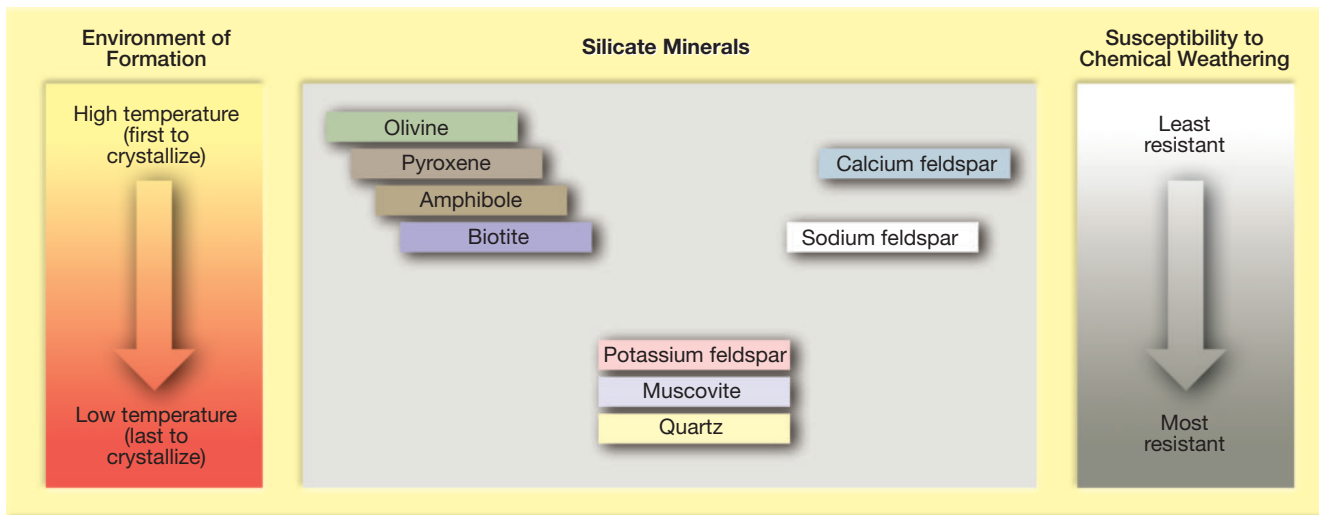
**FIGURE 6.16** The weathering of common silicate minerals. The order in which the silicate minerals chemically weather is essentially the same as their order of crystallization.

Science, in recent years, has focused more and more on the Earth as a planet, one that for all we know is unique—where a thin blanket of air, a thinner film of water, and the thinnest veneer of soil combine to support a web of life of wondrous diversity in continuous change.*

Soil has accurately been called "the bridge between life and the inanimate world." All life—the entire biosphere—owes its existence to a dozen or so elements that must ultimately come from Earth's crust. Once weathering and other processes create soil, plants carry out the intermediary role of assimilating the necessary elements and making them available to animals, including humans.

## An Interface in the Earth System

When Earth is viewed as a system, soil is referred to as an *interface*—a common boundary where different parts of a system interact. This is an appropriate designation because soil forms where the geosphere, the atmosphere, the hydrosphere, and the biosphere meet. Soil is a material that develops in response to complex environmental interactions among different parts of the Earth system. Over time, soil gradually evolves to a state of equilibrium or balance with the environment. Soil is dynamic and sensitive to almost every aspect of its surroundings. Thus, when environmental changes occur, such as climate, vegetative cover, and animal (including human) activity, the soil responds. Any such change produces a gradual alteration of soil characteristics until a new balance is reached. Although thinly distributed over the land surface, soil functions as a fundamental interface, providing an excellent example of the integration among many parts of the Earth system.

## What Is Soil?

With few exceptions, Earth's land surface is covered by **regolith** (*rhegos* = blanket, *lithos* = stone), the layer of rock and mineral fragments produced by weathering. Some would call this material soil, but soil is more than an accumulation of weathered debris. **Soil** is a combination of mineral and organic matter, water, and air—that portion of the regolith that supports the growth of plants. Although the proportions of the major components in soil vary, the same four components always are present to some extent (Figure 6.17). About one-half
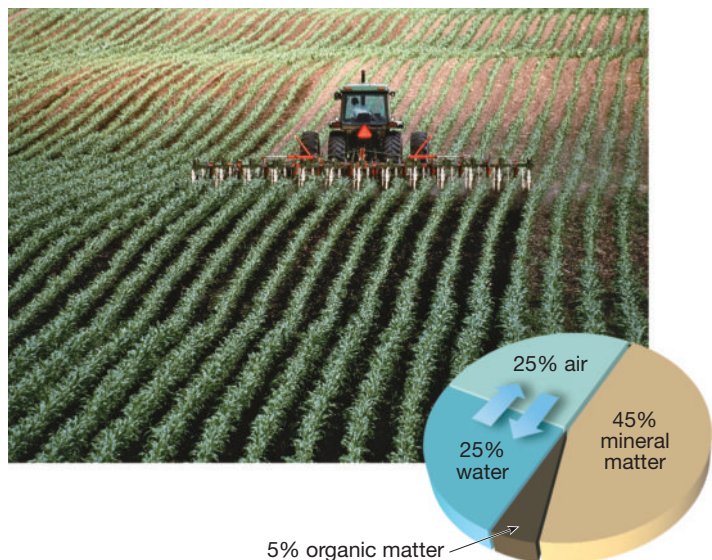


**FIGURE 6.17** Soil is an essential resource that we often take for granted. Soil is not a living entity, but it contains a great deal of life. Moreover, this complex medium supports nearly all plant life, which in turn supports animal life. The pie chart shows the composition (by volume) of a soil in good condition for plant growth. Although the percentages vary, each soil is composed of mineral and organic matter, water, and air. (Photo by Colin Molyneux/Getty Images)

*Jack Eddy, "A Fragile Seam of Dark Blue Light," in *Proceedings of the Global Change Research Forum.* U.S. Geological Survey Circular 1086, 1993, p. 15.

of the total volume of a good-quality surface soil is a mixture of disintegrated and decomposed rock (mineral matter) and **humus,** the decayed remains of animal and plant life (organic matter). The remaining half consists of pore spaces among the solid particles where air and water circulate.

Although the mineral portion of the soil is usually much greater than the organic portion, humus is an essential component. In addition to being an important source of plant nutrients, humus enhances the soil's ability to retain water. Because plants require air and water to live and grow, the portion of the soil consisting of pore spaces that allow for the circulation of these fluids is as vital as the solid soil constituents.

Soil water is far from "pure" water; instead, it is a complex solution containing many soluble nutrients. Soil water not only provides the necessary moisture for the chemical reactions that sustain life, it also supplies plants with nutrients in a form they can use. The pore spaces not filled with water contain air. This air is the source of necessary oxygen and carbon dioxide for most microorganisms and plants that live in the soil.

