Weathering and Soil

Differential weathering and erosion at Bryce Canyon National Park in Utah has produced spires in the sandstone beds. *Photo © Doug Sherman/Geofile*

LEARNING OBJECTIVES

- Why is weathering important to life on Earth?
- Explain the differences between and the processes involved in mechanical and chemical weathering.
- Name and describe the types of features formed by weathering.
- Discuss the role of acids in chemical weathering, and list the weathering products of the common rock-forming minerals.

- Describe the factors that affect the formation of soil.
- Name and sketch the soil horizons that form in a humid climate, and explain how the layers form.

In this chapter, you will study several visible signs of weathering in the world around you, ranging from the cliffs and slopes of the Grand Canyon to the rounded edges of boulders. As you study these features, keep in mind that weathering processes make the planet suitable for human habitation. The weathering of rock affects the composition of Earth's atmosphere, helping to maintain a habitable climate. Weathering also produces soils, upon which grow the forests, grasslands, and agriculture of the world.

How does rock weather? You learned in chapters 3 and 4 that the minerals making up igneous rocks crystallize at relatively high temperatures and sometimes at high pressures as magma and lava cool. Although these minerals are stable when they form, most of them are not stable during prolonged exposure at the surface. In this chapter, you see how minerals and rocks change when they are subjected to the physical and chemical conditions existing at the surface. Rocks undergo mechanical weathering (physical disintegration) and chemical weathering (decomposition) as they are attacked by air, water, and microorganisms. Your knowledge of the chemical composition and atomic structure of minerals will help you understand the reactions that occur during chemical weathering.

Weathering processes create sediments (primarily mud and sand) and soil. Sedimentary rocks, which form from sediments, are discussed in chapter 6. In a general sense, weathering prepares rocks for erosion and is a fundamental part of the rock cycle (figure 5.1), transforming rocks into the raw material that eventually becomes sedimentary rocks. Through weathering, there are important links between the rock cycle and the atmosphere and biosphere.

WEATHERING, EROSION, AND TRANSPORTATION

Rocks exposed at Earth's surface are constantly being changed by water, air, varying temperature, and other environmental factors. Granite may seem indestructible, but given time and exposure to air and water, it can decompose and disintegrate into soil. The processes that affect rock are *weathering, erosion,* and *transportation.*

The term **weathering** refers to the processes that change the physical and chemical character of rock at or near the surface. For example, if you abandon a car, particularly in a wet climate, eventually the paint will flake off and the metal will

rust. The car weathers. Similarly, the tightly bound crystals of any rock can be loosened and altered to new minerals when exposed to air and water during weathering. Weathering breaks down rocks that are either stationary or moving.

Erosion is the picking up or *physical removal* of rock particles by an agent such as ocean waves, running water, or glaciers. Weathering helps break down a solid rock into loose particles that are easily eroded. Rainwater flowing down a cliff or hillside removes the loose particles produced by weathering. Similarly, if you sandblast rust off of a car, erosion takes place. Humans, of course, are awesome agents of erosion. A single pass by a bulldozer can do more to change a landscape than thousands of years of natural weathering and erosion.

After a rock fragment is picked up (eroded), it is transported. **Transportation** is the movement of eroded particles by agents such as rivers, waves, glaciers, or wind. Weathering processes continue during transportation. A boulder being transported by a stream can be physically worn down and chemically altered as it is carried along by the water. In the car analogy,
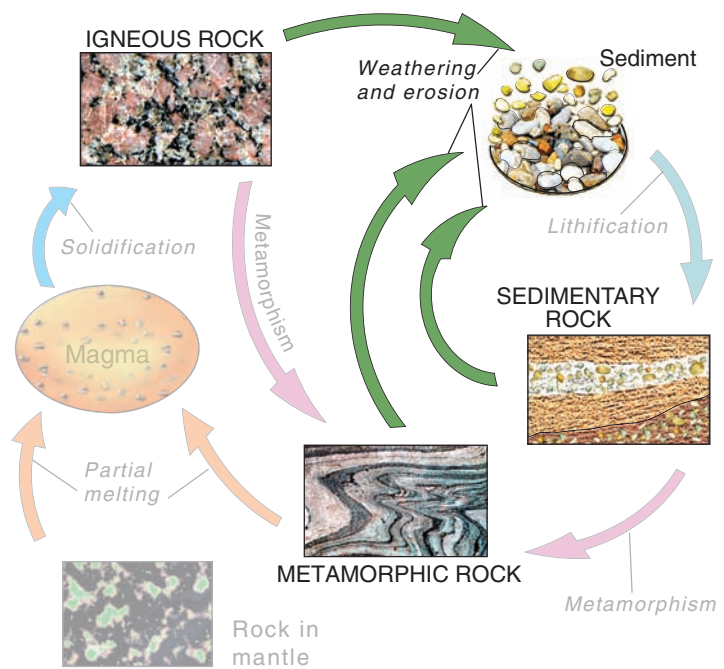

FIGURE 5.1

The rock cycle shows how rocks can be weathered and eroded and recycled into sediment to form new rocks.

transportation would take place when a stream of rust-bearing water flows away from a car in which rust is being hosed off.

Water is necessary for chemical weathering to take place. Oxygen dissolved in water oxidizes iron in rocks. Carbon dioxide mixed with water makes a weak acid that causes most minerals to decompose; this acid is the primary cause of chemical weathering. Running water contributes to weathering and erosion by loosening and removing particles and by abrading rocks during transportation in streams. Ice in glaciers is a very effective agent of erosion as rocks frozen in the base of a glacier grind down the underlying bedrock. Freezing and thawing of water in cracks in rock is also very effective at mechanically breaking them up.

HOW WEATHERING CHANGES ROCKS

Rocks undergo both mechanical weathering and chemical weathering. **Mechanical weathering** (physical disintegration) includes several processes that break rock into smaller pieces. The change in the rock is physical; there is little or no chemical change. For example, water freezing and expanding in cracks can cause rocks to disintegrate physically. **Chemical weathering** is the decomposition of rock from exposure to water and atmospheric gases (principally carbon dioxide, oxygen, and water vapor). As rock is decomposed by these agents, new chemical compounds form.

Mechanical weathering breaks up rock but does not change the composition. A large mass of granite may be broken into smaller pieces by frost action, but its original crystals of quartz, feldspar, and ferromagnesian minerals are unchanged. On the other hand, if the granite is being chemically weathered, some of the original minerals are chemically changed into different minerals. Feldspar, for example, will change into a clay mineral (with a crystal structure similar to mica). In nature, mechanical and chemical weathering usually occur together, and the effects are interrelated.

Weathering is a relatively long, slow process. Typically, cracks in rock are enlarged gradually by frost action or plant growth (as roots pry into rock crevices), and as a result, more surfaces are exposed to attack by chemical agents. Chemical weathering initially works along contacts between mineral grains. Tightly bound crystals are loosened as weathering products form at their contacts. Mechanical and chemical weathering then proceed together, until a once tough rock slowly crumbles into individual grains.

Solid minerals are not the only products of chemical weathering. Some minerals—calcite, for example—dissolve when chemically weathered. We can expect limestone and marble, rocks consisting mainly of calcite, to weather chemically in quite a different way than granite.

EFFECTS OF WEATHERING

The results of chemical weathering are easy to find. Look along the edges or corners of old stone structures for evidence. The

A
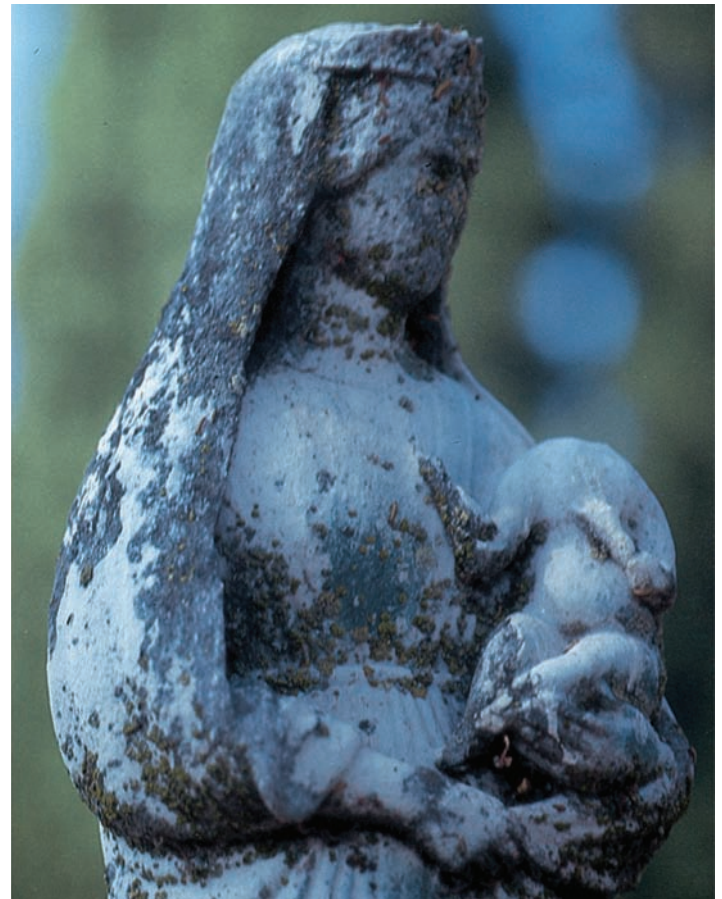
B

FIGURE 5.2

(*A*) The effects of chemical weathering are obvious in the marble gravestone on the right but not in the slate gravestone on the left, which still retains its detail. Both gravestones date to the 1780s. (*B*) This marble statue has lost most of the fine detail on the face and the baby's head has been dissolved by chemical weathering. *Photo A by C. C. Plummer; photo B by David McGeary*

inscriptions on statues and gravestones that have stood for several decades may no longer be sharp (figure 5.2). Building blocks of limestone or marble exposed to rain and atmospheric gases may show solution effects of chemical weathering in a surprisingly short time. Granite and slate gravestones and building materials are much more resistant to weathering due to the strong silicon-oxygen bonds in the silicate minerals. However, after centuries, the mineral grains in granite may be loosened, cracks enlarged, and the surface discolored and dulled by the products of weathering. Surface discoloration is also common on rock *outcrops,* where rock is exposed to view, with no plant or soil cover. That is why field geologists carry rock hammers—to break rocks to examine unweathered surfaces.

We tend to think of weathering as destructive because it mars statues and building fronts. As rock is destroyed, however, valuable products can be created. Soil is produced by rock weathering, so most plants depend on weathering for the soil they need in order to grow. In a sense, then, all agriculture depends on weathering. Weathering products transported to the sea by rivers as dissolved solids make seawater salty and serve as nutrients for many marine organisms. Some metallic ores, such as those of copper and aluminum, are concentrated into economic deposits by chemical weathering.

Weathering has also had a dramatic impact on the composition of Earth's atmosphere. Chemical weathering removes carbon dioxide from the atmosphere, allowing it to be transformed into limestone and stored in the crust. Without chemical weathering, the elevated levels of carbon dioxide in the atmosphere would have long ago made Earth too hot to sustain life.

