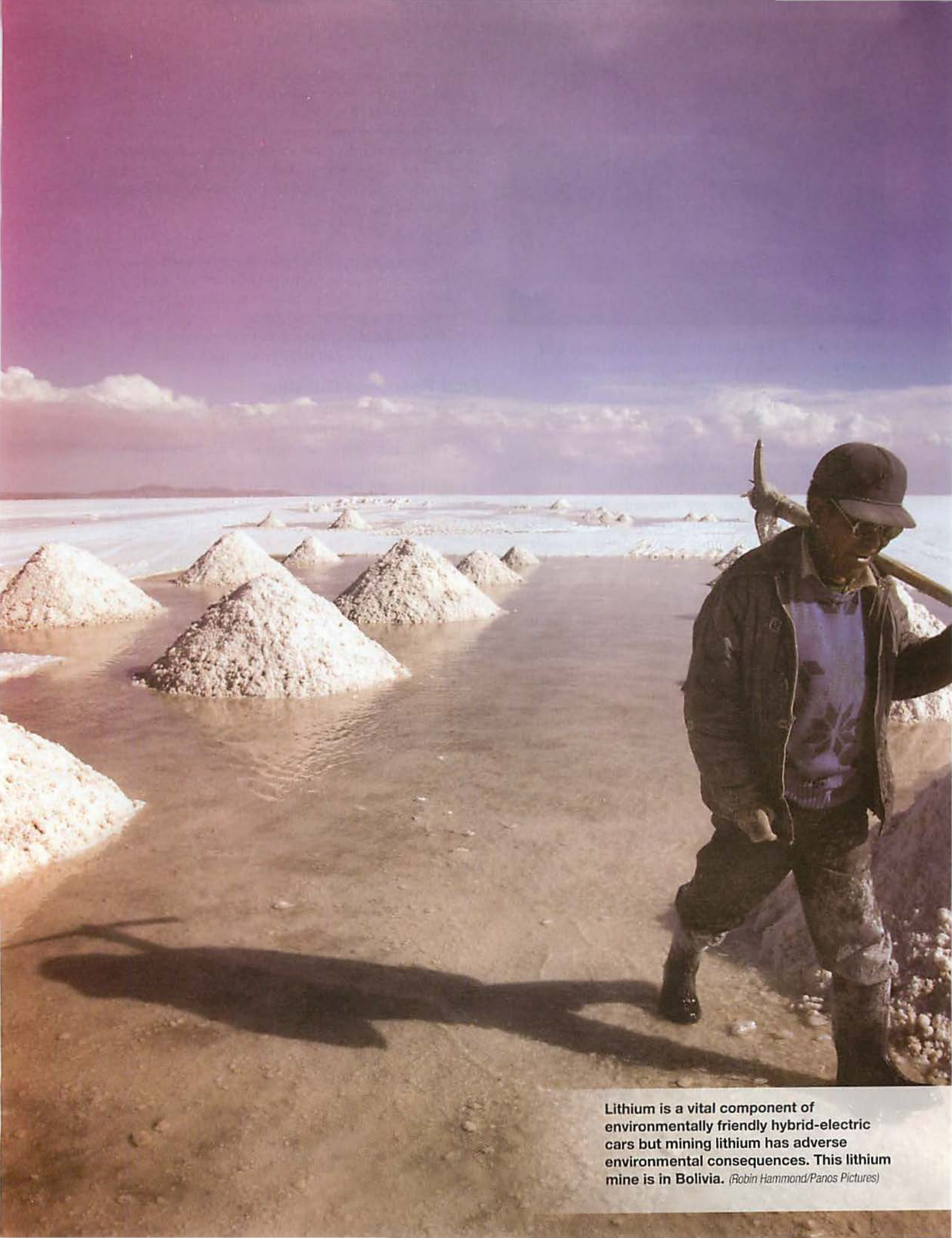


Lithium is a vital component of environmentally friendly hybrid-electric cars but mining lithium has adverse environmental consequences. This lithium mine is in Bolivia. *(Robin Hammond/Panos Pictures)* chapter 8

Earth Systems

Module 24 Mineral Resources and Geology

Module 25 Weathering and Soil Science

Are Hybrid Electric Vehicles as Environmentally Friendly as We Think?

Many people in the environmental science community believe that hybrid electric vehicles (HEV) and all-electric vehicles are some of the most exciting innovations of the last decade. Cars that run on electric power or on a combination of electricity and gasoline are much more efficient in their use of fuel than similarly sized internal combustion (IC) automobiles. Some of these cars use no gasoline at all, while others are able to run as much as twice the distance as a conventional IC car on the same amount of gasoline.

Although HEV and all-electric vehicles reduce our consumption of liquid fossil fuels, they do come with environmental trade offs. The construction of HEV vehicles uses scarce metals, including neodymium, lithium, and lanthanum. Neodymium is needed to form the magnets used in the electric motors, and lithium and lanthanum are used in the compact high-performance batteries the vehicles require. At present, there appears to be enough lanthanum available in the world to meet the demand of the Toyota Motor Corporation, which has manufactured more than 3 million Prius HEV vehicles. Toyota obtains its lanthanum from China. There are also supplies of lanthanum in various geologic deposits in California, Australia, Bolivia, Canada, and elsewhere, but most of these deposits have not yet been developed for mining. Until this happens, some scientists believe that the production of HEVs and all-electric vehicles will eventually be limited by the availability of lanthanum.

> Although HEV and all-electric vehicles reduce our consumption of liquid fossil fuels, they do come with environmental trade offs.

In addition to the scarcity of metals needed to make HEV and all-electric vehicles, we have to consider how we acquire these metals. Wherever mining occurs, it has a number of environmental consequences. Material extraction leaves a landscape fragmented by holes, and road construction necessary for access to and from the mining site further alters the habitat. Erosion and water contamination are also common results of mining.

A typical Toyota Prius HEV uses approximately 1 kg (2.2 pounds) of neodymium and 10 kg (22 pounds) of lanthanum. Mining these elements involves pumping acids into deep boreholes to dissolve the surrounding rock and then removing the acids and resulting mineral slurry. Lithium is extracted from certain rocks, and lithium carbonate is extracted from brine pools and mineral springs adjacent to or under salt flats. Both extraction procedures are types of surface mining, which can have severe environmental impacts. The holes, open pits, and ground disturbance created by mining these minerals provide the opportunity for air and water to react with other minerals in the rock, such as sulfur, to form an acidic slurry. As this acid mine drainage flows over the land or underground toward rivers and streams, it dissolves metals and other elements. As a result, water near surface mining operations is highly acidic—sometimes with a pH of 2.5 or lower. It may also contain harmful levels of dissolved metals and minerals.

Current HEV technology does represent a step forward in our search to reduce the use of fossil fuels. However, to make good decisions about the use of resources, we must have a full understanding of the costs and benefits.

Sources:
M. Armand and J.-M. Tarascon, Building better batteries, *Nature* 451 (2008): 652–657; Anonymous, Rare earth metals may trigger trade wars, *www.discovery.com*, February 11, 2013.

As we saw in our account of the hybrid-electric car, decisions about resource use are not always simple. Why are some of Earth's mineral resources so limited? Why do certain elements occur in some locations but not in others? What processes create minerals and other Earth materials, and what are the consequences of extracting them? Understanding the answers to these questions helps environmental scientists make informed decisions about the environmental and economic costs and benefits of resource use.