## Controls of Soil Formation

Soil is the product of the complex interplay of several factors, including parent material, time, climate, plants and animals, and topography. Although all these factors are interdependent, their roles will be examined separately.
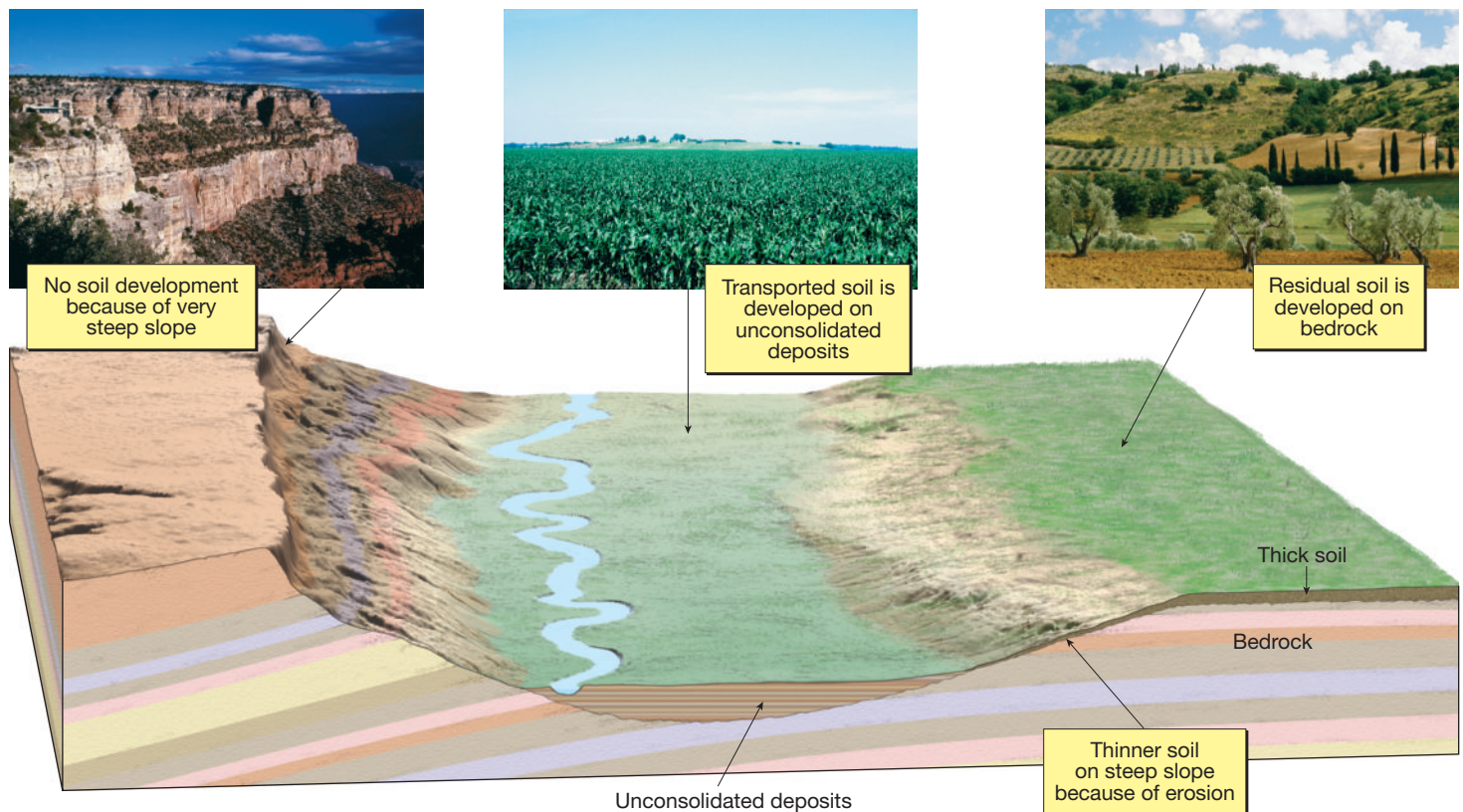
*Students Sometimes Ask . . .*

*I've seen photos of footprints left on the lunar surface by astronauts. Does this mean the Moon has soil?*

Not exactly. The Moon has no atmosphere, no water, and lacks biological activity. Therefore, the chemical weathering, frost wedging, and other weathering processes we are familiar with on Earth are lacking on the Moon. However, all lunar terrains are mantled with a soil-like layer of gray debris, called *lunar regolith,* derived from a few billion years of bombardment by meteorites. The rate of surface change is so slow that the footprints left by the *Apollo* astronauts (see Figure 24.8 on p. 662) will likely remain fresh-looking for millions of years.

## Parent Material

The source of the weathered mineral matter from which soils develop is called the **parent material** and is a major factor influencing a newly forming soil. Gradually it undergoes physical and chemical changes as the processes of soil formation progress. Parent material can either be the underlying bedrock or a layer of unconsolidated deposits. When the parent material is bedrock, the soils are termed *residual soils.* By contrast, those developed on unconsolidated sediment are called *transported soils* (Figure 6.18). It should



No soil development because of very steep slope

Transported soil is developed on unconsolidated deposits

Residual soil is developed on bedrock

Thick soil

Bedrock

Unconsolidated deposits

Thinner soil on steep slope because of erosion

**FIGURE 6.18**    The parent material for residual soils is the underlying bedrock, whereas transported soils form on unconsolidated deposits. Also note that as slopes become steeper, soil becomes thinner. (Left and center photos by E. J. Tarbuck; right photo by Grilly Bernard/Getty Images, Inc./Stone Allstock)

be pointed out that transported soils form *in place* on parent materials that have been carried from elsewhere and deposited by gravity, water, wind, or ice.

The nature of the parent material influences soils in two ways. First, the type of parent material will affect the rate of weathering and thus the rate of soil formation. Also, because unconsolidated deposits are already partly weathered, soil development on such material will likely progress more rapidly than when bedrock is the parent material. Second, the chemical makeup of the parent material will affect the soil's fertility. This influences the character of the natural vegetation the soil can support.

At one time the parent material was thought to be the primary factor causing differences among soils. However, soil scientists came to understand that other factors, especially climate, are more important. In fact, it was found that similar soils often develop from different parent materials and that dissimilar soils have developed from the same parent material. Such discoveries reinforce the importance of other soil-forming factors.

## Time

Time is an important component of *every* geological process, and soil formation is no exception. The nature of soil is strongly influenced by the length of time that processes have been operating. If weathering has been going on for a comparatively short time, the character of the parent material strongly influences the characteristics of the soil. As weathering processes continue, the influence of parent material on soil is overshadowed by the other soil-forming factors, especially climate. The amount of time required for various soils to evolve cannot be listed because the soil-forming processes act at varying rates under different circumstances. However, as a rule, the longer a soil has been forming, the thicker it becomes and the less it resembles the parent material.