Many weathered rocks display interesting shapes. **Spheroidal weathering** occurs where rock has been rounded by weathering from an initial blocky shape. It is rounded because chemical weathering acts more rapidly or intensely on the corners and edges of a rock than on the smooth rock faces (figure 5.3).

Differential weathering describes the tendency for different types of rock to weather at different rates. For example, shale (composed of soft clay minerals) tends to weather and erode much faster than sandstone (composed of hard quartz mineral). Figure 5.4 shows a striking example of differential weathering. Figure 5.5 illustrates how layers of resistant rock tend to weather to form steep cliffs while softer layers form shallow slopes of eroded rock debris.

MECHANICAL WEATHERING

Of the many processes that cause rocks to disintegrate, the most effective are pressure release and frost action.
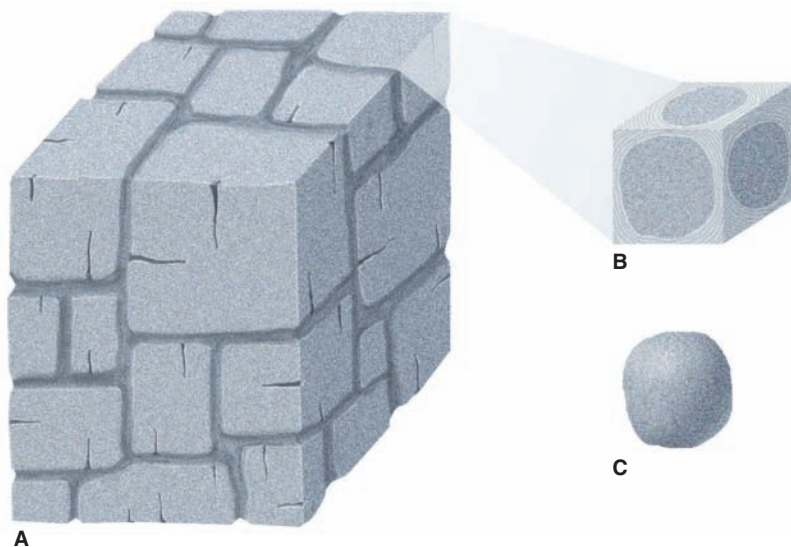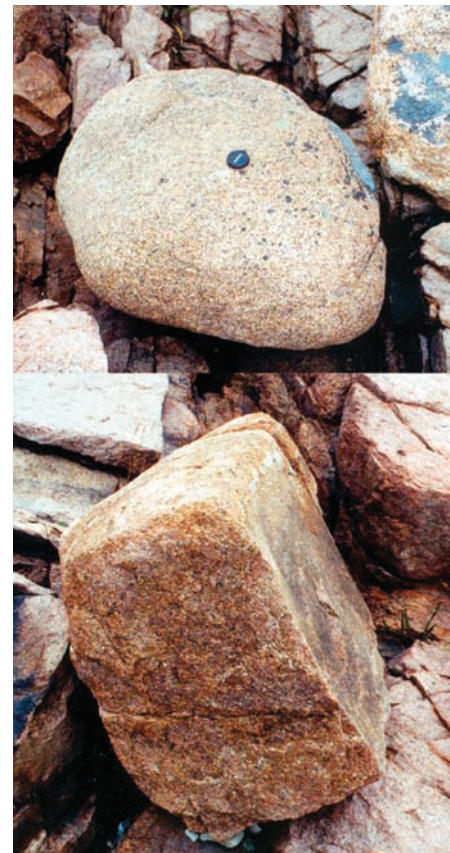

FIGURE 5.3

(*A*) Water penetrating along cracks at right angles to one another in an igneous rock produces spheroidal weathering of once-angular blocks. The increase in surface area exposed by the cracks increases chemical weathering. (*B*) Because of the increased surface area, chemical weathering attacks edges and particularly the corners more rapidly than the flat faces, creating the spheroidal shape shown in (*C*). (*D*) Newly eroded granite block with rounded corners contrasted with extensively weathered, spheroidal granite boulder, Acadia National Park, Maine. *Photo by Bret Bennington*
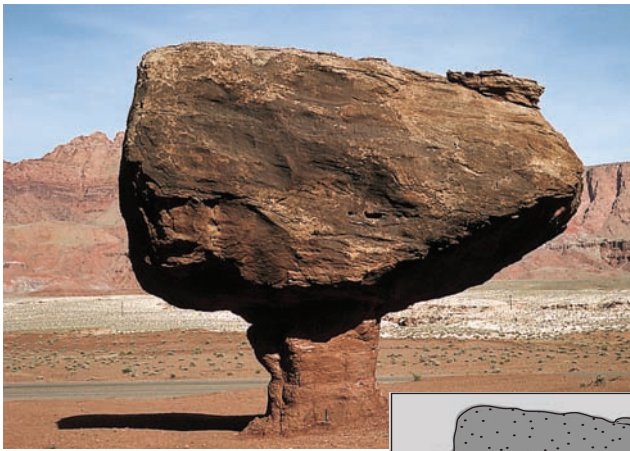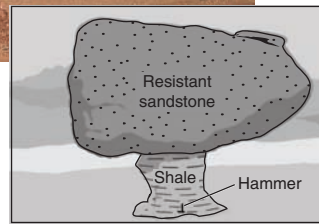
FIGURE 5.4

Pedestal rock near Lees Ferry, Arizona. Resistant sandstone cap protects weak shale pedestal from weathering and erosion. Hammer for scale is barely visible at base of pedestal. *Photo by David McGeary*

Geologist's View

Pressure Release

The reduction of pressure on a body of rock can cause it to crack as it expands; **pressure release** is a significant type of mechanical weathering. A large mass of rock, such as a batholith, originally forms under great pressure from the weight of several kilometers of rock above it. This batholith is gradually exposed by tectonic uplift of the region followed by erosion of the overlying rock (figure 5.6). The removal of the great weight of rock above the batholith, usually termed *unloading,* allows the granite to expand upward. Cracks called **sheet joints** develop parallel to the outer surface of the rock as the outer part of the rock expands more than the inner part (figures 5.6*A* and *B*). On slopes, gravity may cause the rock between such joints to break loose in concentric slabs from the underlying granite mass. This process of spalling off of rock layers is called **exfoliation**; it is somewhat similar to peeling layers from an onion. **Exfoliation domes** (figure 5.7) are large, rounded landforms developed in massive rock, such as granite, by exfoliation. Some famous examples of exfoliation domes include Stone Mountain in Georgia and Half Dome in Yosemite.

Frost Action

Did you ever leave a bottle of water in the freezer, coming back later to find the water frozen and the bottle burst open? When water freezes at 0°C (32°F), the individual water molecules jumbled together in the liquid align into an ordered crystal structure, forming ice. Because the crystal structure of ice takes up more space than the liquid, water expands 9% in volume when it freezes. This unique property makes water a potent agent of mechanical weathering in any climate where the temperature falls below freezing.

Frost action—the mechanical effect of freezing water on rocks—commonly occurs as frost wedging or frost heaving. In **frost wedging**, the expansion of freezing water pries rock apart. Most rock contains a system of cracks called *joints,* caused by the slow flexing of brittle rock by deep-seated Earth forces (see chapter 15). Water that has trickled into a joint in a rock can freeze and expand when the temperature drops below 0°C (32°F). The expanding ice wedges the rock apart, extending the joint or even breaking the rock into pieces (figure 5.8). Frost wedging is most effective in areas with many days of freezing and thawing (mountaintops and midlatitude regions with pronounced seasons). Partial thawing during the day adds new water to the ice in the crack; refreezing at night adds new ice to the old ice.

Frost heaving lifts rock and soil vertically. Solid rock conducts heat faster than soil, so on a cold winter day, the bottom of a partially buried rock will be much colder than soil at the same depth. As the ground freezes in winter, ice forms first under large rock fragments in the soil. The expanding ice layers push boulders out of the ground, a process well known to New England farmers and other residents of rocky soils. Frost heaving bulges the ground surface upward in winter, breaking up roads and leaving lawns spongy and misshapen after the spring thaw.
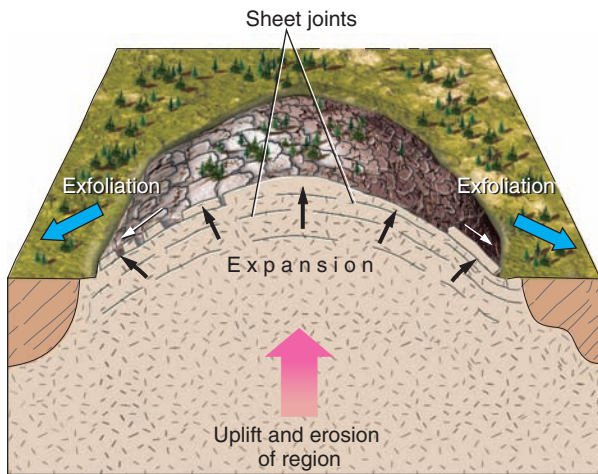
FIGURE 5.5

Sedimentary rocks in the Grand Canyon, Arizona. In the foreground, layers of sandstone resist weathering and form steep cliffs. Less resistant layers of shale weather to form gentler slopes of talus between cliffs. *Photo by David McGeary*
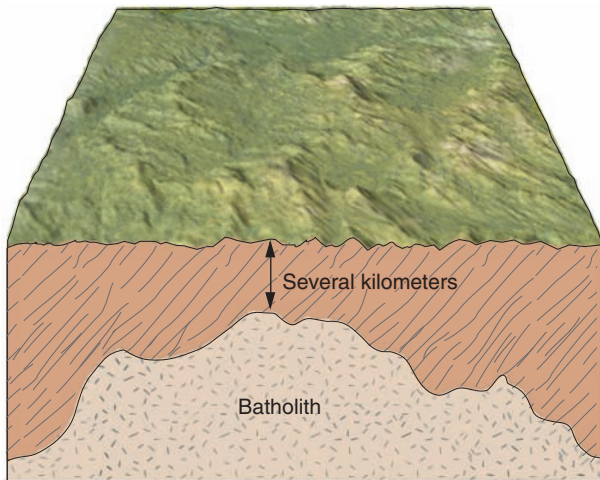
A