In this chapter we will explore the subjects of resources, geology, and soil science. We will look inside Earth to explore its structure, its formation, and the ongoing processes that affect the composition and availability of elements and minerals on our planet. We will then turn to the surface of Earth to explore how the rock cycle distributes these resources. With this foundation, we will examine the formation of soil, which is essential for so many biological activities on Earth. Finally, we will look at the problems we face in extracting resources from Earth—an issue of great concern to environmental scientists and others.

module

24

Mineral Resources and Geology

Almost all of the mineral resources on Earth accumulated when the planet formed 4.6 billion years ago. But Earth is a dynamic planet. Earth's geologic processes form and break down rocks and minerals, drive volcanic eruptions and earthquakes, determine the distribution of scarce mineral resources, and create the soil in which plants grow. In this module we will examine the distribution of Earth's mineral resources and some of the geological processes that continue to affect this distribution.

Learning Objectives

After reading this module you should be able to

- describe the formation of Earth and the distribution of critical elements on Earth.
- define the theory of plate tectonics and discuss its relevance to the study of the environment.
- describe the rock cycle and discuss its importance in environmental science.

The availability of Earth's resources was determined when the planet was formed

Earth's history is measured using the geologic time scale, shown in FIGURE 24.1. It's hard to believe that events that took place 4.6 billion years ago continue to have such an influence on humans and their interactions with Earth. The distribution of chemicals, minerals, and ores around the world is in part a function of the processes that occurred during the formation of Earth.

The Formation and Structure of Earth

Nearly all the elements found on Earth today are as old as the planet itself. FIGURE 24.2 illustrates how Earth formed roughly 4.6 billion years ago from cosmic dust in the solar system. The early Earth was a hot, molten sphere. For a period of time, additional debris from the formation of the Sun bombarded Earth. As this molten material slowly cooled, the elements within it separated into layers according to their mass. Heavier elements such as iron sank toward Earth's center, and lighter elements such as silica floated toward its surface. Some gaseous elements left the solid planet and became part of Earth's atmosphere. Although asteroids occasionally strike Earth today, the bombardment phase of planet formation has largely ceased and the elemental composition of Earth has stabilized. In other words, the elements and minerals that were present when the planet formed—and which are distributed unevenly around the globe—are all that we have.

Some minerals such as silicon dioxide—the primary component of sand and glass—are readily available

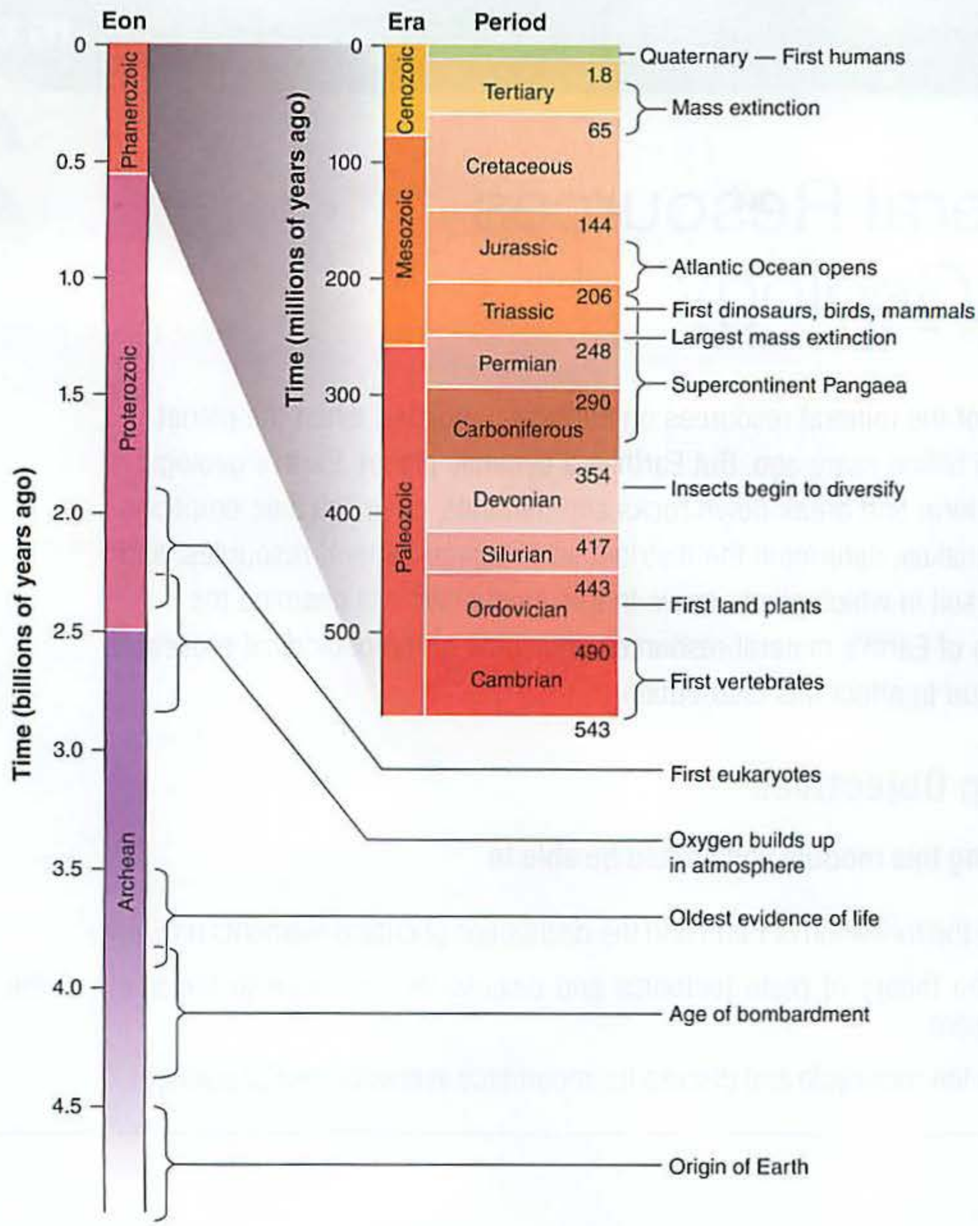


FIGURE 24.1 The geologic time scale. Time since the origin of Earth through the present is divided into three eons. The most recent eon, the Phanerozoic, is broken down into three eras. The Phanerozoic can also be divided into 11 periods, the most recent of which is the Quaternary.

worldwide on beaches and in shallow marine and glacial deposits. Others such as diamonds—which are formed from carbon that has been subjected to intense pressure—are found in relatively few isolated locations. Over the course of human history, this uneven geographic distribution has driven many economic and political conflicts.

Because Earth's elements settled into place according to their mass, the planet is characterized by distinct vertical zonation. If we could slice into Earth as shown in FIGURE 24.3 we would see concentric layers composed of various materials. The innermost zone is the planet's **core,** over 3,000 km (1,860 miles) below Earth's surface. The core is a dense mass largely made of nickel and some iron. The inner core is solid, and the outer core is liquid. Above the core is the **mantle,** containing molten rock, or **magma,** that slowly circulates in convection cells, much as the atmosphere

Core The innermost zone of Earth's interior, composed mostly of iron and nickel. It includes a liquid outer layer and a solid inner layer.