## Climate

Climate is considered to be the most influential control of soil formation. Temperature and precipitation are the elements that exert the strongest impact on soil formation. Variations in temperature and precipitation determine whether chemical or mechanical weathering will predominate and also greatly influence the rate and depth of weathering. For instance, a hot, wet climate may produce a thick layer of chemically weathered soil in the same amount of time that a cold, dry climate produces a thin mantle of mechanically weathered debris. Also, the amount of precipitation influences the degree to which various materials are removed from the soil by percolating waters (a process called *leaching*), thereby affecting soil fertility. Finally, climatic conditions are an important control on the type of plant and animal life present.

## Plants and Animals

Plants and animals play a vital role in soil formation. The types and abundance of organisms present have a strong influence on the physical and chemical properties of a soil (Figure 6.19). In fact, for well-developed soils in many regions, the significance of natural vegetation in influencing soil type is frequently implied in the description used by soil scientists. Such phrases as *prairie soil, forest soil,* and *tundra soil* are common.

Plants and animals furnish organic matter to the soil. Certain bog soils are composed almost entirely of organic matter, whereas desert soils might contain as little as a small fraction of 1 percent. Although the quantity of organic matter varies substantially among soils, it is the rare soil that completely lacks it.

The primary source of organic matter in soil is plants, although animals and an infinite number of microorganisms also contribute. When organic matter is decomposed, important nutrients are supplied to plants, as well as to animals and microorganisms living in the soil. Consequently, soil fertility is in part related to the amount of organic matter present. Furthermore, the decay of plant and animal remains causes the formation of various organic acids. These complex acids hasten the weathering process. Organic matter also has a high water-holding ability and thus aids water retention in a soil.

Microorganisms, including fungi, bacteria, and single-celled protozoa, play an active role in the decay of plant and animal remains. The end product is humus, a material that no longer resembles the plants and animals from which it is formed. In addition, certain microorganisms aid soil fertility because they have the ability to convert atmospheric nitrogen into soil nitrogen.

Earthworms and other burrowing animals act to mix the mineral and organic portions of a soil. Earthworms, for example, feed on organic matter and thoroughly mix soils in which they live, often moving and enriching many tons per acre each year. Burrows and holes also aid the passage of water and air through the soil.

## Topography

The lay of the land can vary greatly over short distances. Such variations in topography can lead to the development of a variety of localized soil types. Many of the differences exist because the length and steepness of slopes have a significant impact on the amount of erosion and the water content of soil.

On steep slopes, soils are often poorly developed. In such situations the quantity of water soaking in is slight; as a result, the moisture content of the soil may not be sufficient for vigorous plant growth. Further, because of accelerated erosion on steep slopes, the soils are thin or in some cases nonexistent (Figure 6.18).

In contrast, poorly drained and waterlogged soils found in bottomlands have a much different character. Such soils are usually thick and dark. The dark color results from the large quantity of organic matter that accumulates because saturated conditions retard the decay of vegetation. The optimum terrain for soil development is a flat-to-undulating upland surface. Here we find good drainage, minimum erosion, and sufficient infiltration of water into the soil.

**FIGURE 6.19** The northern coniferous forest in Alaska's Denali National Park. The type of vegetation strongly influences soil formation. The organic litter received by the soil from the conifers is high in acid resins, which contributes to an accumulation of acid in the soil. As a result, intensive acid leaching is an important soil-forming process here. (Photo by Carr Clifton)

*Slope orientation*, or the direction the slope is facing, is another consideration. In the midlatitudes of the Northern Hemisphere, a south-facing slope will receive a great deal more sunlight than a north-facing slope. In fact, a steep north-facing slope may receive no direct sunlight at all. The difference in the amount of solar radiation received will cause differences in soil temperature and moisture, which in turn influence the nature of the vegetation and the character of the soil.

Although this section dealt separately with each of the soil-forming factors, remember that all of them work together to form soil. No single factor is responsible for a soil's character; rather, it is the combined influence of parent material, time, climate, plants and animals, and topography that determines this character.

## The Soil Profile

Because soil-forming processes operate from the surface downward, variations in composition, texture, structure, and color gradually evolve at varying depths. These vertical differences, which usually become more pronounced as time passes, divide the soil into zones or layers known as **horizons.** If you were to dig a trench in soil, you would see that its walls are layered. Such a vertical section through all of the soil horizons constitutes the **soil profile** (Figure 6.20).

**FIGURE 6.20** A soil profile is a vertical cross section from the surface through all of the soil's horizons and into the parent material. **A.** This profile shows a well-developed soil in southeastern South Dakota. (Photo by E. J. Tarbuck) **B.** The boundaries between horizons in this soil in Puerto Rico are indistinct, giving it a relatively uniform appearance. (Photo courtesy of Soil Science Society of America)
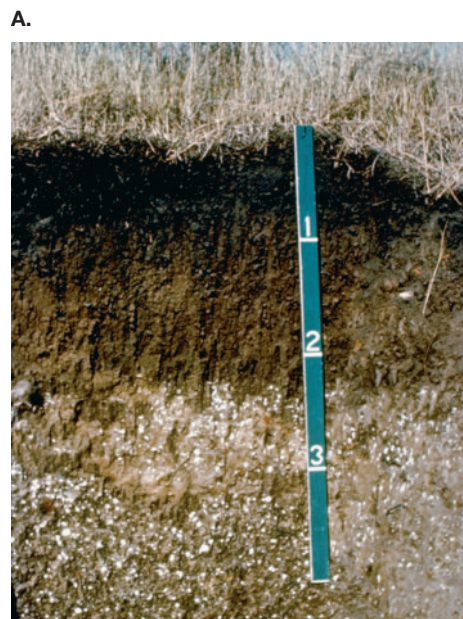
**A.**



**B.**

Figure 6.21 presents an idealized view of a well-developed soil profile in which five horizons are identified. From the surface downward, they are designated as *O, A, E, B,* and *C.* These five horizons are common to soils in temperate regions. The characteristics and extent of development of horizons vary in different environments. Thus, different localities exhibit soil profiles that can contrast greatly with one another.

The *O* soil horizon consists largely of organic material. This is in contrast to the layers beneath it, which consist mainly of mineral matter. The upper portion of the *O* horizon is primarily plant litter, such as loose leaves and other organic debris that are still recognizable. By contrast, the lower portion of the *O* horizon is made up of partly decomposed organic matter (humus) in which plant structures can no longer be identified. In addition to plants, the *O* horizon is teeming with microscopic life, including bacteria, fungi, algae, and insects. All of these organisms contribute oxygen, carbon dioxide, and organic acids to the developing soil.