B

C

FIGURE 5.6

Sheet joints caused by pressure release. A granite batholith (*A*) is exposed by regional uplift followed by the erosion of the overlying rock (*B*). Unloading reduces pressure on the granite and causes outward expansion. Sheet joints are closely spaced at the surface where expansion is greatest. Exfoliation of rock layers produces rounded exfoliation domes. (*C*) Sheet joints in a granite outcrop near the top of the Sierra Nevada, California. The granite formed several kilometers below the surface and expanded outward when it was exposed by uplift and erosion. *Photo by David McGeary*
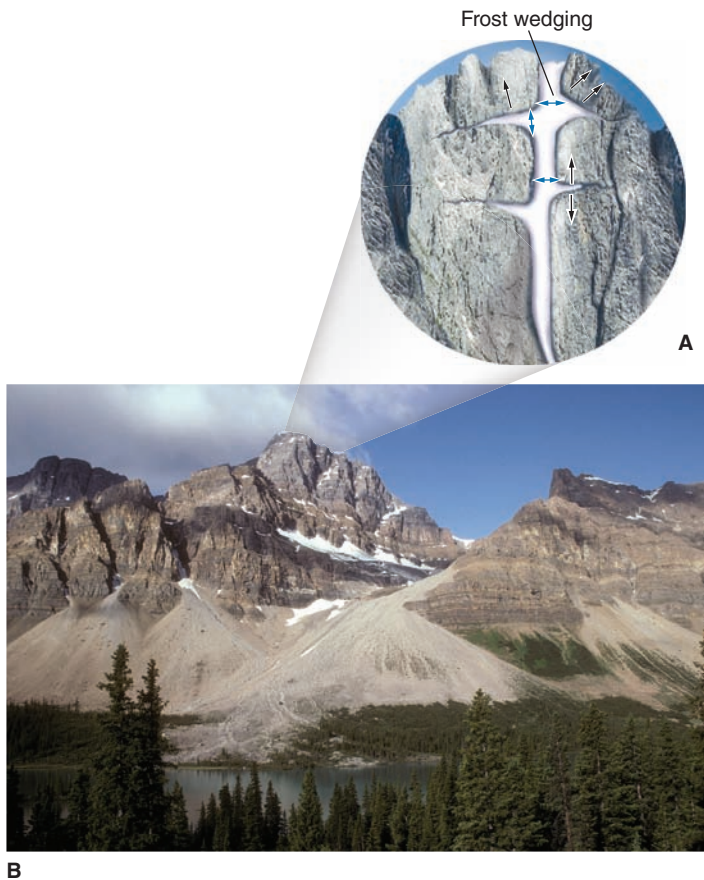

FIGURE 5.7

Half Dome in Yosemite National Park, California, is an example of an exfoliation dome. Note the onion-like layers of rock that are peeling off the dome, and the climbers on a cable ladder for scale. *Photo © by Dean Conger/CORBIS*

Other Processes

Several other processes mechanically weather rock but in most environments are less effective than frost action and pressure release. *Plant growth,* particularly roots growing in cracks (figure 5.9*A*), can break up rocks, as can *burrowing animals.* Such activities help to speed up chemical weathering by enlarging passageways for water and air. *Extreme changes in temperature,* as in a desert environment (figure 5.9*B*) or in a forest fire, can cause a rock to expand until it cracks. The *pressure of salt crystals* formed as water evaporates inside small spaces in rock also helps to disintegrate desert rocks. Whatever processes of mechanical weathering are at work, as rocks disintegrate into smaller fragments, the total surface area increases (figure 5.10), allowing more extensive chemical weathering by water and air.

CHEMICAL WEATHERING

The processes of chemical weathering, or *rock decomposition,* transform rocks and minerals exposed to water and air into new chemical products. A mineral that crystallized deep underground from a water-deficient magma may eventually be exposed at the surface, where it can react with the abundant water there to form a new, different mineral. A mineral containing very little oxygen may react with oxygen in the air, extracting oxygen atoms from the atmosphere and incorporating them into its own crystal structure, thus forming a different mineral. These new minerals are weathering products. They have adjusted to physical and chemical conditions at (or near) Earth's surface. Minerals change gradually at the surface until

Frost wedging

A

B

FIGURE 5.8

(*A*) Frost wedging occurs when water fills joints (cracks) in a rock and then freezes. The expanding ice wedges the rock apart. (*B*) Frost wedging has broken the rock and sculpted Crawford Mountain in Banff National Park, Alberta, Canada. The broken rock forms cone-shaped piles of debris (talus) at the base of the mountains. *Photo B by Marli Miller*

they come into *equilibrium,* or balance, with the surrounding conditions.

Role of Oxygen

Oxygen is abundant in the atmosphere and quite active chemically, so it often combines with minerals or with elements within minerals that are exposed at Earth's surface.

The rusting of an iron nail exposed to air is a simple example of chemical weathering. Oxygen from the atmosphere combines with the iron to form iron oxide, the reaction being expressed as follows:

$$4Fe^{+3} + 3O_2 \rightarrow 2Fe_2O_3$$
$$\text{iron} + \text{oxygen} \rightarrow \text{iron oxide}$$
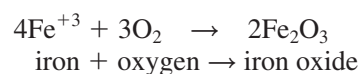
Iron oxide formed in this way is a weathering product of numerous minerals containing iron, such as the ferromagnesian group (pyroxenes, amphiboles, biotite, and olivine). The iron in the ferromagnesian silicate minerals must first be separated from the silica in the crystal structure before it

A

B

FIGURE 5.9

(*A*) Tree roots will pry this rock apart as they grow within the rock joints, Sierra Nevada Mountains, California. (*B*) This rock is being broken by the extreme temperature variation in a desert, Mojave Desert, California. Note the tremendous increase in surface area that results from the rock being split into layers. *Photo A by Diane Carlson; photo B by Crystal Hootman and Diane Carlson*

can oxidize. The iron oxide (Fe_2O_3) formed is the mineral **hematite**, which has a brick-red color when powdered. If water is present, as it usually is at Earth's surface, the iron oxide combines with water to form **limonite**, which is the name for a group of mostly amorphous, hydrated iron oxides
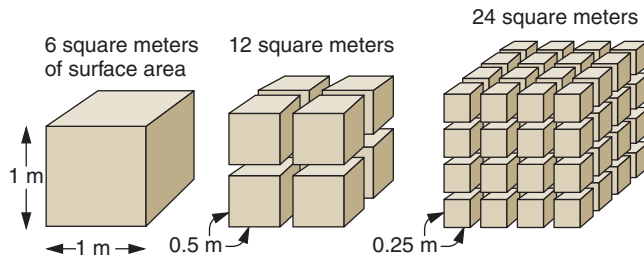
FIGURE 5.10

Mechanical weathering can increase the surface area of a rock, accelerating the rate of chemical weathering. As a cube breaks up into smaller pieces, its volume remains the same, but its surface area increases.

FIGURE 5.11

Sandstone has been colored red by hematite, released by the chemical weathering of ferromagnesian minerals, Thermopolis, Wyoming. *Photo by Diane Carlson*

(often including the mineral *goethite*), which are yellowish-brown when powdered. The general formula for this group is $Fe_2O_3 \cdot nH_2O$ (the *n* represents a small, whole number such as 1, 2, or 3 to show a variable amount of water). The brown, yellow, or red color of soil and many kinds of sedimentary rock is commonly the result of small amounts of hematite and limonite released by the weathering of iron-containing minerals (figure 5.11).

Role of Acids

The most effective agent of chemical weathering is acid. Acids are chemical compounds that give off hydrogen ions (H^+) when they dissociate, or break down, in water. Strong acids produce a great number of hydrogen ions when they dissociate, and weak acids produce relatively few such ions.

The hydrogen ions given off by natural acids disrupt the orderly arrangement of atoms within most minerals. Because a hydrogen ion has a positive electrical charge and a very small size, it can substitute for other positive ions (such as Ca^{++}, Na^+, or K^+) within minerals. This substitution changes the chemical composition of the mineral and disrupts its atomic structure. The mineral decomposes, often into a different mineral, when it is exposed to acid.

Some strong acids occur naturally on Earth's surface, but they are relatively rare. Sulfuric acid is a strong acid emitted during many volcanic eruptions. It can kill trees and cause intense chemical weathering of rocks near volcanic vents. The bubbling mud of Yellowstone National Park's mudpots (figure 5.12) is produced by rapid weathering caused by acidic sulfur gases that are given off by some hot springs. Strong acids also drain from some mines as sulfur-containing minerals such as pyrite oxidize and form acids at the surface (figure 5.13). Uncontrolled mine drainage can kill fish and plants downstream and accelerate rock weathering.

The most important natural source of acid for rock weathering at Earth's surface is dissolved carbon dioxide (CO_2) in water. Water and carbon dioxide form *carbonic acid* (H_2CO_3), a weak acid that dissociates into the hydrogen ion and the bicarbonate ion (see equation *A* in table 5.1). Even though carbonic acid is a weak acid, it is so abundant at Earth's surface that it is the single most effective agent of chemical weathering.

Earth's atmosphere (mostly nitrogen and oxygen) contains 0.03% carbon dioxide. Some of this carbon dioxide dissolves in rain as it falls, so most rain is slightly acidic when it hits the ground. Large amounts of carbon dioxide also dissolve in water that percolates through soil. The openings in soil are filled with a gas mixture that differs from air. Soil gas has a much higher content of carbon dioxide (up to 10%) than does air, because carbon dioxide is produced by the decay of organic matter

FIGURE 5.12

A mudpot of boiling mud is created by intense chemical weathering of the surrounding rock by the acid gases dissolved in a hot spring, Yellowstone National Park, Wyoming. *Photo by David McGeary*

and the respiration of soil organisms in the biosphere, such as worms. Rainwater that has trickled through soil is therefore usually acidic and readily attacks minerals in the unweathered rock below the soil (figure 5.14).

Solution Weathering

Some minerals are completely dissolved by chemical weathering. *Calcite,* for instance, goes into solution when exposed to carbon dioxide and water, as shown in equation *B* in table 5.1 and in figure 5.14. The carbon dioxide and water combine to form carbonic acid, which dissociates into the hydrogen ion and the bicarbonate ion, as you have seen, so the equation for the solution of calcite can also be written as equation *C* in table 5.1.

There are no solid products in the last part of the equation, indicating that complete solution of the calcite has occurred. Caves can form underground when flowing groundwater dissolves the sedimentary rock limestone, which is mostly calcite. Rain can discolor and dissolve statues and tombstones carved from the metamorphic rock marble, which is also mostly calcite (see figure 5.2).

Chemical Weathering of Feldspar

The weathering of feldspar is an example of the alteration of an original mineral to an entirely different type of mineral as the weathered product. When feldspar is attacked by the hydrogen ion of carbonic acid (from carbon dioxide and water), it forms clay minerals. In general, a **clay mineral** is a hydrous aluminum silicate with a sheet-silicate structure like that of mica. Therefore, the entire silicate structure of the feldspar crystal is altered by weathering: feldspar is a framework silicate, but the clay mineral product is a sheet silicate, differing both chemically and physically from feldspar.

Let us look in more detail at the weathering of feldspar (equation *D* in table 5.1). Rainwater percolates down through soil, picking up carbon dioxide from the atmosphere and the upper part of the soil. The water, now slightly acidic, comes in contact with feldspar in the lower part of the soil (figure 5.14), as shown in the first part of the equation. The acidic water reacts with the feldspar and alters it to a clay mineral.