Mantle The layer of Earth above the core, containing magma.

Magma Molten rock.

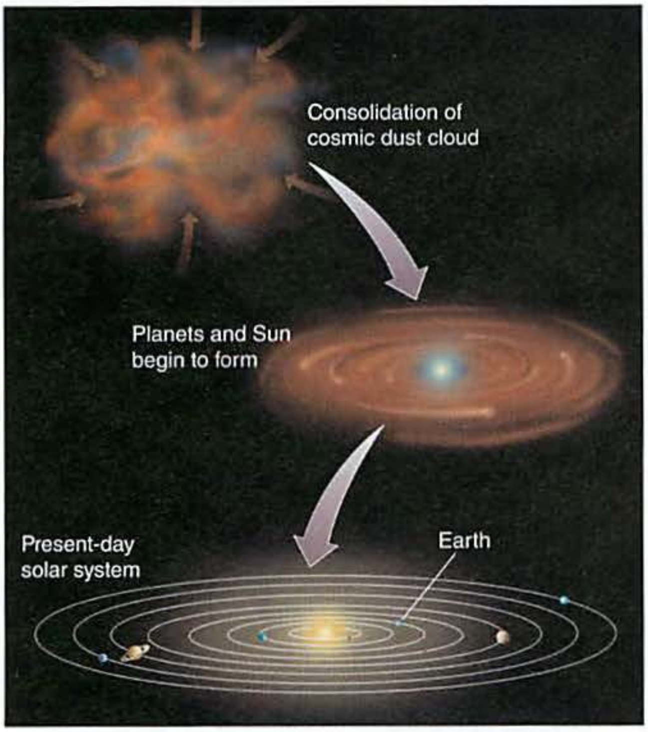
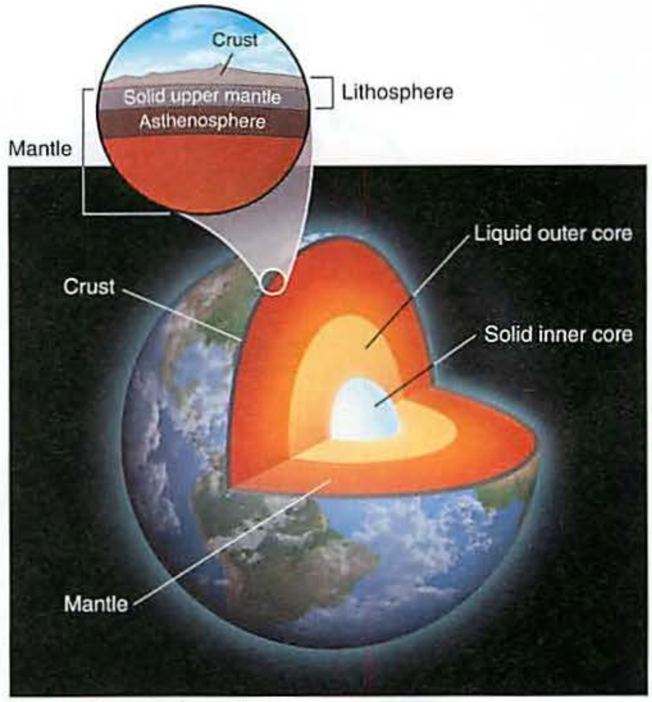
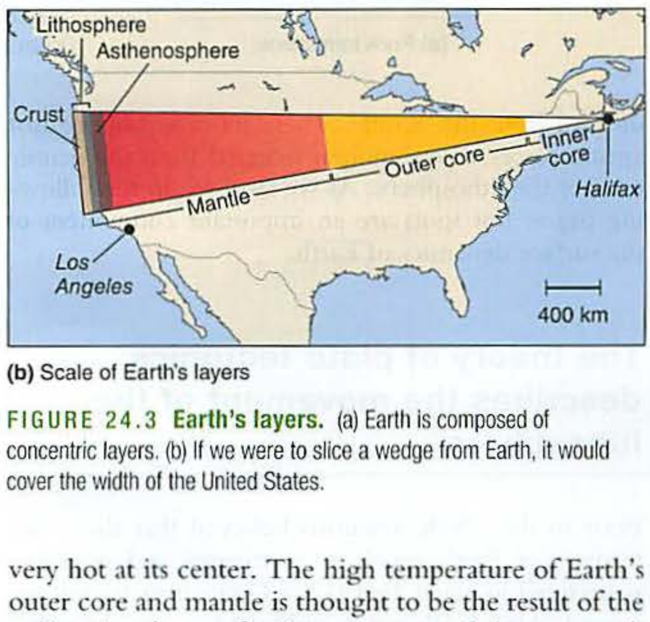


FIGURE 24.2 Formation of Earth and the solar system. The processes that formed Earth 4.6 billion years ago determined the distribution and abundance of elements and minerals today.



(a) Earth's vertical zonation



(b) Scale of Earth's layers

FIGURE 24.3 Earth's layers. (a) Earth is composed of concentric layers. (b) If we were to slice a wedge from Earth, it would cover the width of the United States.

does. The **asthenosphere,** located in the outer part of the mantle, is composed of semi-molten, ductile (flexible) rock. The brittle outermost layer of the planet, called the **lithosphere** (from the Greek word *lithos,* which means "rock"), is approximately 100 km (60 miles) thick. It includes the solid upper mantle as well as the **crust,** the chemically distinct outermost layer of the lithosphere. It is important to recognize that these regions overlap: The lowest part of the lithosphere is also the uppermost portion of the mantle.

The lithosphere is made up of several large and numerous smaller plates, which overlie the convection cells within the atmosphere. Over the crust lies the thin layer of soil that allows life to exist on the planet. The crust and overlying soil provide most of the chemical elements that make up life.

Because Earth contains only a finite supply of mineral resources, we will not be able to extract resources from the planet indefinitely. In addition, once we have mined the deposits of resources that are most easily obtained, we must use more energy to extract the remaining resources. Both of these realities provide an incentive for us to minimize our use of mineral resources and to reuse and recycle them whenever possible.

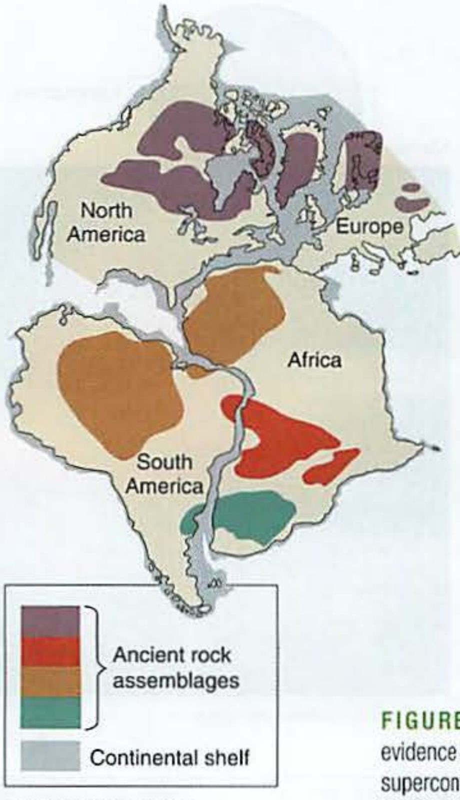
Hot Spots

One of the critical consequences of Earth's formation and elemental composition is that the planet remains very hot at its center. The high temperature of Earth's outer core and mantle is thought to be the result of the radioactive decay of various isotopes of elements such as potassium, uranium, and thorium, which release heat. The heat causes plumes of hot magma to well