Underlying the organic-rich *O* horizon is the *A* horizon. This zone is largely mineral matter, yet biological activity is
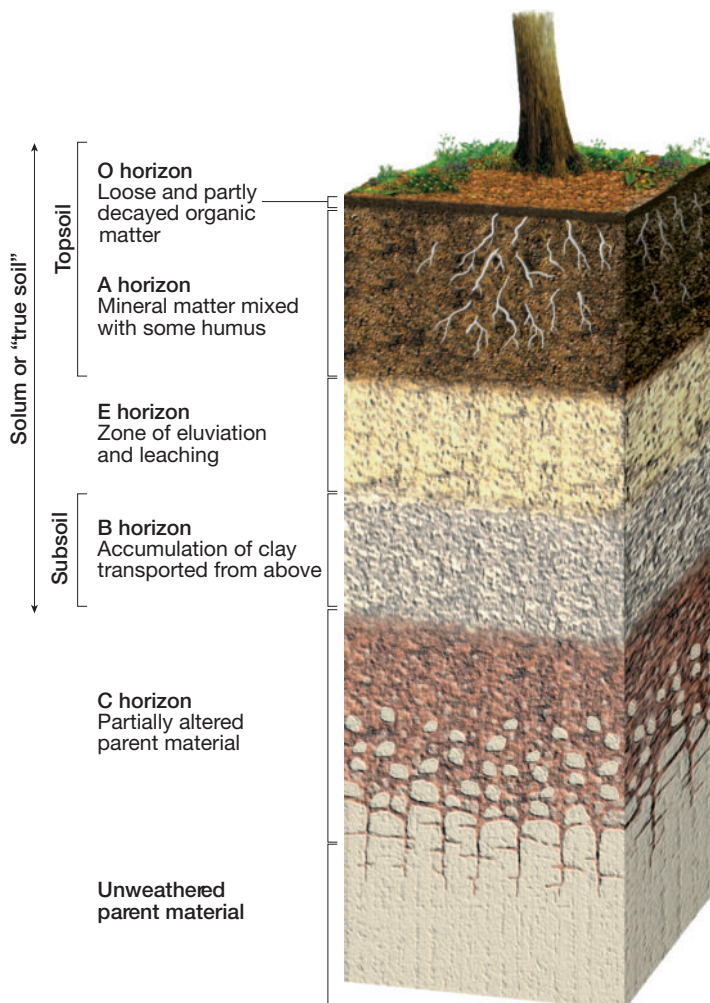
## Students Sometimes Ask . . .

*I was digging in my yard the other day and came across a deep "hardpan" layer that was really difficult to penetrate. How does a hardpan form?*

Hardpans are created by the process of eluviation. As water percolates through the soil, fine clay-size particles from the upper soil layers are moved by eluviation and concentrated in the subsoil (*B* horizon). Over time the accumulation of these clay-size particles creates a nearly impenetrable layer, which is what you found. Sometimes hardpans are so impermeable that they serve as effective barriers to water movement, preventing further infiltration of water. Hardpans are also called *adobe layers,* because their high clay content makes them suitable for use as construction bricks.

high and humus is generally present—up to 30 percent in some instances. Together the *O* and *A* horizons make up what is commonly called the *topsoil.* Below the *A* horizon, the *E* horizon is a light-colored layer that contains little organic material. As water percolates downward through this zone, finer particles are carried away. This washing out of fine soil components is termed **eluviation** (*elu* = get away from, *via* = a way). Water percolating downward also dissolves soluble inorganic soil components and carries them to deeper zones. This depletion of soluble materials from the upper soil is termed **leaching.**

Immediately below the *E* horizon is the *B* horizon, or *subsoil.* Much of the material removed from the *E* horizon by eluviation is deposited in the *B* horizon, which is often referred to as the *zone of accumulation.* The accumulation of the fine clay particles enhances water retention in the subsoil. The *O, A, E,* and *B* horizons together constitute the **solum,** or "true soil." It is in the solum that the soil-forming processes are active and that living roots and other plant and animal life are largely confined.

Below the solum and above the unaltered parent material is the *C* horizon, a layer characterized by partially altered parent material. Whereas the *O, A, E,* and *B* horizons bear little resemblance to the parent material, it is easily identifiable in the *C* horizon. Although this material is undergoing changes that will eventually transform it into soil, it has not yet crossed the threshold that separates regolith from soil.

The characteristics and extent of development can vary greatly among soils in different environments. The boundaries between soil horizons may be sharp, or the horizons may blend gradually from one to another. Consequently, a well-developed soil profile indicates that environmental conditions have been relatively stable over an extended time span and that the soil is *mature.* By contrast, some soils lack horizons altogether.

Such soils are called *immature* because soil building has been going on for only a short time. Immature soils are also



**FIGURE 6.21** Idealized soil profile from a humid climate in the middle latitudes. The topsoil and subsoil together comprise the solum or "true soil."

characteristic of steep slopes, where erosion continually strips away the soil, preventing full development.

## Classifying Soils

There are many variations from place to place and from time to time among the factors that control soil formation. These differences lead to a bewildering variety of soil types. To cope with such variety, it is essential to devise some means of classifying the vast array of data to be studied. By establishing groups consisting of items that have certain important characteristics in common, order and simplicity are introduced. Bringing order to large quantities of information not only aids comprehension and understanding but also facilitates analysis and explanation.

In the United States, soil scientists have devised a system for classifying soils known as the **Soil Taxonomy.** It emphasizes the physical and chemical properties of the soil profile and is organized on the basis of observable soil characteristics. There are six hierarchical categories of classification, ranging from *order,* the broadest category, to *series,* the most specific category. The system recognizes 12 soil orders and more than 19,000 soil series.

The names of the classification units are combinations of syllables, most of which are derived from Latin or Greek. The names are descriptive. For example, soils of the order Aridosol (from the Latin *aridus,* dry, and *solum,* soil) are characteristically dry soils in arid regions. Soils in the order Inceptisols (from Latin *inceptum,* beginning, and *solum,* soil) are soils with only the beginning or inception of profile development.

Brief descriptions of the 12 basic soil orders are provided in Table 6.2. Figure 6.22 shows the complex worldwide distribution pattern of the Soil Taxonomy's 12 soil orders (see Box 6.3). Like many classification systems, the Soil Taxonomy is not suitable for every purpose. It is especially useful for agricultural and related land-use purposes, but it is not a useful system for engineers who are preparing evaluations of potential construction sites.

## Soil Erosion

Soils are just a tiny fraction of all Earth materials, yet they are a vital resource. Because soils are necessary for the growth of rooted plants, they are the very foundation of the human life-support system. Just as human ingenuity can increase the agricultural productivity of soils through fertilization and irrigation, soils can be damaged or destroyed by careless activities. Despite their basic role in providing food, fiber, and other basic materials, soils are among our most abused resources.

Perhaps this neglect and indifference has occurred because a substantial amount of soil seems to remain even where soil erosion is serious. Nevertheless, although the loss of fertile topsoil may not be obvious to the untrained eye, it is a growing problem as human activities expand and disturb more and more of Earth's surface.