The hydrogen ion (H^+) attacks the feldspar structure, becoming incorporated into the clay mineral product. When

FIGURE 5.13
Spring Creek debris dam collects acid mine drainage from the Iron Mountain Mines Superfund site in northern California. *Photo by Charles Alpers, U.S. Geological Survey*

TABLE 5.1　Chemical Equations Important to Weathering

A. Solution of Carbon Dioxide in Water to Form Acid

CO_2 carbon dioxide	$+$	H_2O water	$\rightleftharpoons$	H_2CO_3 carbonic acid	$\rightleftharpoons$	H^+ hydrogen ion	$+$	HCO_3^- bicarbonate ion

B. Solution of Calcite

$CaCO_3$ calcite	$+$	CO_2 carbon dioxide	$+$	H_2O water	$\rightleftharpoons$	Ca^{++} calcium ion	$+$	$2HCO_3^-$ bicarbonate ion

C. Solution of Calcite

$CaCO_3$	$+$	H^+	$+$	HCO_3^-	$\rightleftharpoons$	Ca^{++}	$+$	$2HCO_3^-$

D. Chemical Weathering of Feldspar to Form a Clay Mineral

$2KAlSi_3O_8$ potassium feldspar	$+$	$2H^+ + 2HCO_3^-$ (from CO_2 and H_2O)	$+$ H_2O	$\rightarrow$	$Al_2Si_2O_5(OH)_4$ clay mineral	$+$	$2K^+ + 2HCO_3^-$ (soluble ions)	$+$	$4\ SiO_2$ silica in solution or as fine solid particles
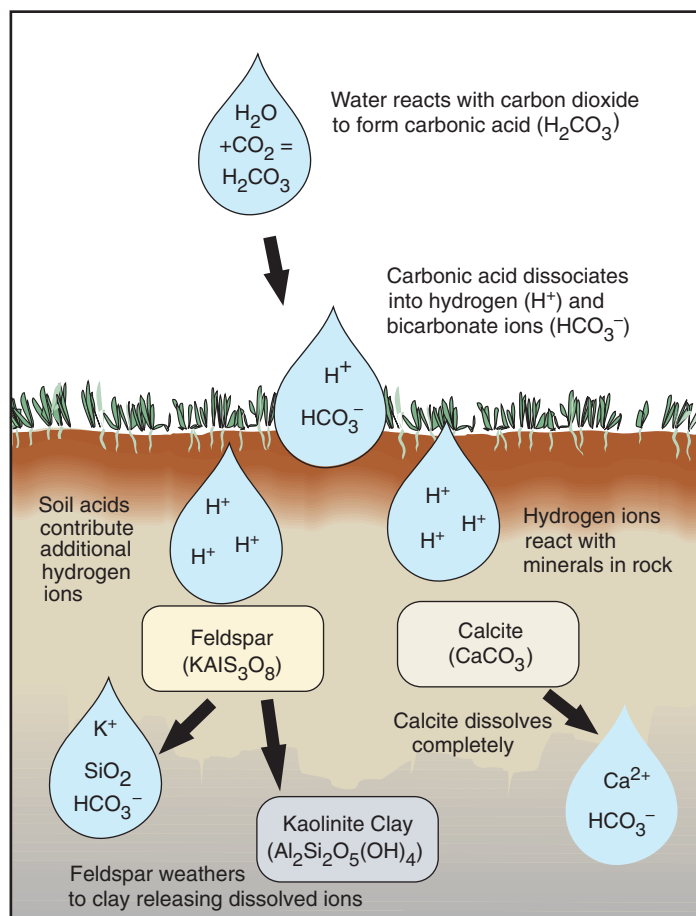
the hydrogen moves into the crystal structure, it releases potassium (K) from the feldspar. The potassium is carried away in solution as a dissolved ion (K^+). The bicarbonate ion from the original carbonic acid does not enter into the reaction; it reappears on the right side of the equation. The soluble potassium and bicarbonate ions are carried away by water (groundwater or streams).

All the silicon from the feldspar cannot fit into the clay mineral, so some is left over and is carried away as silica (SiO_2) by the moving water. This excess silica may be carried in solution or as extremely small solid particles.

The weathering process is the same regardless of the type of feldspar: K-feldspar forms potassium ions; Na-feldspar and Ca-feldspar (plagioclase) form sodium ions and calcium ions, respectively. The ions that result from the weathering of Ca-feldspar are calcium ions (Ca^{++}) and bicarbonate ions (HCO_3^-), both of which are very common in rivers and underground water, particularly in humid regions.

Chemical Weathering of Other Minerals

The weathering of ferromagnesian or dark minerals is much the same as that of feldspars. Two additional products are found on the right side of the equation—magnesium ions and iron oxides (hematite, limonite, and goethite).

The susceptibility of the rock-forming minerals to chemical weathering is dependent on the strength of the mineral's chemical bonding within the crystal framework. Because of the strength of the silicon-oxygen bond, quartz is quite resistant to chemical weathering. Thus, quartz (SiO_2) is the rock-forming mineral least susceptible to chemical attack at Earth's surface.

Ferromagnesian minerals such as olivine, pyroxene, and amphibole include other positively charged ions such as Al, Fe, Mg, and Ca. The presence of these positively charged ions in the crystal framework makes these minerals vulnerable to chemical attack due to the weaker chemical bonding between these ions and oxygen, as compared to the much stronger silicon-oxygen bonds. For example, olivine—$(Fe, Mg)_2SiO_4$—weathers rapidly because its isolated silicon-oxygen tetrahedra are held together by relatively weak ionic bonds between oxygen and iron and magnesium. These ions are replaced by H^+ ions during chemical weathering similar to that described for the feldspars.

Weathering and Diamond Concentration

Diamond is the hardest mineral known and is also extremely resistant to weathering. This is due to the very strong covalent bonding of carbon, as described in chapter 2. But diamonds are often concentrated by weathering, as illustrated in figure 5.15. Diamonds are brought to the surface of Earth in *kimberlite pipes,* columns of brecciated or broken ultramafic rock that have risen from the upper mantle. Diamonds are widely scattered in diamond pipes when they form. At the surface, the ultramafic rock in the pipe is preferentially weathered and eroded away. The diamonds, being more resistant to weathering, are left behind, concentrated in rich deposits on top of the pipes. Rivers may redistribute and reconcentrate the diamonds, as in South Africa and India. In Canada, kimberlite pipes have been eroded by glaciers, and diamonds may be found widely scattered in glacial deposits.

Weathering Products

Table 5.2 summarizes weathering products for the common minerals. Note that quartz and clay minerals commonly are left after complete chemical weathering of a rock. Sometimes other solid products, such as iron oxides, also are left after weathering.

The solution of calcite supplies substantial amounts of calcium ions (Ca^{++}) and bicarbonate ions (HCO_3^-) to underground water. The weathering of Ca-feldspars (plagioclase) into clay minerals can also supply Ca^{++} and HCO_3^- ions, as well as silica (SiO_2), to water. Under ordinary chemical
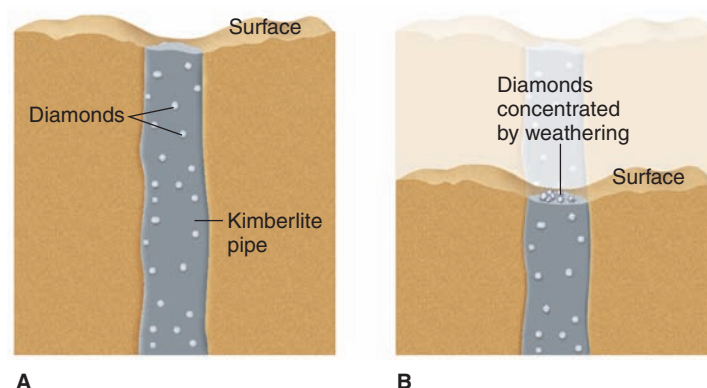

FIGURE 5.15

Residual concentration by weathering. (*A*) Cross-sectional view of diamonds widely scattered within kimberlite pipe. (*B*) Diamonds concentrated on surface by removal of rock by weathering and erosion.

circumstances, the dissolved Ca^{++} and HCO_3^- can combine to form solid $CaCO_3$ (calcium carbonate), the mineral calcite. Dissolved silica can also precipitate as a solid from underground water. This is significant because calcite and silica are the most common materials precipitated as *cement,* which binds loose particles of sand, silt, and clay into solid sedimentary rock (see chapter 6). The weathering of calcite, feldspars, and other minerals is a likely source for such cement.

If the soluble ions and silica are not precipitated as solids, they remain in solution and may eventually find their way into a stream and then into the ocean. Enormous quantities of dissolved material are carried by rivers into the sea (one estimate is 4 billion tons per year). This is the main reason seawater is salty.

Factors Affecting Weathering

The intensity of both mechanical and chemical weathering is affected by a variety of factors. Chemical weathering is largely a function of the availability of liquid water. Rock chemically weathers much faster in humid climates than in arid climates. Limestone, which is extremely susceptible to dissolution,

TABLE 5.2	Weathering Products of Common Rock-Forming Minerals		
Original Mineral	**Under Influence of CO_2 and H_2O**	**Main Solid Product**	**Other Products (Mostly Soluble)**
Feldspar	$\rightarrow$	Clay mineral +	Ions (Na^+, Ca^{++}, K^+), SiO_2
Ferromagnesian minerals (including biotite mica)	$\rightarrow$	Clay mineral +	Ions (Na^+, Ca^{++}, K^+, Mg^{++}), SiO_2, Fe oxides
Muscovite mica	$\rightarrow$	Clay mineral +	Ions (K^+), SiO_2
Quartz	$\rightarrow$	Quartz grains (sand and silt)	
Calcite	$\rightarrow$	—	Ions (Ca^{++}, HCO_3^-)

Weathering, the Carbon Cycle, and Global Climate

Weathering has affected the long-term climate of Earth by changing the carbon dioxide content of the atmosphere through the inorganic carbon cycle (see box figure 1). Carbon dioxide is a "greenhouse gas" that traps solar heat near the surface, warming the Earth. The planet Venus has a dense atmosphere composed mostly of CO_2, which traps so much solar heat that the surface temperature averages a scorching 480°C (about 900°F—see chapter 22). Earth has comparatively very little CO_2 in its atmosphere (see box table 1)—enough to keep most of the surface above freezing but not too hot to support life. However, when Earth first formed, its atmosphere was probably very much like that of Venus, with much more CO_2. What happened to most of the original carbon dioxide in Earth's atmosphere? Geologists think that a quantity of CO_2 equal to approximately 65,000 times the mass of CO_2 in the present atmosphere lies buried in the crust and upper mantle of Earth. Some of this CO_2 was used to make organic molecules during photosynthesis and is now trapped as buried organic matter and fossil fuels in sedimentary rocks. However, the majority of the missing CO_2 was converted to bicarbonate ion (HCO_3^-) during chemical weathering and is locked away in carbonate minerals (primarily $CaCO_3$) that formed layers of limestone rock.

The inorganic carbon cycle helps to regulate the climate of Earth because CO_2 is a greenhouse gas, chemical weathering accelerates with warming, and the formation of limestone occurs mostly in warm, tropical oceans. When Earth's climate is warm,

chemical weathering and the formation of limestone increase, drawing CO_2 from the atmosphere, which cools the climate. When the global climate cools, chemical weathering and limestone formation slow down, allowing CO_2 to accumulate in the atmosphere from volcanism, which warms the Earth. An increase in chemical weathering can also lead to global cooling by removing more CO_2 from the atmosphere. For example, the Cenozoic uplift and weathering of large regions of high mountains such as the Alps and the Himalaya may have triggered the global cooling that culminated in the glaciations of the Pleistocene epoch.