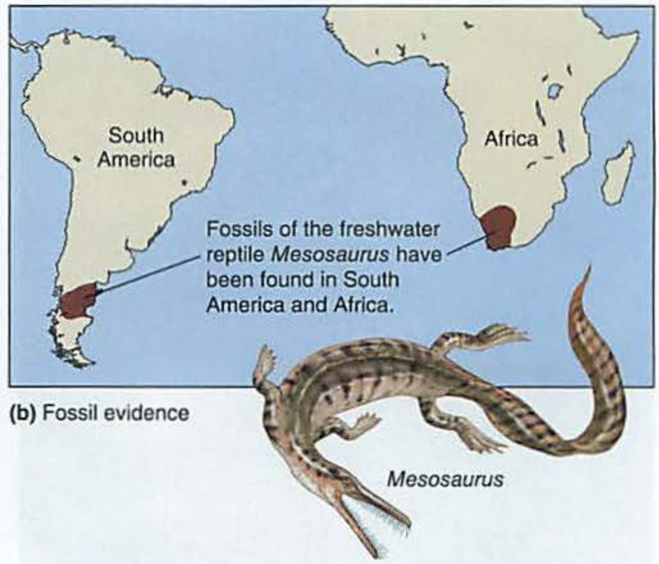
Asthenosphere The layer of Earth located in the outer part of the mantle, composed of semi-molten rock.

Lithosphere The outermost layer of Earth, including the mantle and crust.

Crust In geology, the chemically distinct outermost layer of the lithosphere.



(a) Rock formations



(b) Fossil evidence

FIGURE 24.4 Evidence of drifting continents. Several lines of evidence show that the current landmasses were once joined together in a single supercontinent. (a) Identical rock formations are found on both sides of the Atlantic Ocean. (b) Fossils of the same species have been collected from different continents.

upward from the mantle. These plumes produce **hot spots:** places where molten material from the mantle reaches the lithosphere. As we shall see in the following pages, hot spots are an important component of the surface dynamics of Earth.

The theory of plate tectonics describes the movement of the lithosphere

Prior to the 1900s, scientists believed that the major features of Earth—such as continents and oceans—were fixed in place. In 1912, a German meteorologist named Alfred Wegener published a revolutionary hypothesis proposing that the world's continents had once been joined in a single landmass, which he called "Pangaea." His evidence included observations of identical rock formations on both sides of the Atlantic Ocean, as shown in FIGURE 24.4a. The positions of these formations suggested that a single supercontinent may have broken up into separate landmasses. Fossil evidence also suggested that a single large continent existed in the past. Today, we can find fossils of the same species on different continents that are separated by oceans; Figure 24.4b shows one example.

Many resisted the idea that Earth's lithosphere could move laterally. However, following the publication of Wegener's hypothesis, scientists found additional evidence that Earth's landmasses had existed in several different configurations over time. This led to the theory of **plate tectonics,** which states that Earth's lithosphere is divided into plates, most of which are in constant motion. The **tectonic cycle** is the sum of the processes that build up and break down the lithosphere.

The theory of plate tectonics is often called a unifying theory in geology and earth sciences because it relates to so many different aspects of the earth sciences.

Hot spot In geology, a place where molten material from Earth's mantle reaches the lithosphere.

Plate tectonics The theory that the lithosphere of Earth is divided into plates, most of which are in constant motion.

Tectonic cycle The sum of the processes that build up and break down the lithosphere.

Plate Movement

We now know that the lithosphere consists of a number of plates. Oceanic plates lie primarily beneath the oceans, whereas continental plates lie beneath landmasses. The crust of oceanic plates is dense and rich in iron, while the crust of continental plates generally contains more silicon dioxide, which is much less dense than iron. The continental plates are therefore lighter and

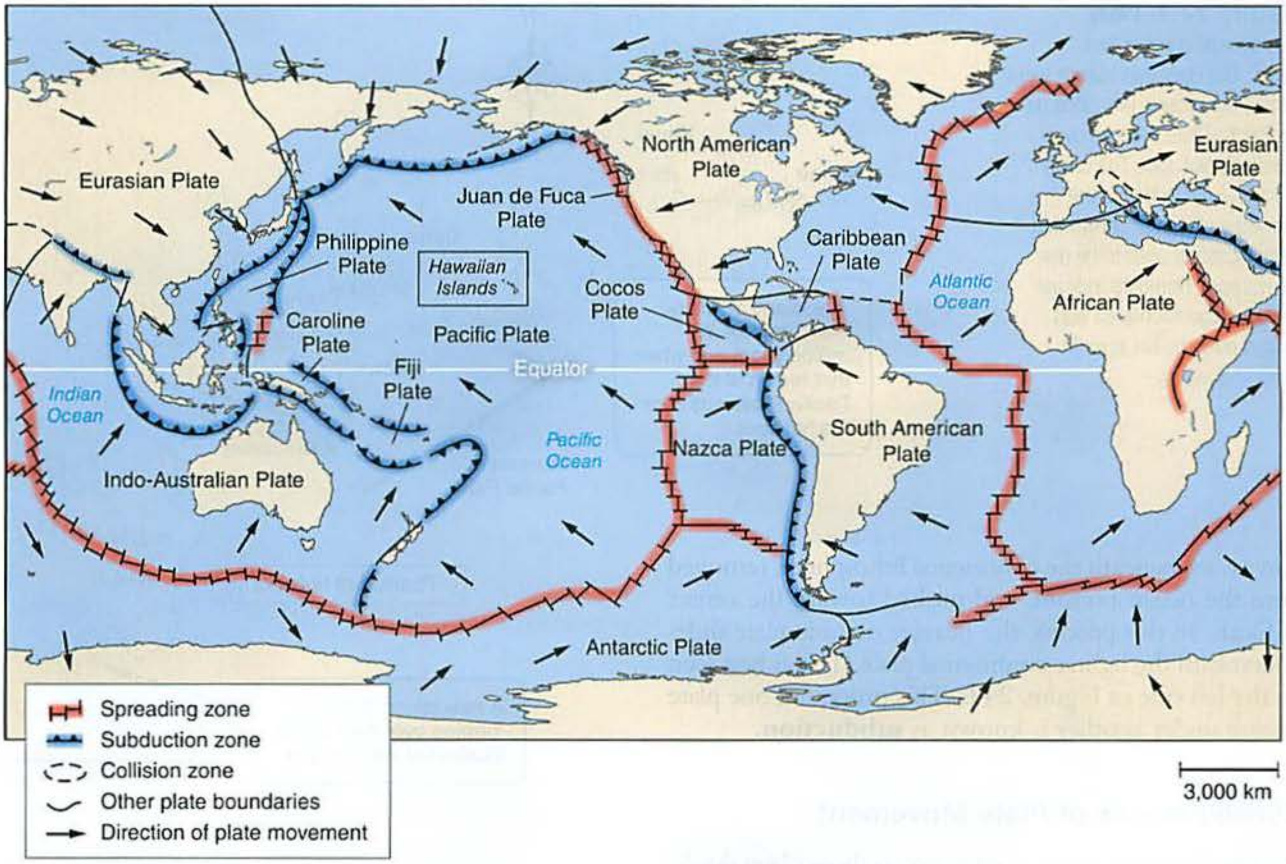


FIGURE 24.5 Tectonic plates. Earth is covered with tectonic plates, most of which are in constant motion. The arrows indicate the direction of plate movement. New lithosphere is added at spreading zones and older lithosphere is recycled into the mantle at subduction zones.

typically rise above the oceanic plates. FIGURE 24.5 identifies Earth's major plates.