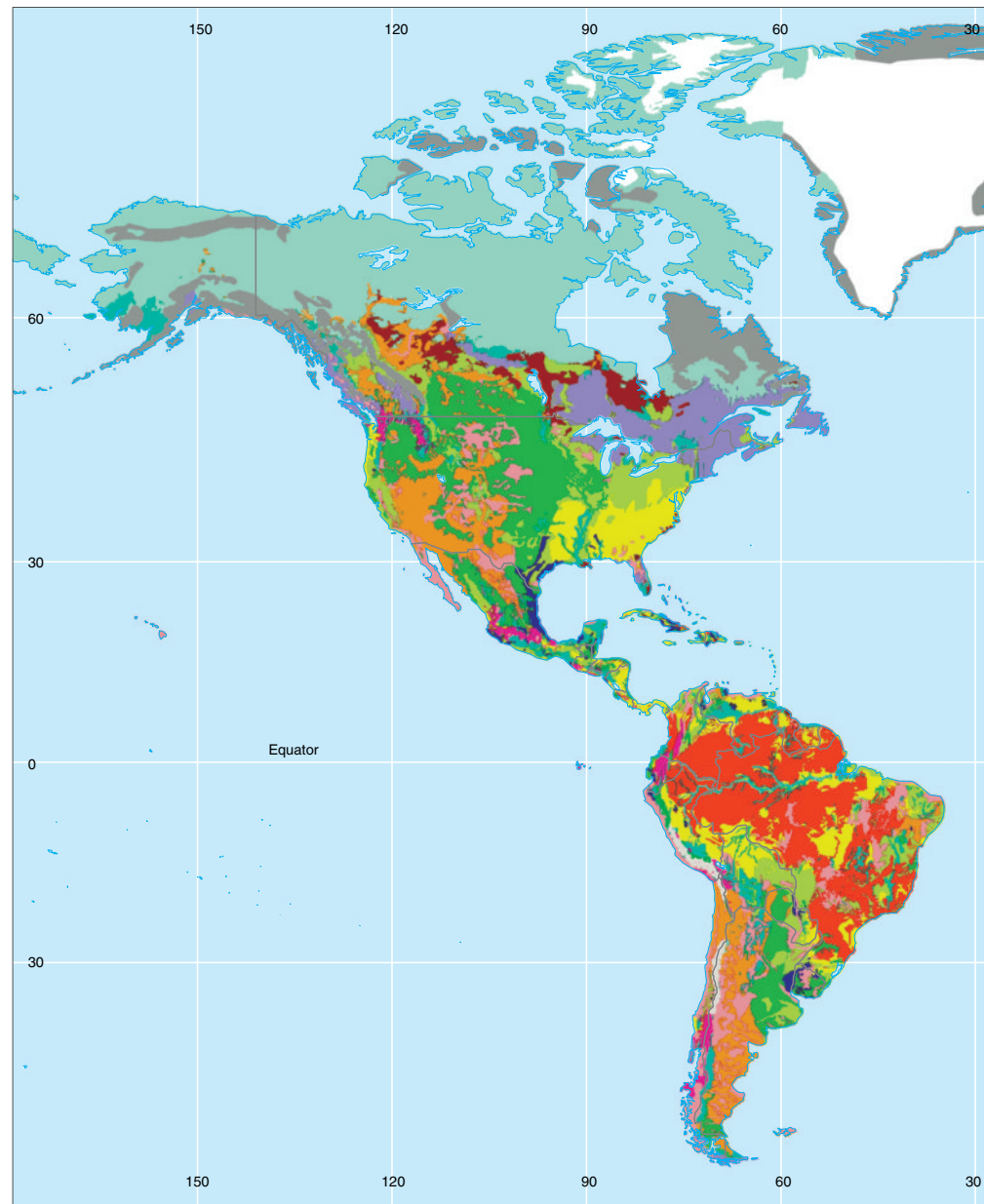| TABLE 6.2 | World Soil Orders |
|---|---|
| Alfisols | Moderately weathered soils that form under boreal forests or broadleaf deciduous forests, rich in iron and aluminum. Clay particles accumulate in a subsurface layer in response to leaching in moist environments. Fertile, productive soils, because they are neither too wet nor too dry. |
| Andisols | Young soils in which the parent material is volcanic ash and cinders, deposited by recent volcanic activity. |
| Aridosols | Soils that develop in dry places; insufficient water to remove soluble minerals, may have an accumulation of calcium carbonate, gypsum, or salt in subsoil; low organic content. |
| Entisols | Young soils having limited development and exhibiting properties of the parent material. Productivity ranges from very high for some formed on recent river deposits to very low for those forming on shifting sand or rocky slopes. |
| Gelisols | Young soils with little profile development that occur in regions with permafrost. Low temperatures and frozen conditions for much of the year; slow soil-forming processes. |
| Histosols | Organic soils with little or no climatic implications. Can be found in any climate where organic debris can accumulate to form a bog soil. Dark, partially decomposed organic material commonly referred to as *peat.* |
| Inceptisols | Weakly developed young soils in which the beginning (inception) of profile development is evident. Most common in humid climates, they exist from the Arctic to the tropics. Native vegetation is most often forest. |
| Mollisols | Dark, soft soils that have developed under grass vegetation, generally found in prairie areas. Humus-rich surface horizon that is rich in calcium and magnesium. Soil fertility is excellent. Also found in hardwood forests with significant earthworm activity. Climatic range is boreal or alpine to tropical. Dry seasons are normal (see Figure 6.20A). |
| Oxisols | Soils that occur on old land surfaces unless parent materials were strongly weathered before they were deposited. Generally found in the tropics and subtropical regions. Rich in iron and aluminum oxides, oxisols are heavily leached; hence are poor soils for agricultural activity (see Figure 6.20B). |
| Spodosols | Soils found only in humid regions on sandy material. Common in northern coniferous forests (see Figure 6.19) and cool humid forests. Beneath the dark upper horizon of weathered organic material lies a light-colored horizon of leached material, the distinctive property of this soil. |
| Ultisols | Soils that represent the products of long periods of weathering. Water percolating through the soil concentrates clay particles in the lower horizons (argillic horizons). Restricted to humid climates in the temperate regions and the tropics, where the growing season is long. Abundant water and a long frost-free period contribute to extensive leaching, hence poorer soil quality. |
| Vertisols | Soils containing large amounts of clay, which shrink upon drying and swell with the addition of water. Found in subhumid to arid climates, provided that adequate supplies of water are available to saturate the soil after periods of drought. Soil expansion and contraction exert stresses on human structures. |

## How Soil Is Eroded

Soil erosion is a natural process; it is part of the constant recycling of Earth materials that we call the *rock cycle.* Once soil forms, erosional forces, especially water and wind, move soil components from one place to another. Every time it rains, raindrops strike the land with surprising force (Figure 6.23). Each drop acts like a tiny bomb, blasting movable soil particles out of their positions in the soil mass. Then, water flowing across the surface carries away the dislodged soil particles. Because the soil is moved by thin sheets of water, this process is termed *sheet erosion.*

After flowing as a thin, unconfined sheet for a relatively short distance, threads of current typically develop, and tiny channels called *rills* begin to form. Still deeper cuts in the soil, known as *gullies,* are created as rills enlarge (Figure 6.24). When normal farm cultivation cannot eliminate the channels, we know the rills have grown large enough to be called gullies. Although most dislodged soil particles move only a short distance during each rainfall, substantial quantities eventually leave the fields and make their way downslope to a stream. Once in the stream channel, these soil particles, which can now be called *sediment,* are transported downstream and eventually deposited.