For more information on the carbon cycle, see box 21.2.

Additional Resource

- http://earthobservatory.nasa.gov/Features/CarbonCycle/
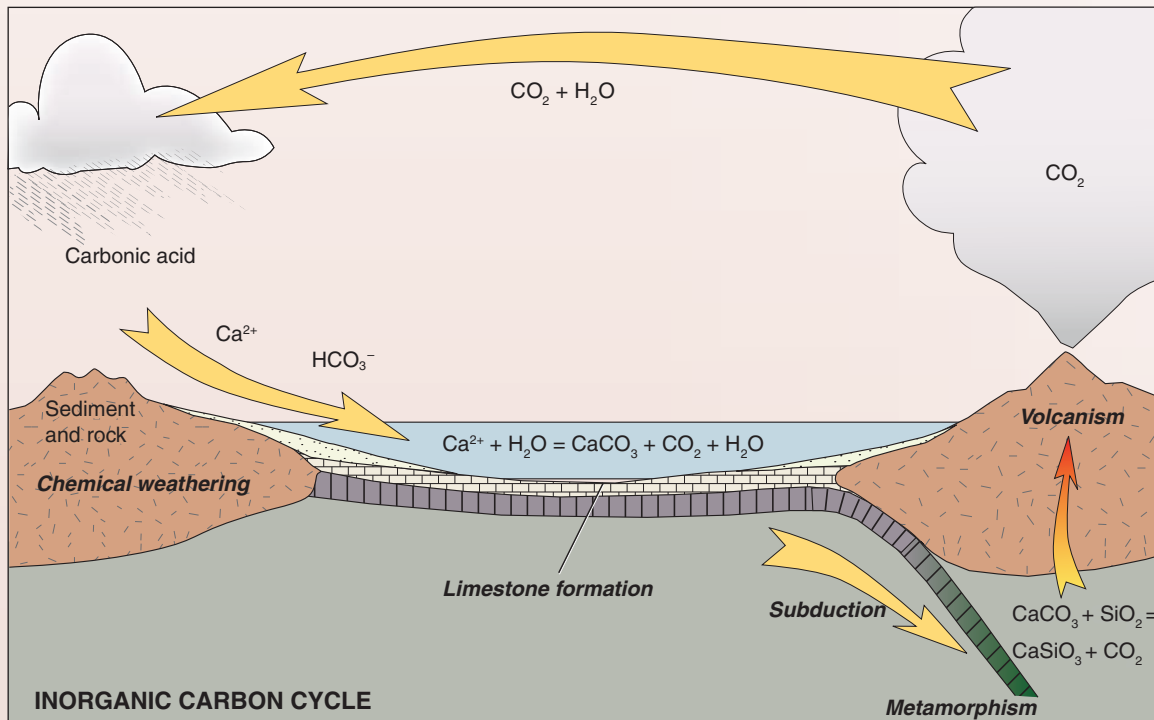
BOX 5.1 ■ FIGURE 1

Carbon dioxide dissolves in water to form carbonic acid in the atmosphere. Carbonic acid reacts with sediment and rocks during chemical weathering, releasing calcium ions and bicarbonate ions (HCO_3^-), which are carried by rivers into the sea. The precipitation of $CaCO_3$ mineral in the oceans (see chapter 6) forms layers of limestone rock. Deep burial of limestone leads to metamorphism, which causes silica and calcite to form calcium silicate minerals and carbon dioxide. The CO_2 remains trapped in Earth's interior until it is released during volcanic eruptions.

weathers quickly and tends to form valleys in wet regions such as the Appalachian Mountains. However, in the arid west, limestone is a resistant rock that forms ridges and cliffs. Temperature is also a factor in chemical weathering. The most intense chemical weathering occurs in the tropics, which are both wet and hot. Polar regions experience very little chemical weathering because of the frigid temperatures and the absence of liquid water. Mechanical weathering intensity is also related to climate (temperature and humidity), as well as to slope. Temperate climates, where abundant water repeatedly freezes and thaws, promote extensive frost weathering. Steep slopes cause rock to fall and break up under the influence of gravity. The most intense mechanical weathering probably occurs in high mountain peaks where the combination of steep slopes, precipitation, freezing and thawing, and flowing glacial ice rapidly pulverize the solid rock.

SOIL

In terms of Earth systems, soil forms an essential interface between the solid Earth (geosphere), biosphere, hydrosphere, and atmosphere. Soil is an incredibly valuable resource that supports life on Earth. In common usage, soil is the name for the loose, unconsolidated material that covers most of Earth's land surface. Geologists call this material *regolith,* however, and reserve the term **soil** for a layer of weathered, unconsolidated material that contains organic matter and is capable of supporting plant growth. A mature, fertile soil is the product of centuries of mechanical and chemical weathering of rock, combined with the addition and decay of plant and other organic matter.

An average soil is composed of 45% rock and mineral fragments (including clay), 5% decomposed organic matter, or humus, and 50% pore space. The rock and mineral fragments in a soil provide an anchoring place for the roots of plants. The clay minerals attract water molecules (figure 5.16) and plant-nutrient ions (figure 5.17), which are loosely held and available for uptake by plant roots. The humus releases weak acids that contrib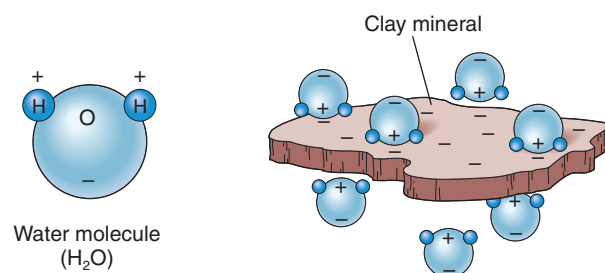ute to the chemical weathering of soil. Humus also produces plant nutrients and increases the water retention ability of the soil. The pore spaces are the final essential component of a fertile soil. Water and air circulate through the pore spaces, carrying dissolved nutrients and carbon dioxide, which is necessary for the growth of plants.

The size and number of pore spaces, and therefore the ability of a soil to transmit air and water, are largely a function of the texture of a soil. *Soil texture* refers to the proportion of different-sized particles, generally referred to as sand, silt, and clay. Quartz generally weathers into sand grains that help keep soil loose and aerated, allowing good water drainage. Partially weathered crystals of feldspar and other minerals can also form sand-sized grains. Soils with too much sand, however, can drain too rapidly and deprive plants of necessary water.

Clay minerals occur as microscopic plates and help hold water and plant nutrients in a soil. Because of ion substitution within their sheet-silicate structure, most clay minerals have a negative electrical charge on the flat surfaces of the plates. This negative charge attracts water and nutrient ions to the clay mineral (figure 5.17). Plant nutrients, such as Ca^{++} and K^+, commonly supplied by the weathering of minerals such as feldspar, are also held loosely on the surface of clay minerals. A plant root is able to release H^+ from organic acids and exchange it for the Ca^{++} and K^+ that the plant needs for healthy growth (figure 5.17). Too much clay in a soil may pack together closely, though, causing pore spaces to be too small to allow water to drain properly. Too much water in the soil and not enough air may cause plant roots to rot and die.

Silt particles are between sand and clay in size. A soil with approximately equal parts sand, silt, and clay is referred to as **loam**. Loamy soils are well-drained, may contain organic matter, and are often very fertile and productive.

Soil Horizons

As soils mature, distinct layers appear in them (figure 5.18). Soil layers are called **soil horizons** and can be distinguished from one another by appearance and chemical composition.

FIGURE 5.16

Negative charge on the outside of a platy clay mineral attracts the positive end of a water molecule.
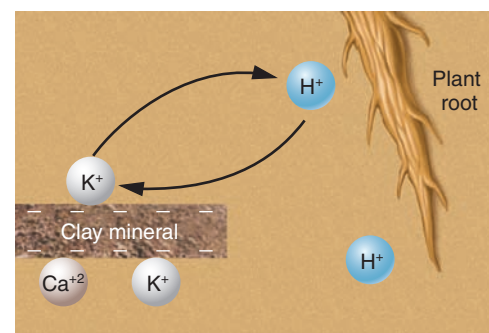

FIGURE 5.17

A plant root releases H^+ (hydrogen) ions from organic acids and exchanges them for plant-nutrient ions held by clay minerals.

Boundaries between soil horizons are usually transitional rather than sharp. By observing a vertical cross section, or *soil profile,* various horizons can be identified.

The **O horizon** is the uppermost layer that consists entirely of organic material. Ground vegetation and recently fallen leaves and needles are included in this horizon, as well as highly decomposed plant material called humus. The humus from the O horizon mixes with weathered mineral matter just below to form the **A horizon**, a dark-colored soil layer that is rich in organic matter and high in biological activity, both plant and animal. The two upper horizons are often referred to as *topsoil.*

Organic acids and carbon dioxide produced by decaying plants in the topsoil percolate down into the **E horizon**, or **zone of leaching**, and help dissolve minerals such as iron and calcium. The downward movement of water in the E horizon carries the dissolved minerals, and fine-grained clay minerals as well, into the soil layer below. This leaching (or *eluviation*) of clay and soluble minerals can make the E horizon pale and sandy.

The material leached downward from the E horizon accumulates in the **B horizon**, or **zone of accumulation**. This layer is often quite clayey and stained red or brown by hematite and limonite. Calcite may also build up in B horizons. This horizon is frequently called the *subsoil.* Within the B horizon, a hard layer of Earth material called *hardpan* may form in wet climates where clay minerals, silica, and iron compounds have accumulated in the B horizon from eluviation of the overlying E horizon. A hardpan layer is very difficult to dig or drill through and may even be too hard for backhoes to dig through; planting a tree in a lawn with a hardpan layer may require a jackhammer. Tree roots may grow laterally along rather than down through hardpan; such shallow-rooted trees are usually uprooted by the wind.