Oceanic and continental plates "float" on top of the denser material beneath them. Their slow movements are driven by convection cells in Earth's mantle. The heat from Earth's core creates these convection cells, which are similar to those in the atmosphere. (See Figure 10.6 on page 115.) Mantle convection drives continuous change: the creation and renewal of Earth materials in some locations of the lithosphere and destruction and removal of Earth material in other locations. As oceanic plates move apart, rising magma forms new oceanic crust on the seafloor at the boundaries between those plates. This process, called seafloor spreading, is shown in the center of FIGURE 24.6. Where oceanic plates meet continental plates, old oceanic crust is pulled

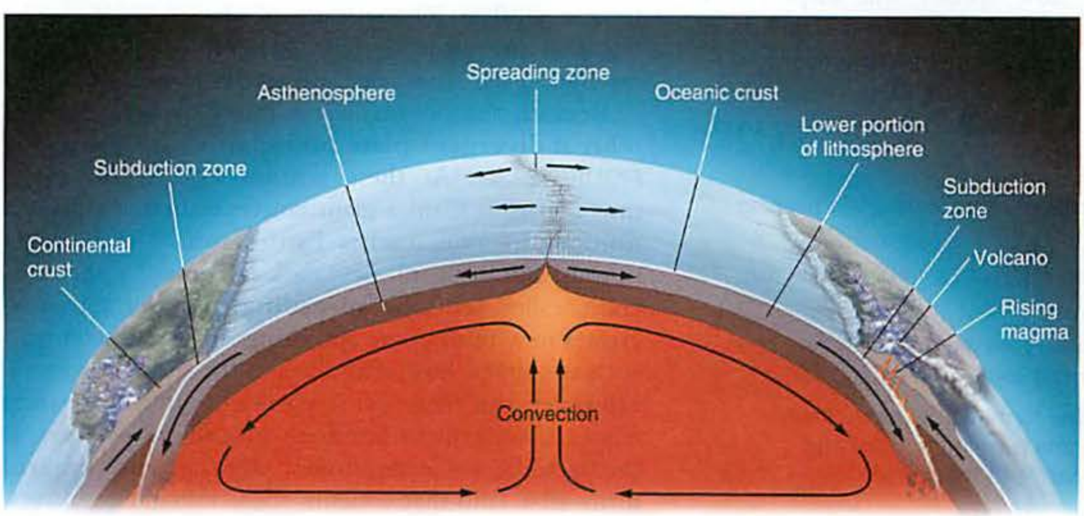
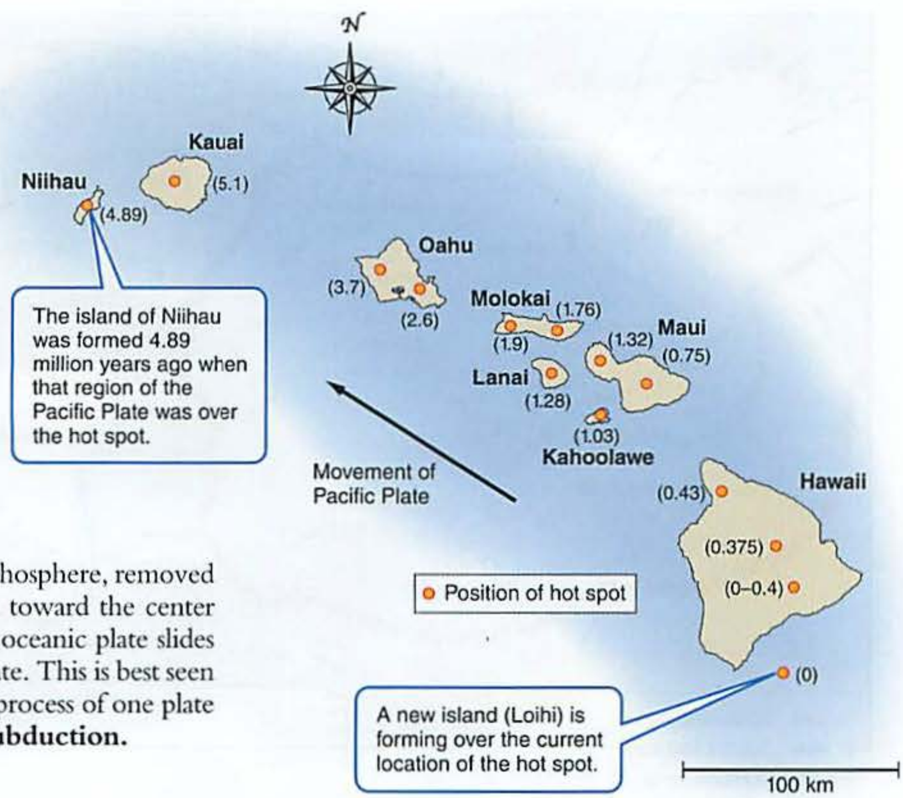


FIGURE 24.6 Convection and plate movement. Convection in the mantle causes oceanic plates to spread apart as new rock rises to the surface at spreading zones. Where oceanic and continental plate margins come together, older oceanic crust is subducted.

FIGURE 24.7 Plate movement over a hot spot. The Hawaiian Islands were formed by volcanic eruptions as the Pacific Plate traveled over a geologic hot spot. The chain of inactive volcanoes to the northwest of Hawaii shows that those locations used to be over the hot spot. Numbers indicate how long ago each area was located over the hot spot (in millions of years).



downward beneath the continental lithosphere, removed from the ocean bottom, and pushed toward the center of Earth. In this process, the heavier oceanic plate slides underneath the lighter continental plate. This is best seen on the left side of Figure. 24.6. This process of one plate passing under another is known as **subduction.**

Consequences of Plate Movement

Because the plates move, continents on those plates slowly drift over the surface of Earth. As the continents have drifted, their climates have changed and geographic barriers were formed or removed, and as a result, species evolved and adapted, or slowly or rapidly went extinct. In some places, as the plates moved a continent that straddled two plates broke apart, creating two separate smaller continents or islands in different climatic regions. As you may recall from our discussion of allopatric speciation in Chapter 5, species that become separated can take different evolutionary paths and over time evolve into two or more separate species. The fossil record tells us how species adapted to the changes that took place over geologic time. Climate scientists and ecologists can use this information to anticipate how species will adapt to the relatively rapid climate changes happening on Earth today.

Although the rate of plate movement is too slow for us to notice, geologic activity provides vivid evidence that the plates are in motion. As a plate moves over a geologic hot spot, heat from the rising mantle plume melts the crust, forming a **volcano**: a vent in Earth's surface that emits ash, gases, and molten lava. Volcanoes are a natural source of atmospheric carbon dioxide, particulates, and metals. Over time, as the plate moves past the hot spot, it can leave behind a trail of extinct volcanic islands, each with the same chemical composition. The Hawaiian Islands, shown in **FIGURE 24.7**, are an excellent example of this pattern.