## Rates of Erosion

We know that soil erosion is the ultimate fate of practically all soils. In the past, erosion occurred at slower rates than it does today because more of the land surface was covered and protected by trees, shrubs, grasses, and other plants. However, human activities such as farming, logging, and construction, which remove or disrupt the natural vegetation, have greatly accelerated the rate of soil erosion. Without the stabilizing effect of plants, the soil is more easily swept away by the wind or carried downslope by sheet wash.

Natural rates of soil erosion vary greatly from one place to another and depend on soil characteristics as well as such factors as climate, slope, and type of vegetation. Over a broad area, erosion caused by surface runoff may be estimated by determining the sediment loads of the streams that drain the region. When studies of this kind were made on a global scale, they indicated that prior to the appearance of humans, sediment transport by rivers to the ocean amounted to just over 9 billion metric tons per year. By contrast, the amount of material currently transported to the sea by rivers is about 24 billion metric tons per year, or more than two and a half times the earlier rate.



**FIGURE 6.22** Global soil regions. Worldwide distribution of the Soil Taxonomy's 12 soil orders. (After U.S. Department of Agriculture, Natural Resources Conservation Service, World Soil Resources Staff)

It is more difficult to measure the loss of soil due to wind erosion. However, the removal of soil by wind is generally much less significant than erosion by flowing water except during periods of prolonged drought. When dry conditions prevail, strong winds can remove large quantities of soil from unprotected fields (Figure 6.25). Such was the case in the 1930s in the portions of the Great Plains that came to be called the Dust Bowl (see Box 6.4).

In many regions the rate of soil erosion is significantly greater than the rate of soil formation. This means that a renewable resource has become nonrenewable in these places. At present, it is estimated that topsoil is eroding faster than
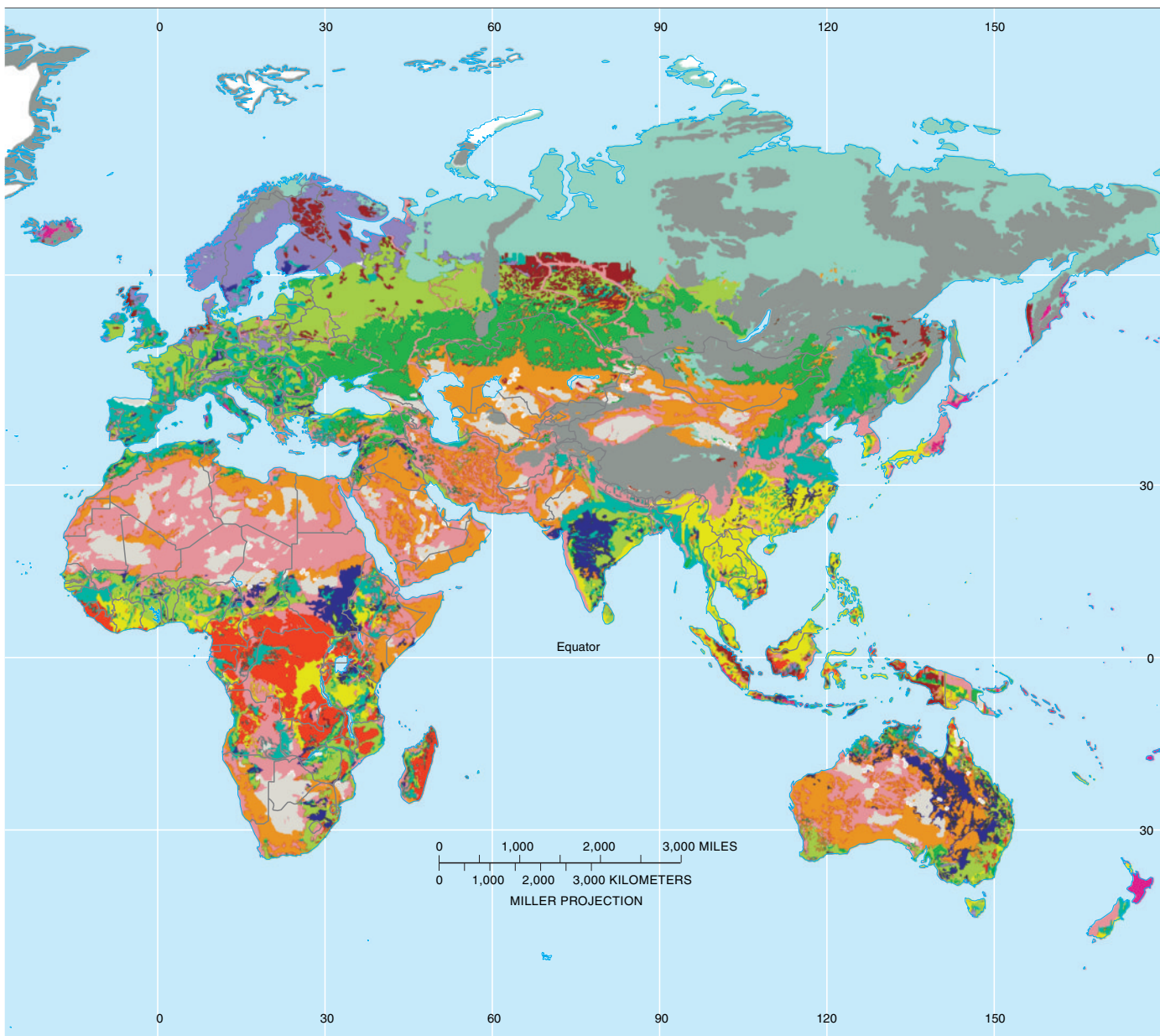
**FIGURE 6.23**    When it is raining, millions of water drops are falling at velocities approaching 10 meters per second (35 kilometers per hour). When water drops strike an exposed surface, soil particles may splash as high as 1 meter into the air and land more than a meter away from the point of raindrop impact. Soil dislodged by splash erosion is more easily moved by sheet erosion. (Photo courtesy of U.S.D.A./Natural Resources Conservation Service)

BOX 6.3 ▶ PEOPLE AND THE ENVIRONMENT

## Clearing the Tropical Rain Forest—The Impact on Its Soils

Thick red soils are common in the wet tropics and subtropics. They are the end product of extreme chemical weathering. Because lush tropical rain forests are associated with these soils, we might assume they are fertile and have great potential for agriculture. However, just the opposite is true—they are among the poorest soils for farming. How can this be?