The **C horizon** is incompletely weathered parent material that lies below the B horizon. The parent material is commonly subjected to mechanical and chemical weathering from frost action, roots, plant acids, and other agents. The C horizon is transitional between the unweathered rock or sediment below and the developing soil above.
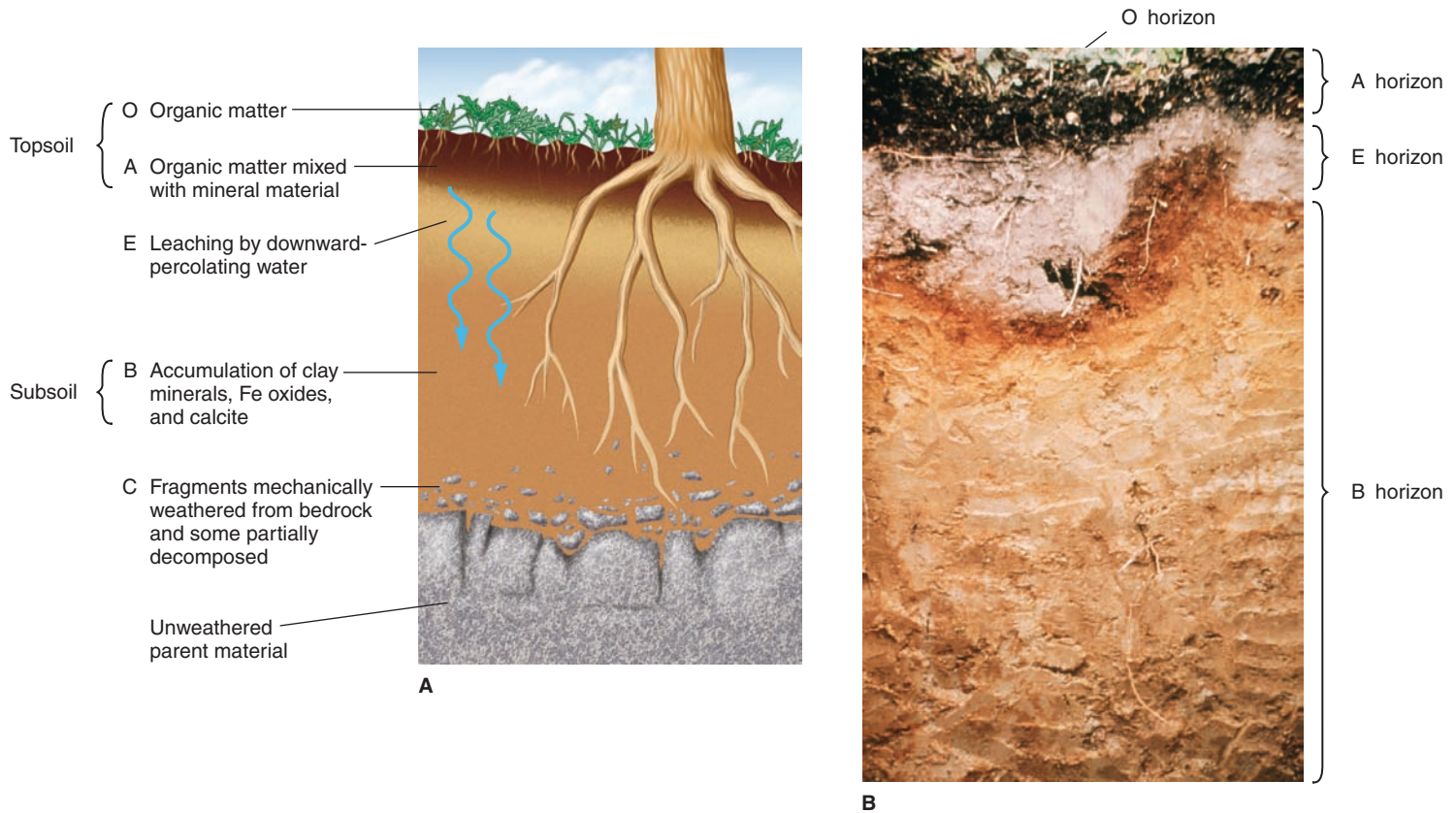

A

B

FIGURE 5.18

(*A*) Horizons (O, A, E, B, and C) in a soil profile that form in a humid climate. (*B*) Soil profile that shows the A horizon stained dark by humus. The E horizon is lighter in color, sandy, and crumbly. The clayey B horizon is stained red by hematite, leached downward from the E horizon. *Photo by USDA Natural Resources Conservation Service*

Factors Affecting Soil Formation

Most soils take a long time to form. The rate of soil formation is controlled by rainfall, temperature, slope, and, to some extent, the type of rock that weathers to form soil. High temperature and abundant rainfall speed up soil formation, but in most places, a fully developed soil that can support plant growth takes hundreds or thousands of years to form.

It would seem that the properties of a soil should be determined by the rock (the *parent material*) from which it formed, and this is partly true. Several other factors, however, are important in the formation of a soil, sometimes playing a larger role than the rocks themselves in determining the types of soils formed. These additional factors, *slope, living organisms, climate,* and *time,* are discussed in the following paragraphs.

Parent Material

The character of a soil depends partly on the parent material from which it develops. The parent material is the source of the weathered mineral matter that makes up most of a soil. A soil developing on weathering granite will be sandy, as sand-sized particles of quartz and feldspar are released from the granite. As the feldspar grains weather completely, fine-grained clay minerals are formed. The resulting soil will contain a variety of grain sizes and will have drainage and water-retention properties conducive to plant growth.

A soil forming on basalt may never be sandy, even in its early stages of development. If chemical weathering processes are more prevalent than mechanical weathering processes, the fine-grained feldspars in the basalt will weather directly to fine-grained clay minerals. Since the parent rock had no coarse-grained minerals and no quartz to begin with, the resulting soil may lack sand. Such a soil may not drain well, although it can be quite fertile.

Both of these soils are called **residual soils**; they develop from weathering of the bedrock beneath them (figure 15.9). Figure 5.18*A* is a diagram of residual soil developing in a humid climate from a bedrock source. **Transported soils** do not develop from locally formed rock, but from regolith brought in from some other region (figure 5.19). (Keep in mind that it is not the soil itself that is transported, but the parent material from which it is formed.) For example, mud deposited by a river during times of flooding can form an excellent agricultural soil next to the river after floodwaters recede. Wind deposits called *loess* (see chapter 13) form the base for some of the most valuable food-producing soils in the Midwest and the Pacific Northwest. Transported soils are generally more fertile than residual soils because the parent material is transported from many different locations; there is more variety in the chemical makeup of the parent material, so a greater variety of minerals and nutrients are supplied to the resulting soil.

Slope

The slope of the land surface provides an important control on the formation of soil (figure 5.19). Soils tend to be thin or nonexistent on steep slopes, where gravity keeps water and soil particles moving downhill. Vegetation is sparse on steep slopes, so there are not many roots to hold the weathering rock in place and little organic matter to provide nutrients. By contrast, soils in bottomlands may be very thick but poorly drained and waterlogged. Vegetation in the bottomlands does not decay completely, and thick, dark layers of peat may form.

The optimal topography for soil formation is flat or gently sloping uplands, allowing good drainage, minimal erosion, and healthy vegetation cover.

Living Organisms

The biosphere plays an important role in soil development. The chief function of living organisms is to provide organic material to the soil. Decomposing plants form humus, which supplies nutrients to the soil and aids in water retention. The decaying plant matter releases organic acids that increase chemical weathering of rocks. Growing plants send roots deep into the soil, breaking up the underlying bedrock and opening up pore spaces.

Burrowing organisms such as ants, worms, and rodents bring soil particles to the surface and mix the organic and mineral components of the soil. They create passageways that allow for the circulation of air and water, increasing chemical weathering and accelerating soil formation. Microorganisms such as bacteria, fungi, and protozoa promote the decomposition of organic matter to humus, and some bacteria fix nitrogen in the soil, making it available for uptake by plants. The interdependency of plants, animals, and soil is a mutually beneficial and delicately balanced system.
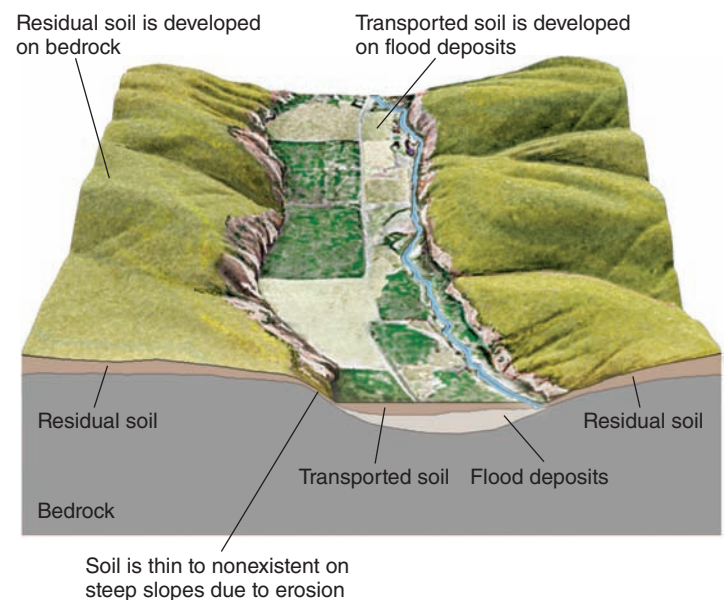

FIGURE 5.19

Residual soil develops from weathering of bedrock beneath the hills, whereas transported soil develops on top of flood plain deposits (regolith) in the stream valley. Soils are thin to nonexistent on the steeper slopes because of erosion.

Climate

Climate is perhaps the most influential factor affecting soil thickness and character. The same parent materials in the same topography will form significantly different soil types under different climatic conditions. Temperature and precipitation determine whether chemical or mechanical weathering processes will dominate and strongly influence the rate and depth of weathering. The amount and types of vegetation and animal life that contribute to soil formation are also determined by climate.

Soils in temperate, moist climates, as in Europe and the eastern United States, tend to be thick and are generally characterized by downward movement of water through Earth materials (figure 5.18 shows such a soil). In general, these soils tend to be fertile, have a high content of aluminum and iron oxides and well-developed horizons, and are marked by effective downward leaching due to high rainfall and to the acids produced by decay of abundant humus.

In arid climates, as in many parts of the western United States, soils tend to be thin and are characterized by little leaching, scant humus, and the *upward* movement of soil water beneath the land surface. The water is drawn up by subsurface evaporation and capillary action. As the water evaporates beneath the land surface, salts are precipitated within the soil (figure 5.20). An extreme example of salt buildup can be found in desert *alkali soils,* in which heavy concentrations of toxic sodium salts may prevent plant growth.

Another example of the control of climate on soil formation is found in the tropical rain forests of the world. The high temperatures and abundant rainfall combine to form extremely thick red soils called *oxisols,* or laterites, that are highly leached and generally infertile. See box 5.2 for a discussion of these soils.

Time

Note that the character of a soil changes with time. In a soil that has been weathering for a short period of time, the characteristics are largely determined by the parent material. Young soils can retain the structure of the parent rock, such as bedding layers. As time progresses, other factors become more important and climate eventually predominates. Soils forming from many different kinds of igneous, metamorphic, and sedimentary rocks can become quite similar, given the same climate and enough time. In the long term, the only characteristic of the parent rock to have significance is the presence or absence of coarse grains of quartz.