Subduction The process of one crustal plate passing under another.

Volcano A vent in the surface of Earth that emits ash, gases, or molten lava.

Divergent plate boundary An area beneath the ocean where tectonic plates move away from each other.

Seafloor spreading The formation of new ocean crust as a result of magma pushing upward and outward from Earth's mantle to the surface.

Types of Plate Contact

Many other geologic events occur at the zones of contact that result from the movements of plates relative to one another. These zones of plate contact can be classified into three types: *divergent plate boundaries, convergent plate boundaries,* and *transform fault boundaries.*

Beneath the oceans, plates move away from each other at **divergent plate boundaries,** as illustrated in **FIGURE 24.8a**. At these boundaries, oceanic plates move apart as if on a giant conveyer belt. As magma from the mantle reaches Earth's surface and pushes upward and outward, new rock is formed, a phenomenon, called **seafloor spreading.** Seafloor spreading creates new lithosphere and brings important elements such as copper, lead, and silver to the surface of Earth. However, this new rock typically lies under the deep ocean. Over tens to hundreds of millions of years, as the tectonic cycle continues, some of that material forms new land that contains these valuable resources.

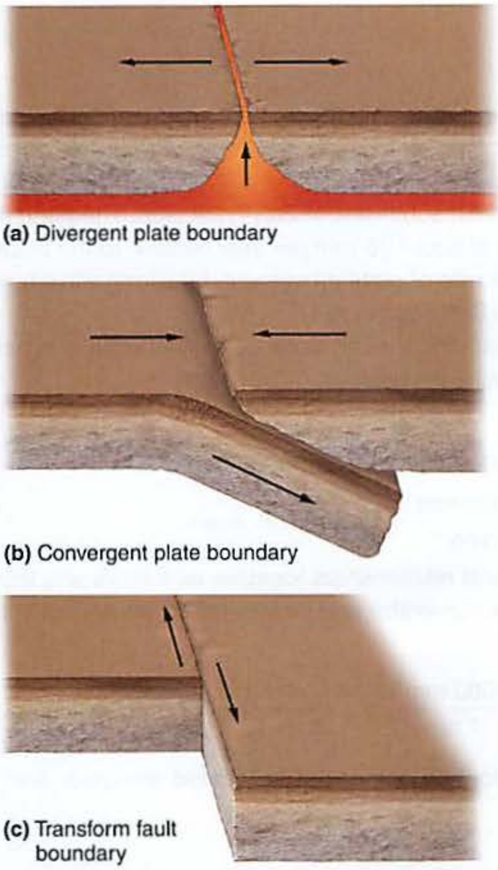


FIGURE 24.8 Types of plate boundaries. (a) At divergent plate boundaries, plates move apart. (b) At convergent plate boundaries, plates collide. (c) At transform fault boundaries, plates slide past each other.

Clearly, if tectonic plates are diverging in one place, and if the surface of Earth has a finite area, the plates must be moving together somewhere else. **Convergent plate boundaries** form where plates move toward one another and collide, as shown in Figure 24.8b. The plates generate a great deal of pressure as they push against one another.

When plates move sideways past each other, the result is a **transform fault boundary,** shown in Figure 24.8c. A **fault** is a fracture in rock across which there is movement. Where this occurs, it is said that there is a high level of **seismic activity,** which is the frequency and intensity of earthquakes experienced over time. A **fault zone** is a large expanse of rock where a fault has occurred. Fault zones—also called areas of high seismic activity—form in the brittle upper lithosphere where two plates meet or slide past one another. In these large expanses of rock where movement has occurred, the rock near the plate margins becomes fractured and deformed from the immense pressures exerted by plate movement. We'll discuss faults and earthquakes in more detail in the next section.

If two continental plates meet, both plate margins may be lifted, forming a mid-continental mountain range such as the Himalayas in Asia (FIGURE 24.9a). As

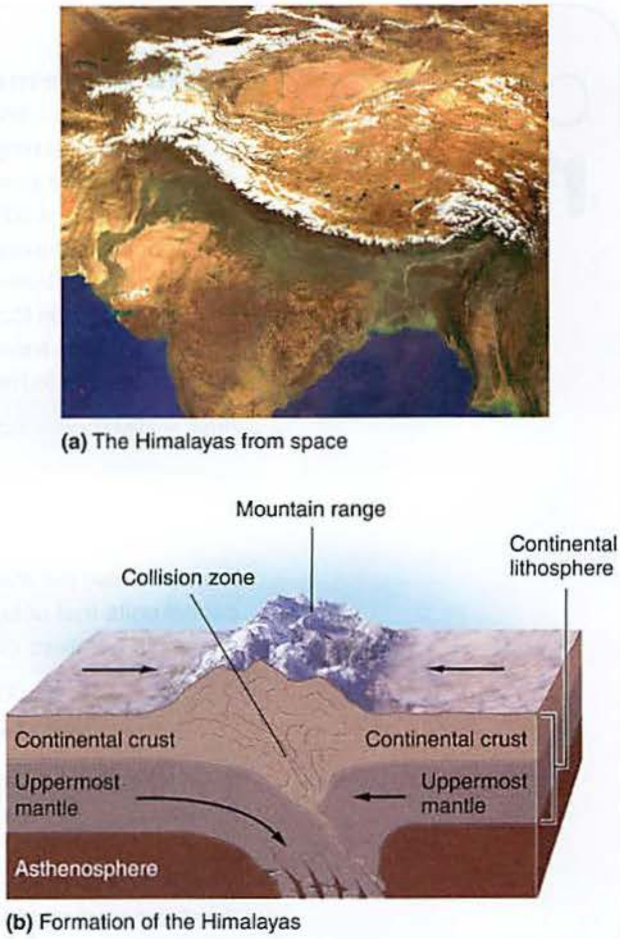


FIGURE 24.9 Collision of two continental plates. (a) A satellite image of the Himalayas, which include the highest mountains on Earth. (b) The Himalayan mountain range was formed when the collision of two continental plates forced the margins of both plates upward. *(European Space Agency)*

shown in Figure 24.9b, when both plates are composed of material of equal density, one does not get subducted under the other. Instead, they are forced into one another, and the force of the plate movement pushes material upward in one of the processes that leads to the formation of mountains.

Most plates and continents move at about the same rate as your fingernails grow: roughly 36 mm, or 1.4

Convergent plate boundary An area where plates move toward one another and collide.

Transform fault boundary An area where tectonic plates move sideways past each other.

Fault A fracture in rock caused by a movement of Earth's crust.

Seismic activity The frequency and intensity of earthquakes experienced over time.

Fault zone A large expanse of rock where a fault has occurred.

do the math

Plate Movement

If two cities lie on different tectonic plates, and those plates are moving so that the cities are approaching each other, how many years will it take for the two cities to be situated adjacent to each other?

Los Angeles is 630 km (380 miles) southeast of San Francisco. The plate under Los Angeles is moving northward at about 36 mm per year relative to the plate under San Francisco. Given this average rate of plate movement, how long will it take for Los Angeles to be located next to San Francisco?