Because rain forest soils develop under conditions of high temperature and heavy rainfall, they are severely leached. Not only does leaching remove the soluble materials such as calcium carbonate but the great quantities of percolating water also remove much of the silica, with the result that insoluble oxides of iron and aluminum become concentrated in the soil. Iron oxides give the soil its distinctive red color. Because bacterial activity is very high in the tropics, rain forest soils contain practically no humus. Moreover, leaching destroys fertility because most plant nutrients are removed by the large volume of downward-percolating water. Therefore, even though the vegetation may be dense and luxuriant, the soil itself contains few available nutrients.

Most nutrients that support the rain forest are locked up in the trees themselves. As vegetation dies and decomposes, the



**FIGURE 6.E**    Clearing the tropical rain forest in West Kalimantan (Borneo), Indonesia. The thick soil is highly leached. (Photo by Wayne Lawler/Photo Researchers, Inc.)

**FIGURE 6.24**    **A.** Soil erosion from this field in northeastern Wisconsin is obvious. Just 1 millimeter of soil lost from a single acre of land amounts to about five tons. (Photo by D. P. Burnside/Photo Researchers, Inc.) **B.** Gully erosion is severe in this poorly protected soil in southern Colombia. (Photo by Carl Purcell/Photo Researchers, Inc.)

**A.**



**B.**

**FIGURE 6.F**  This ancient temple at Angkor Wat, Cambodia, was built of bricks made of laterite. (Photo by R. Ian Lloyd/The Stock Market)

roots of the rain forest trees quickly absorb the nutrients before they are leached from the soil. The nutrients are continuously recycled as trees die and decompose.

Therefore, when forests are cleared to provide land for farming or to harvest the timber, most of the nutrients are removed as well (Figure 6.E). What remains is a soil that contains little to nourish planted crops.

The clearing of rain forests not only removes plant nutrients but also accelerates erosion. When vegetation is present, its roots anchor the soil, and its leaves and branches provide a canopy that protects the ground by deflecting the full force of the frequent heavy rains.

The removal of vegetation also exposes the ground to strong direct sunlight. When baked by the Sun, these tropical soils can

harden to a bricklike consistency and become practically impenetrable to water and crop roots. In only a few years, soils in a freshly cleared area may no longer be cultivable.

The term *laterite,* which is often applied to these soils, is derived from the Latin word *latere,* meaning "brick," and was first applied to the use of this material for brickmaking in India and Cambodia. Laborers simply excavated the soil, shaped it, and allowed it to harden in the Sun. Ancient but still well-preserved structures built of laterite remain standing today in the wet tropics (Figure 6.F). Such structures have withstood centuries of weathering because all of the original soluble materials were already removed from the soil by chemical weathering. Laterites are therefore virtually insoluble and very stable.

In summary, we have seen that some rain forest soils are highly leached products of extreme chemical weathering in the warm, wet tropics. Although they may be associated with lush tropical rain forests, these soils are unproductive when vegetation is removed. Moreover, when cleared of plants, these soils are subject to accelerated erosion and can be baked to bricklike hardness by the Sun.



A.

B.

**FIGURE 6.25    A.** Windbreaks protecting wheat fields in North Dakota. These flat expanses are susceptible to wind erosion especially when the fields are bare. The rows of trees slow the wind and deflect it upward, which decreases the loss of fine soil particles. (Photo by Erwin C. Cole/ U.S.D.A./Natural Resources Conservation Service) **B.** This windbreak of conifers in Indiana provides year-round protection from wind erosion for this cropland. (Photo by Erwin C. Cole/U.S.D.A./Natural Resources Conservation Service)

BOX 6.4 ▶ PEOPLE AND THE ENVIRONMENT

## Dust Bowl—Soil Erosion in the Great Plains

During a span of dry years in the 1930s, large dust storms plagued the Great Plains. Because of the size and severity of these storms, the region came to be called the Dust Bowl, and the time period the Dirty Thirties. The heart of the Dust Bowl was nearly 100 million acres in the panhandles of Texas and Oklahoma and adjacent parts of Colorado, New Mexico, and Kansas (Figure 6.G). To a lesser extent, dust storms were also a problem over much of the Great Plains, from North Dakota to west-central Texas.

At times dust storms were so severe that they were called "black blizzards" and "black rollers" because visibility was reduced to only a few feet. Numerous storms lasted for hours and stripped huge volumes of topsoil from the land.

In the spring of 1934, a windstorm that lasted for a day and a half created a dust cloud 2000 kilometers (1200 miles) long. As the sediment moved east, New York had "muddy rains" and Vermont "black snows." Another storm carried dust more than 3 kilometers (2 miles) into the atmosphere and transported it 3000 kilometers from its source in Colorado to create "midday twilight" in New England and New York.

What caused the Dust Bowl? Clearly, the fact that portions of the Great Plains experienced some of North America's strongest winds is important. However, it was the expansion of agriculture that set the stage for the disastrous period of



**FIGURE 6.G**    An abandoned farmstead shows the disastrous effects of wind erosion and deposition during the Dust Bowl period. This photo of a previously prosperous farm was taken in Oklahoma in 1937. Also see Figure 19.10, p. 000. (Photo courtesy of Soil Conservation Service, U.S. Department of Agriculture)

soil erosion. Mechanization allowed the rapid transformation of the grass-covered prairies of this semiarid region into farms. Between the 1870s and 1930, cultivation expanded nearly tenfold, from about 10 million acres to more than 100 million acres.

As long as precipitation was adequate, the soil remained in place. However, when a prolonged drought struck in the 1930s, the unprotected fields were vulnerable to

the wind. The result was severe soil loss, crop failure, and economic hardship.

Beginning in 1939, a return to rainier conditions brought relief. New farming practices that reduced soil loss by wind were instituted. Although dust storms are less numerous and not as severe as in the Dirty Thirties, soil erosion by strong winds still occurs periodically whenever the combination of drought and unprotected soil exists.

## *Students Sometimes Ask . . .*

*Is the amount of farmland in the United States and worldwide shrinking?*

Yes, indeed. It's been estimated that between 3 and 5 million acres of prime U.S. farmland are lost each year through mismanagement (including soil erosion) and conversion to non-agricultural uses. According to the United Nations, since 1950, more than one-third of the world's farmable land has been lost to soil erosion.

it forms on more than one-third of the world's croplands. The result is lower productivity, poorer crop quality, reduced agricultural income, and an ominous future.

## Sedimentation and Chemical Pollution

Another problem related to excessive soil erosion involves the deposition of sediment. Each year in the United States hundreds of millions of tons of eroded soil are deposited in lakes, reservoirs, and streams. The detrimental impact of this process can be significant. For example, as more and more sediment is deposited in a reservoir, the capacity of the reser-

voir is diminished, limiting its usefulness for flood control, water supply, and/or hydroelectric power generation. In addition, sedimentation in streams and other waterways can restrict navigation and lead to costly dredging operations.