With time, soils tend to become thicker. In regions of ongoing volcanic activity, the length of time between eruptions can be estimated by the thickness of the soil that has formed on each flow (figure 5.21). A soil that has been buried by a lava flow, volcanic ash, windblown dust, glacial deposits, or other sediment is called a buried soil, or *paleosol* (*paleo* = ancient). Such soils may be distinctive and traceable over wide regions and may contain buried organic remains, making them useful
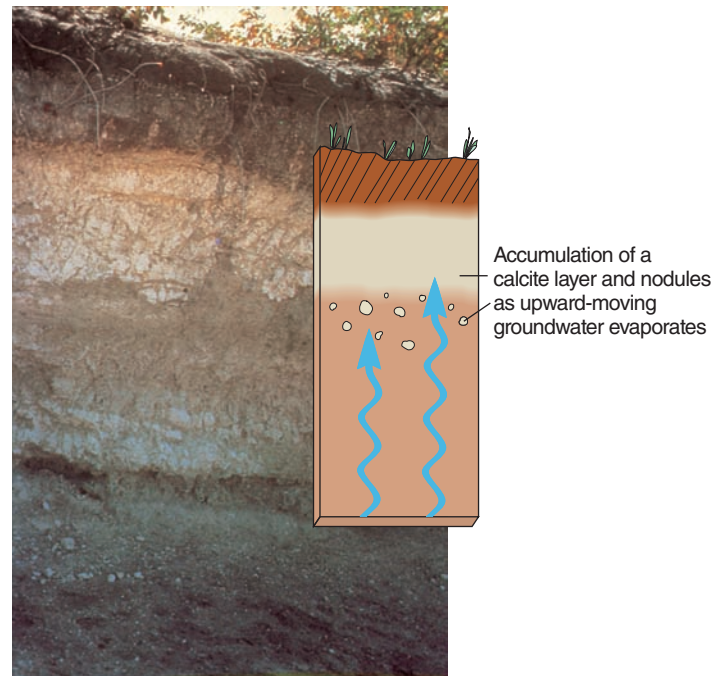

FIGURE 5.20

Soil profile marked by upward-moving groundwater that evaporates underground in a drier climate, precipitating calcium carbonate within the soil, sometimes forming a light-colored layer. *Photo by Donald Yost, USDA Natural Resources Conservation Service*

for dating rocks and sediments and for interpreting past climates and topography.

Soil Erosion

Although soil accounts for an almost insignificant fraction of all Earth materials, it is one of the most significant resources in terms of its effect on life. Soil provides nourishment and

FIGURE 5.21

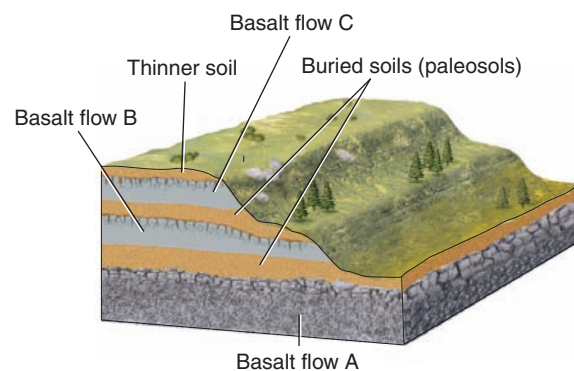Because soils tend to become thicker with time, the thickness of soils developed on successive basalt flows can be used to estimate the length of time between eruptions. Based on the soil thickness, more time elapsed between the eruption of basalt flows A and B than between flows B and C. These soils have been covered by the youngest basalt flow (C) and are examples of buried soils or *paleosols.*

Where Do Aluminum Cans Come From?

The answer can be found in tropical soils where extreme chemical weathering occurs. The high temperatures and abundant rainfall in tropical regions produce some of the thickest soil on Earth. Lush vegetation grows over this soil, but the soil itself is very infertile. As water percolates down through the soil in this hot, humid climate, plant nutrients are dissolved and carried downward, out of reach of plant roots. Even silica is dissolved in this environment, and the soil that remains is composed almost entirely of iron and aluminum oxides. This highly leached soil is an oxisol, commonly called *laterite,* and it is characteristically red in color (box figure 1). The iron oxides give the soil its red color, but the iron is seldom rich enough to mine. The aluminum oxides, however, may form rich ore deposits near the surface.

As leaching proceeds, nearly pure layers of bauxite ($Al(OH)_3$), the principal ore of aluminum, are left near the surface in large deposits that are on average 4–6 meters thick and may cover many square kilometers (box figure 2). Eighty percent of the world's aluminum is mined from large blanket deposits in West Africa, Australia, South America, and India.

The bauxite ore is washed, crushed, and then dissolved under high temperature and pressure in a caustic solution of sodium hydroxide. The chemical equation for this process is:

$$Al(OH)_3 + Na^+ + OH^- \rightarrow Al(OH)_4^- + Na^+$$
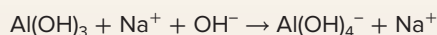
BOX 5.2 ■ FIGURE 1

Laterite soil (oxisol) develops in very wet climates, where intense, downward leaching carries away all but iron and aluminum oxides. Many laterites are a rusty orange to deep red color from the oxidation of the iron oxides. *Photo by USDA Natural Resources Conservation Service*

The undissolved residue, mostly iron, silica, and titanium, settles to the bottom, and the sodium aluminate solution is pumped into precipitators, where the previous reaction is reversed.

$$Al(OH)_4^- + Na^+ \rightarrow Al(OH)_3 + Na^+ + OH^-$$

The sodium hydroxide is recovered and returned to the beginning of the process, and the pure bauxite crystals are passed to another process that drives off water to form a white alumina (aluminum oxide) powder.

$$2Al(OH)_3 \rightarrow Al_2O_3 + 3H_2O$$

The alumina is then smelted by passing electric currents through the powder to separate the metallic aluminum from the oxygen. Small amounts of other metals may be added to the molten aluminum to form alloys, and the aluminum is cast into blocks that are sent to factories for further processing. The aluminum alloy used for beverage cans contains manganese, which helps the metal become more ductile as it is rolled into the thin sheets from which the cans are formed.

Aluminum smelting is very energy-intensive; 15.7 kilowatt-hours of electricity are required to produce a single kilogram of aluminum (the average home in the United States uses 24 kilowatt-hours of electricity each day). To control costs, smelters are frequently located near hydroelectric power plants, which are built for the sole purpose of powering the smelters.

Aluminum can be recycled repeatedly. Recycling uses only 5% of the energy required to make "new" aluminum. Twenty recycled cans can be produced with the same amount of energy required to produce a single can from bauxite. Worldwide, over 40% of the aluminum demand is supplied by recycled material. The aluminum from the beverage can that you toss into the recycle bins is recovered, mixed with a small percent of new aluminum, and is back on the shelves as a new can of soda in 6 to 8 weeks.

Additional Resource

• www.world-aluminium.org/

Web page for the *International Aluminum Institute* contains additional information on the production and use of aluminum.
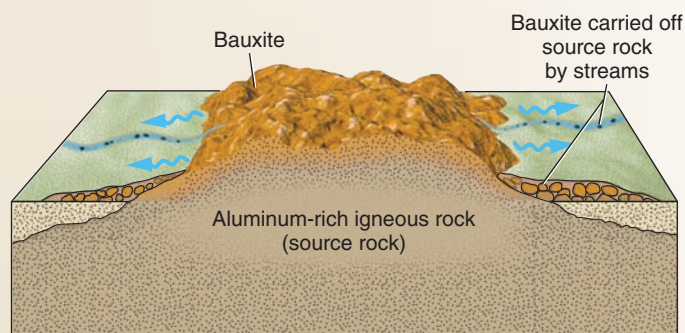
BOX 5.2 ■ FIGURE 2

Bauxite forms by intense tropical weathering of an aluminum-rich source rock such as a volcanic tuff.

physical support for plant life. It is the very base of the food chain that supports human existence. As such, soil is one of Earth's most vital resources, but it is also one of Earth's most abused.

The upper layers of a soil, the O and A horizons, are the most fertile and productive. These are the layers that are most vulnerable to erosion due to land mismanagement by poor farming and grazing practices. Scientists estimate that the Earth has lost about 10% of its productive value (the ability to provide crops, pasture, and forest products) over the last 50 years. If measures are not taken to curb the loss of fertile soils to erosion, an additional 10% of Earth's productivity could be lost in the next 25 years.

How Soil Erodes

Soil particles are small and are therefore easily eroded by water and wind. Raindrops strike unprotected soil like tiny bombs, dislodging soil particles in a process called *splash erosion* (figure 5.22*A*). As rain continues, a thin sheet of running water forms over the landscape, carrying the dislodged soil particles away (*sheet erosion*). Currents that form in the sheet of water cut tiny channels called *rills* in the exposed soil (figure 5.22*B*). The rills deepen into *gullies,* which merge into stream channels. Rivers that turn brown and muddy after rain storms are evidence of the significant amount of soil that can be transported by water.

Wind erosion is generally less significant than erosion by water, but it is a particular problem in arid and semiarid regions. The wind picks up the lighter components of a soil, such as the clays, silts, and organic matter, and may transport them many kilometers. These components are the ones that contribute most to soil fertility. Agricultural soils that have been depleted by wind erosion require increased use of fertilizers to maintain their productivity.

Rates of Erosion

The rate of soil erosion is influenced by several factors: soil characteristics, climate, slope, and vegetation. Coarse-grained soils with organic content tend to have larger pore spaces and can absorb more water than soils dominated by clay-sized particles. Less runoff occurs on the coarser soils, and less of the soil is eroded away. The type of rainfall also influences the amount of erosion. A gentle rain over a long period of time produces less splash erosion than a short, heavy rainstorm. More water can infiltrate the soil during the gentle rainfall, and there is less likelihood of sheet erosion occurring. Slope also plays an important role in soil erosion. Water moves more slowly on gentle slopes and is more likely to percolate down into the soil. The faster-moving water on steeper slopes does not infiltrate and has a greater ability to dislodge and transport soil particles down from the slope.

A very significant control on soil erosion rate is the amount and type of vegetation present. Plant roots form networks in the O and A horizons that bind soil particles. The leaf canopy protects the soil from the impact of raindrops, lowering the risk of splash erosion. Thick vegetation can reduce the

A

B

FIGURE 5.22

Soil erosion. (*A*) Splash erosion dislodges soil particles, making them available for removal by sheet erosion and rill erosion. (*B*) Smaller channels (rills) merge into larger channels as water erodes the loose material on this slope in the Badlands of the western United States. *Photo A courtesy of USDA Soil Conservation Service; photo B © Brand X Pictures/PunchStock RF*

wind velocity near the ground surface, preventing the loss of soil due to wind erosion. Human activity in the last two centuries has done much to remove the natural vegetation cover on the world's land surface. Large-scale farming operations, grazing, logging, mining, and construction have disrupted prairies, forests, and other natural environments, such as rain forests, leaving the underlying soils vulnerable to the effects of wind and water (figure 5.23).

Consequences of Erosion

All of the soil particles that are eroded by wind and water have to go somewhere, and they end up being deposited as sediments in streams, flood plains, lakes, and reservoirs. Erosion and sedimentation are natural processes, but they have been proceeding at an unnatural rate since the advent of mechanized farming. Since colonial times, forest land in the Chesapeake

FIGURE 5.23

Soil erosion caused by clear cutting of rain forest near Lake Baringo, Kenya, Africa. *Photo © Mark Boulton/Alamy*

A

B

FIGURE 5.24

The Dust Bowl. (*A*) A "black roller" bears down on a truck on Highway No. 59, south of Lamar, Colorado, in 1937. (*B*) Drifts of dust buried vehicles and outbuildings in Gregory County, South Dakota, 1936. *Photos by U.S. Department of Agriculture*

Bay watershed has been cleared for farming and timber. Over the last 150 years, so much sediment from the cleared land has been carried into the Chesapeake Bay that 787 acres of new land have been added to Maryland. The average water depth in the bay has been reduced by almost a meter in some places, requiring increased dredging to keep shipping channels open. Fine-grained sediments remain suspended in the water column, reducing water clarity and preventing light from reaching the bottom of the bay. The aquatic vegetation that supports and protects the oysters and other shellfish for which the bay is famous cannot survive in the reduced light.