The distance traveled is 630 km, and the net distance moved is 36 mm per year. We can use this formula to determine the answer

time = distance ÷ rate

$$630 \text{ km} = 630{,}000 \text{ m} = 630{,}000{,}000 \text{ mm}$$

$$\frac{630{,}000{,}000 \text{ mm}}{36 \text{ mm/year}} = 17{,}500{,}000 \text{ years}$$

We could also put these dimensional relationships together as follows and then cancel units that occur in both the numerator and denominator. We are left with an answer in numbers of years

$$630 \text{ km}\left(\frac{1{,}000 \text{ m}}{1 \text{ km}}\right) \times \left(\frac{1{,}000 \text{ mm}}{1 \text{ m}}\right) \times \left(\frac{1 \text{ year}}{36 \text{ mm}}\right) = 17{,}500{,}000 \text{ years}$$

It will take about 18 million years for Los Angeles to be located alongside San Francisco.

Your Turn How long will it take for a plate that moves at 20 mm per year to travel the distance of one football field? Note that a football field is 91.44 m (100 yards) long.

inches, per year. While this movement is far too slow to notice on a daily basis, the two plates underlying the Atlantic Ocean have spread apart and come together twice over the past 500 million years, causing Europe and Africa to collide with North America and South America and separate from them again. "Do the Math: Plate Movement" shows how we can calculate the time it takes for plates to move.

Faults, Earthquakes, and Volcanoes

Although the plates are always in motion, their movement, while generally slow, is not necessarily smooth. Imagine rubbing two rough and jagged rocks past each other. The rocks would resist that movement and get stuck together. The rock along a fault is also jagged and thus resists movement, but the mounting pressure eventually overcomes the resistance and the plates give way, slipping quickly. This is an **earthquake,** which is a sudden movement of Earth's crust caused by the release of potential energy along a fault, causing vibration or movement at the surface. Earthquakes occur when the rocks of the lithosphere rupture unexpectedly along a fault. The plates can move up to several meters in just a few seconds. Earthquakes are common in fault zones, which are areas of seismic activity. FIGURE 24.10 shows one such area, the San Andreas Fault in California, which is a transform fault. The **epicenter** of an earthquake is the exact point on the surface of Earth directly above the location where the rock ruptures, also shown in Figure 24.10.

Earthquakes are a direct result of the movement of plates and their contact with each other. Volcanic eruptions happen when molten magma beneath the crust is released to the atmosphere. Sometimes the two events are observed together, most often along plate boundaries where tectonic activity is high. FIGURE 24.11 shows one example, in which earthquake locations and volcanoes form a circle of tectonic activity, called the "Ring of Fire," around the Pacific Ocean.

Earthquake The sudden movement of Earth's crust caused by a release of potential energy along a geologic fault and usually causing a vibration or trembling at Earth's surface.

Epicenter The exact point on the surface of Earth directly above the location where rock ruptures during an earthquake.

Richter scale A scale that measures the largest ground movement that occurs during an earthquake.

The Environmental and Human Toll of Earthquakes and Volcanoes

Plate movements, volcanic eruptions, seafloor spreading, and other tectonic processes bring molten rock from deep beneath Earth's crust to the surface, and subduction sends surface crust deep into the mantle. This tectonic cycle of surfacing and sinking is a continuous Earth process. When humans live in close proximity to areas of seismic or volcanic activity, however, the results can be dramatic and devastating.

Earthquakes occur many times a day throughout the world, but most are so small that humans do not feel them. The magnitude of an earthquake is reported on the **Richter scale,** a measure of the largest ground movement that occurs during an earthquake. The Richter scale, like the pH scale described in Chapter 2, is logarithmic. On a logarithmic scale, a value increases by a factor of 10 for each unit increase. Thus a magnitude 7.0 earthquake, which causes serious damage, is 10 times greater than a magnitude 6.0

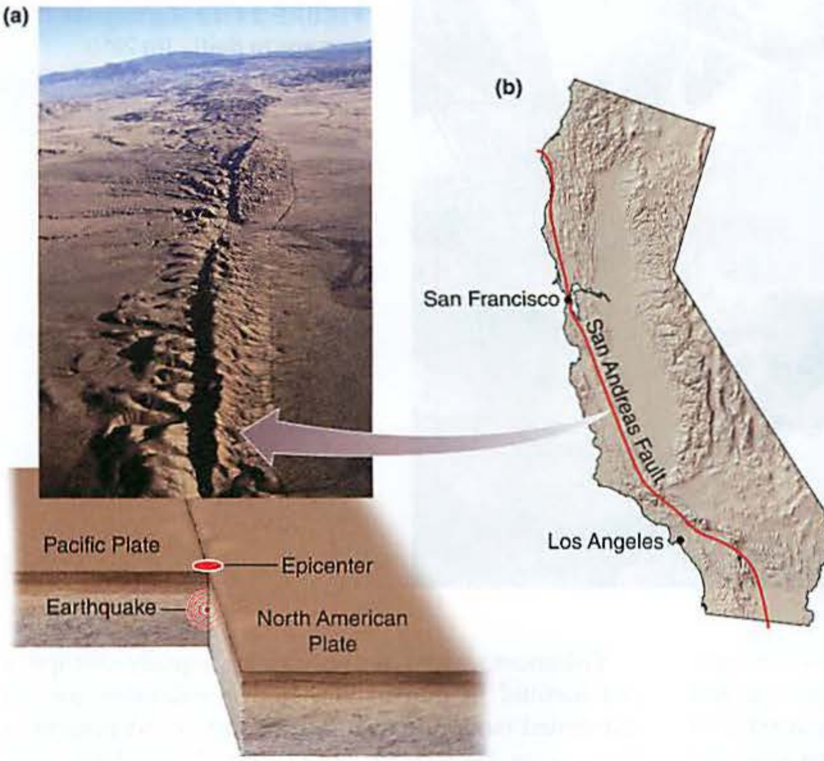


FIGURE 24.10 A fault zone. Many areas of seismic activity, including the San Andreas Fault in California, are characterized by a transform fault. The epicenter of an earthquake is the point on the surface of Earth directly above the location where the rock ruptures. *(age fotostock/SuperStock)*