In some cases soil particles are contaminated with pesticides used in farming. When these chemicals are introduced into a lake or reservoir, the quality of the water supply is threatened and aquatic organisms may be endangered. In addition to pesticides, nutrients found naturally in soils as well as those added by agricultural fertilizers make their way into streams and lakes, where they stimulate the growth of plants. Over a period of time, excessive nutrients accelerate the process by which plant growth leads to the depletion of oxygen and an early death of the lake.

The availability of good soils is critical if the world's rapidly growing population is to be fed. On every continent, unnecessary soil loss is occurring because appropriate conservation measures are not being used. Although it is a recognized fact that soil erosion can never be completely eliminated, soil conservation programs can substantially reduce the loss of this basic resource. Windbreaks (rows of trees), terracing, and plowing along the contours of hills are some of the effective measures, as are special tillage practices and crop rotation.

## Summary

- External processes include (1) *weathering*—the disintegration and decomposition of rock at or near Earth's surface; (2) *mass wasting*—the transfer of rock material downslope under the influence of gravity; and (3) *erosion*—the removal of material by a mobile agent, usually water, wind, or ice. They are called *external processes* because they occur at or near Earth's surface and are powered by energy from the Sun. By contrast, *internal processes,* such as volcanism and mountain building, derive their energy from Earth's interior.

- *Mechanical weathering* is the physical breaking up of rock into smaller pieces. Rocks can be broken into smaller fragments by *frost wedging* (where water works its way into cracks or voids in rock and, upon freezing, expands and enlarges the openings), *salt crystal growth, unloading* (expansion and breaking due to a great reduction in pressure when the overlying rock is eroded away), *thermal expansion* (weakening of rock as the result of expansion and contraction as it heats and cools), and *biological activity* (by humans, burrowing animals, plant roots, etc.).

- *Chemical weathering* alters a rock's chemistry, changing it into different substances. Water is by far the most important agent of chemical weathering. *Dissolution* occurs when water-soluble minerals such as halite become dissolved in water. Oxygen dissolved in water will *oxidize* iron-rich minerals. When carbon dioxide ($CO_2$) is dissolved in water, it forms *carbonic acid,* which accelerates the decomposition of silicate minerals by *hydrolysis.* The chemical weathering of silicate minerals frequently produces (1) soluble products containing sodium, calcium, potassium, and magnesium ions, and silica in solution; (2) insoluble iron oxides; and (3) clay minerals.

- The rate at which rock weathers depends on such factors as (1) *particle size*—small pieces generally weather faster than large pieces; (2) *mineral makeup*—calcite readily dissolves in mildly acidic solutions, and silicate minerals that form first from magma are least resistant to chemical weathering; and (3) *climatic factors,* particularly temperature and moisture. Frequently, rocks exposed at Earth's surface do not weather at the same rate. This *differential weathering* of rocks is influenced by such factors as mineral makeup and degree of jointing.

- *Soil* is a combination of mineral and organic matter, water, and air—the portion of the *regolith* (the layer of rock and mineral fragments produced by weathering) that supports the growth of plants. About half of the total volume of a good-quality soil is a mixture of disintegrated and decomposed rock (mineral matter) and *humus* (the decayed remains of animal and plant life); the remaining half consists of pore spaces, where air and water circulate. The most important factors that control soil formation are *parent material, time, climate, plants* and *animals,* and *slope.*

- Soil-forming processes operate from the surface downward and produce zones or layers in the soil that are called *horizons.* From the surface downward, the soil horizons are respectively designated as *O* (largely organic matter), *A* (largely mineral matter), *E* (where the fine soil components and soluble materials have been removed by *eluviation* and *leaching*), *B* (or *subsoil,* often referred to as the *zone of accumulation*), and *C* (partially altered parent material). Together the *O* and *A* horizons make up what is commonly called the *topsoil.*

- In the United States, soils are classified using a system known as the *Soil Taxonomy.* It is based on physical and chemical properties of the soil profile and includes six hierarchical categories. The system is especially useful for agricultural and related land-use purposes.

- Soil erosion is a natural process; it is part of the constant recycling of Earth materials that we call the rock cycle. Once in a stream channel, soil particles are transported downstream and eventually deposited. *Rates of soil erosion* vary from one place to another and depend on the soil's characteristics as well as such factors as climate, slope, and type of vegetation.

## Review Questions

1. Describe the role of external processes in the rock cycle.

2. If two identical rocks were weathered, one mechanically and the other chemically, how would the products of weathering for the two rocks differ?

3. In what type of environment is frost wedging most effective?

4. Describe the formation of an exfoliation dome. Give an example of such a feature.

5. How does mechanical weathering add to the effectiveness of chemical weathering?

6. Granite and basalt are exposed at the surface in a hot, wet region.

   a. Which type of weathering will predominate?

   b. Which of these rocks will weather most rapidly? Why?

7. Heat speeds up a chemical reaction. Why then does chemical weathering proceed slowly in a hot desert?

8. How is carbonic acid ($H_2CO_3$) formed in nature? What results when this acid reacts with potassium feldspar?

9. List some possible environmental effects of acid precipitation (see Box 6.1).

10. What is the difference between soil and regolith?

11. What factors might cause different soils to develop from the same parent material, or similar soils to form from different parent materials?

12. Which of the controls of soil formation is most important? Explain.

13. How can topography influence the development of soil? What is meant by the term *slope orientation?*

14. List the characteristics associated with each of the horizons in a well-developed soil profile. Which of the horizons constitute the solum? Under what circumstances do soils lack horizons?

15. The tropical soils described in Box 6.3 support luxuriant rain forests yet are considered to have low fertility. Explain.

16. List three detrimental effects of soil erosion other than the loss of topsoil from croplands.

17. Briefly describe the conditions that led to the Dust Bowl of the 1930s (see Box 6.3).

## Key Terms

chemical weathering (p. 166)
differential weathering (p. 177)
dissolution (p. 171)
eluviation (p. 182)
erosion (p. 166)
exfoliation dome (p. 169)

external process (p. 166)
frost wedging (p. 167)
horizon (p. 181)
humus (p. 179)
hydrolysis (p. 173)
internal process (p. 166)
leaching (p. 182)
mass wasting (p. 166)

mechanical weathering (p. 166)
oxidation (p. 173)
parent material (p. 179)
regolith (p. 178)
sheeting (p. 169)
soil (p. 178)
soil profile (p. 181)

Soil Taxonomy (p. 183)
solum (p. 182)
spheroidal weathering (p. 176)
talus slope (p. 167)
weathering (p. 166)

## Web Resources

The *Earth* Website uses the resources and flexibility of the Internet to aid in your study of the topics in this chapter. Written and developed by geology instructors, this site will help improve your understanding of geology. Visit **http://www.prenhall.com/tarbuck** and click on the cover of *Earth 9e* to find:

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• Critical writing exercises.

• Links to chapter-specific Web resources.

• Internet-wide key-term searches.

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