Perhaps one of the most devastating consequences of soil erosion occurred in the American Midwest during the 1930s. Agriculture had expanded nearly tenfold in the Great Plains region between the 1870s and the 1930s. Advances in farm equipment allowed farmers to practice "intensive row crop agriculture," in which more than 100 million acres of prairie were plowed under and planted in long rows of crops such as corn, soybeans, and wheat. After several years of drought in the 1930s, the row crops failed and the soil was left exposed to the high winds that came whipping across the plains. Huge dust clouds called "black rollers" billowed up, burying vehicles and drifting like snow against houses (figure 5.24). The clouds of sediment drifted east, darkening the sky and falling as muddy rain and snow on the East Coast states. Years of hardship and suffering followed for the inhabitants of the Dust Bowl states.

The fertile agricultural soils of the Canadian plains and the northern United States took more than 10,000 years to develop on glacial deposits after the thick continental ice sheet melted. These soils and many others around the world are eroding at an alarming rate, much faster than they are being replaced by newly formed soils. This essential resource, upon which the base of all life rests, has become a nonrenewable resource. Conservation practices such as windbreaks, contour plowing, terracing, and crop rotation have been implemented in recent years to help reduce the amount of topsoil lost to wind and water. More must be done, especially in developing countries, to protect this fragile resource.

Soil Classification

Early soil classification efforts were based largely on the geology of the underlying rocks. It became apparent, however, that different types of soil could form on the same underlying rock, depending upon climate, topography, and the age of the soil. In many cases, the underlying rock was the least significant factor involved. Several different approaches were tried, and in 1975 a soil classification system was developed that grouped soils into twelve large *orders* based upon the characteristics of the horizons present in soil profiles. Brief descriptions of the orders are given in table 5.3, along with the factors most important in the formation of each soil. Figure 5.25 shows the worldwide distribution of the twelve major orders.

TABLE 5.3 | World Soil Orders

Soil Orders	Description	Controlling Factors
Alfisols	Gray to brown surface horizon, subsurface horizon of clay accumulation; medium to high in plant nutrient ions, common in humid forests.	Climate Organisms
Andisols	Soils formed in volcanic ash.	Parent material
Aridisols	Soils formed in dry climates, low in organic matter, often having horizons of carbonate, gypsum, or salt.	Climate
Entisols	Soils that have no horizons due to young age of parent material or to constant erosion.	Time Topography
Gelisols	Weakly weathered soils with permafrost within 2 meters of the surface.	Climate
Histosols	Wet, organic soils with relatively little mineral material, such as peat in swamps and marshes.	Topography
Inceptisols	Very young soils that have weakly developed horizons and little or no subsoil clay accumulation.	Time Climate
Mollisols	Nearly black surface horizon rich in organic matter and plant nutrient ions; subhumid to semiarid midlatitude grasslands.	Climate Organisms
Oxisols	Heavily weathered soils low in plant nutrient ions, rich in aluminum and iron oxides; humid, tropical climates; also called laterites.	Climate Time
Spodosols	Acid soils low in plant nutrient ions with subsurface accumulation of humus that is complexed with aluminum and iron; cool, humid pine forests in sandy parent material.	Parent material Organisms Climate
Ultisols	Strongly weathered soils low in plant nutrient ions with clay accumulation in the subsurface; humid temperate and tropical acid forest environments.	Climate Time Organisms
Vertisols	Clayey soils that swell when wet and shrink when dry, forming wide, deep cracks.	Parent material

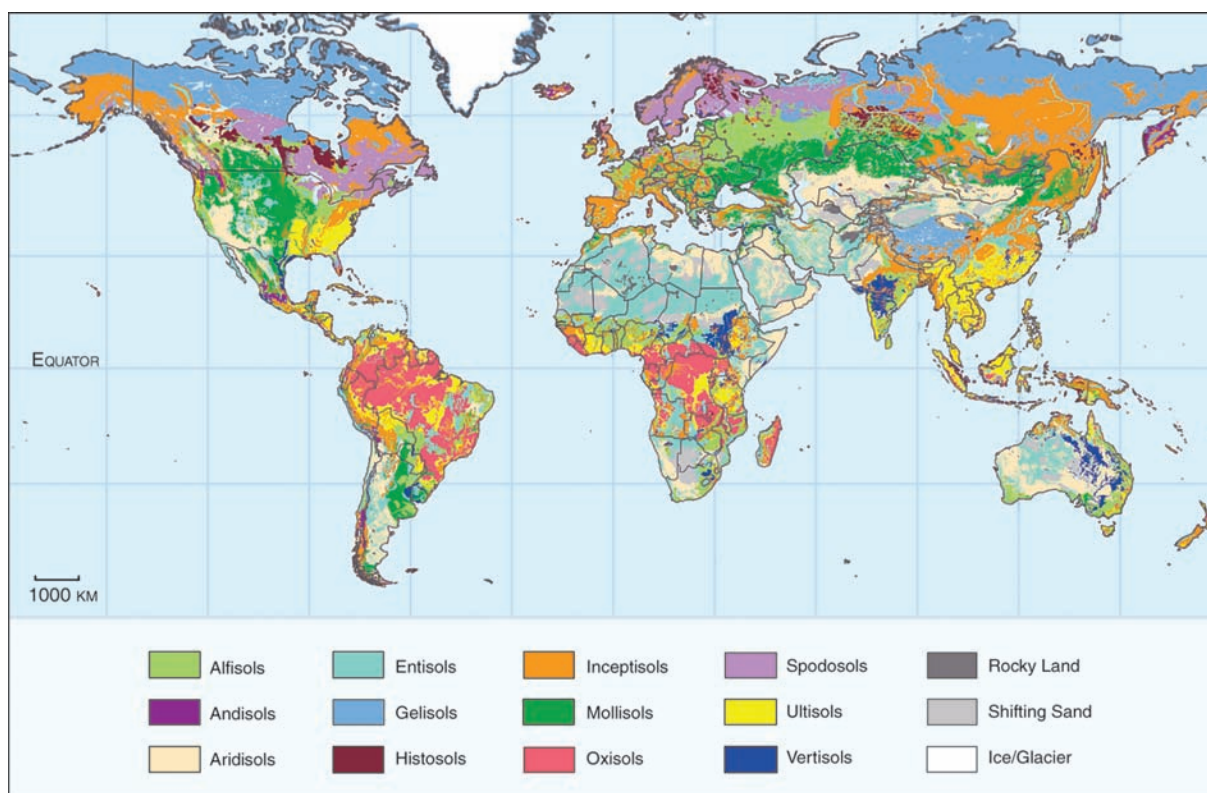After E. Brevik, 2002, *Journal of Geoscience Education,* v. 50, n. 5.

FIGURE 5.25

Worldwide distribution of soil orders. *U.S. Department of Agriculture, Natural Resources Conservation Service, World Soil Resources Division, U.S. Department of Agriculture.*

Summary

When rocks that formed deep in Earth become exposed at the Earth's surface, they are altered by *mechanical* and *chemical weathering.*

Weathering processes produce *spheroidal weathering, differentially weathered* landforms, *sheet joints,* and *exfoliation domes.*

Mechanical weathering, largely caused by *frost action* and *pressure release* after unloading, disintegrates (breaks) rocks into smaller pieces.

By increasing the exposed surface area of rocks, mechanical weathering helps speed chemical weathering.

Chemical weathering results when a mineral is unstable in the presence of water and atmospheric gases. As chemical weathering proceeds, the mineral's components recombine into new minerals that are more in equilibrium.

Weak acid, primarily from the solution of carbon dioxide in water, is an effective agent of chemical weathering.

Calcite dissolves when it is chemically weathered. Most of the silicate minerals form *clay minerals* when they chemically weather. Quartz is very resistant to chemical weathering.

Soil develops by chemical and mechanical weathering of a parent material. Some definitions of soil require that it contain organic matter and be able to support plant growth.

Soils, which can be *residual* or *transported,* usually have distinguishable layers, or *horizons,* caused in part by water movement within the soil.

Climate is the most important factor determining soil type. Other factors in soil development are parent material, time, slope, and organic activity.

Terms to Remember

A horizon   118
B horizon (zone of
   accumulation)   118
C horizon   118
chemical weathering   107
clay mineral   113
differential weathering   108
E horizon (zone of leaching)   118
erosion   106
exfoliation   109
exfoliation dome   109
frost action   109
frost heaving   109
frost wedging   109

hematite   111
limonite   111
loam   117
mechanical weathering   107
O horizon   118
pressure release   109
residual soil   119
sheet joints   109
soil   117
soil horizon   117
spheroidal weathering   108
transportation   106
transported soil   119
weathering   106

Testing Your Knowledge

Use the following questions to prepare for exams based on this chapter.

1. Why are some minerals stable several kilometers underground but unstable at Earth's surface?

2. Describe what happens to each mineral within granite during the complete chemical weathering of granite in a humid climate. List the final products for each mineral.

3. Explain what happens chemically when calcite dissolves. Show the reaction in a chemical equation.

4. Why do stone buildings tend to weather more rapidly in cities than in rural areas?

5. Describe at least three processes that mechanically weather rock.

6. How can mechanical weathering speed up chemical weathering?

7. Name at least three natural sources of acid in solution. Which one is most important for chemical weathering?

8. What is the difference between a residual soil and a transported soil?

9. What factors affect the formation of soil?

10. How do soils erode, and why is it important to minimize soil erosion?

11. Name and sketch the soil horizons that form in a humid climate. Explain how the layers (horizons) form.

12. Physical disintegration of rock into smaller pieces is called
    a. chemical weathering.
    b. transportation.
    c. deposition.
    d. mechanical weathering.

13. The decomposition of rock from exposure to water and atmospheric gases is called
    a. chemical weathering.
    b. transportation.
    c. deposition.
    d. mechanical weathering.

14. Which is *not* a type of mechanical weathering?
    a. frost wedging.   b. frost heaving.
    c. pressure release.   d. oxidation.

15. The single most effective agent of chemical weathering at Earth's surface is
    a. carbonic acid H_2CO_3.
    b. water H_2O.
    c. carbon dioxide CO_2.
    d. hydrochloric acid HCl.

16. The most common end product of the chemical weathering of feldspar is
    a. clay minerals.   b. pyroxene.
    c. amphibole.   d. calcite.

17. The most common end product of the chemical weathering of quartz is
    a. clay minerals.   b. pyroxene.
    c. amphibole.   d. calcite.
    e. quartz does not usually weather chemically.