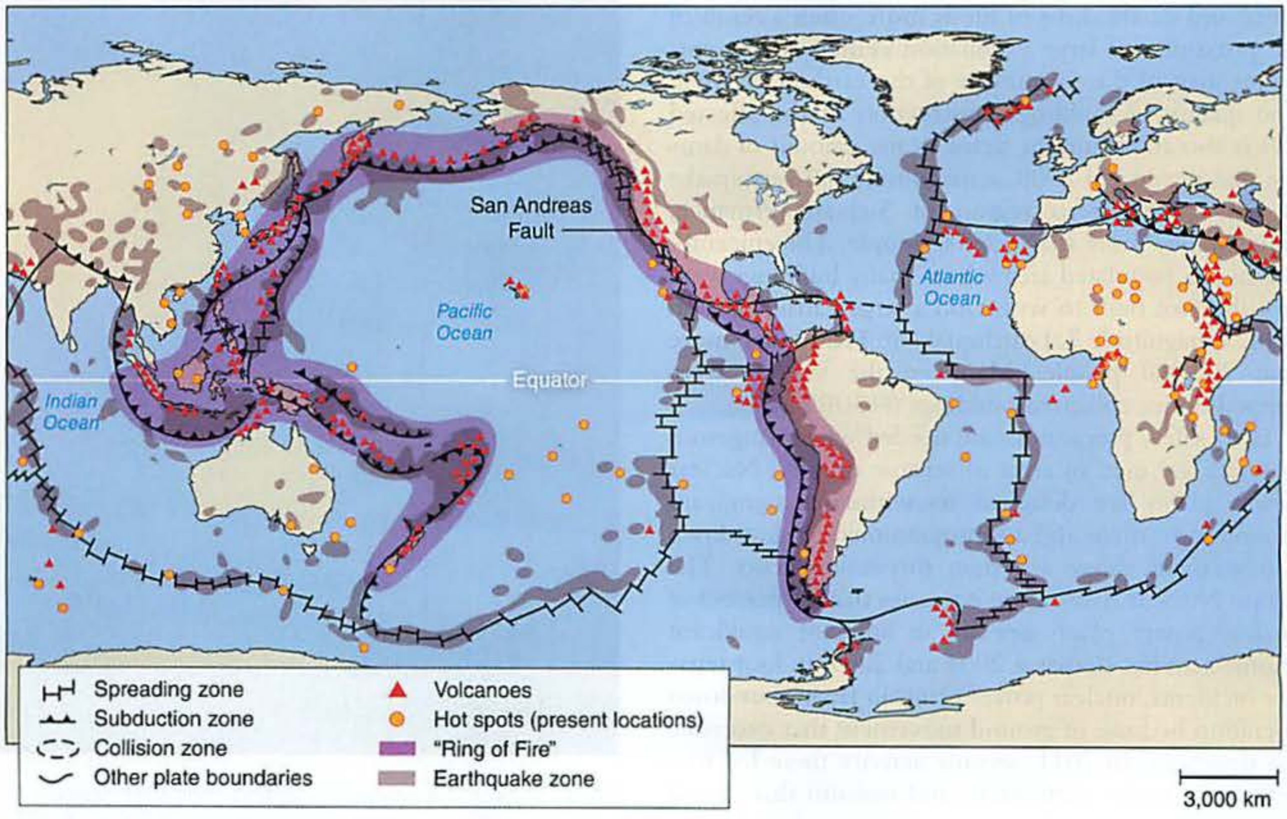


FIGURE 24.11 Locations of earthquakes and volcanoes. A "Ring of Fire" circles the Pacific Ocean along plate boundaries. Other zones of seismic and volcanic activity, including hot spots, are also shown on this map.

FIGURE 24.12 Earthquake damage in Haiti. The 2010 earthquake in Haiti killed more than 200,000 people and destroyed most of the structures in the capital, Port-au-Prince. *(Dominic Nahr/Magnum Photos)*

earthquake and 1,000 (10^3) times greater than a magnitude 4.0 earthquake, which only some people can feel or notice. Worldwide, there may be as many as 800,000 small earthquakes of magnitude 2.0 or less per year, but an earthquake of magnitude 8.0 occurs approximately once every year.

Even a moderate amount of Earth movement can be disastrous. Moderate earthquakes (defined as magnitudes 5.0 to 5.9) lead to collapsed structures and buildings, fires, contaminated water supplies, ruptured dams, and deaths. Loss of life is more often a result of the proximity of large population centers to the epicenter than of the magnitude of the earthquake itself. The quality of building construction in the affected area is also an important factor in the amount of damage that occurs. In 2008, a magnitude 7.9 earthquake in the southwestern region of Sichuan Province, China, killed more than 69,000 people. The epicenter was near a populated area where many buildings were probably not built to withstand a large earthquake. In 2010, a magnitude 7.0 earthquake in Haiti killed more than 200,000 people. Many of the victims were trapped under collapsed buildings (FIGURE 24.12).

Extra safety precautions are needed when dangerous materials are used in areas of seismic activity. Nuclear power plants are designed to withstand significant ground movement and are programmed to shut down if movement above a certain threshold occurs. The World Nuclear Association estimates that 20 percent of nuclear power plants operate in areas of significant seismic activity. Between 2004 and 2009, in four separate incidents, nuclear power plants in Japan shut down operation because of ground movement that exceeded the threshold. In 2011, seismic activity there led to a devastating major earthquake and tsunami that caused the second-worst nuclear power plant accident ever to occur, as we will see in Chapter 13.

Volcanoes, when active, can be equally disruptive and harmful to human life. Active volcanoes are not distributed randomly over Earth's surface; 85 percent of them occur along plate boundaries. As we have seen, volcanoes can also occur over hot spots. Depending on the type of volcano, an eruption may eject cinders, ash, dust, rock, or lava into the air (FIGURE 24.13). Volcanoes

FIGURE 24.13 A volcanic eruption. This 2001 explosive eruption from the Etna volcano in Italy threatened several nearby towns. *(Mario Cipollini/Aurora)*

(a) (b) (c)

FIGURE 24.14 Some common minerals. (a) Pyrite (FeS_2), also called "fool's gold." (b) Graphite, a form of carbon (C). (c) Halite, or table salt (NaCl). *(a–b: John Grotzinger/Ramón Rivera-Moret/Harvard Mineralogical Museum; c: The Natural History Museum/Alamy)*

can result in loss of life, habitat destruction and alteration, reduction in air quality, and many other environmental consequences.

The world gained a new awareness of the impact of volcanoes when eruptions from a volcano in Iceland disrupted air travel to and from Europe in April 2010. Ash from the eruption entered the atmosphere in a large cloud and prevailing winds spread it over a wide area. The ash contained small particles of silicon dioxide, which have the potential to damage airplane engines. Air travel was suspended in many parts of Europe, and millions of travelers were stranded in what may have been the greatest travel disruption ever to have been caused by a volcano.

The rock cycle recycles scarce minerals and elements

The second part of the geologic cycle is the **rock cycle**, which refers to the constant formation and destruction of rock. The rock cycle is the slowest of all of Earth's cycles. Environmental scientists are most often concerned with the part of the rock cycle that occurs at or near Earth's surface.

Rock, the substance of the lithosphere, is composed of one or more minerals (FIGURE 24.14). Minerals are solid chemical substances with uniform (often crystalline) structures that form under specific temperatures and pressures. They are usually compounds, but may be composed of a single element such as silver or gold.

Formation of Rocks and Minerals

FIGURE 24.15 shows the processes of the rock cycle. Rock forms when magma from Earth's interior reaches the surface, cools, and hardens. Once at Earth's surface, rock masses are broken up, moved, and deposited in new locations by processes such as weathering and erosion. New rock may be formed from the deposited material. Eventually, the rock is subducted into the mantle, where it melts and becomes magma again. The rock cycle slowly but continuously breaks down rock and forms new rock.

While magma is the original source of all rock, there are three major ways in which the rocks we see at Earth's surface can form: directly from molten magma; by compression of sediments; and by exposure of rocks and other Earth materials to high temperatures and pressures. These three modes of formation lead to three distinct rock types: *igneous, sedimentary,* and *metamorphic.*

Igneous Rocks

Igneous rocks form directly from magma. They are classified by their chemical composition as basaltic or granitic, and by their mode of formation as intrusive or extrusive.

Basaltic rock is dark-colored rock that contains minerals with high concentrations of iron, magnesium, and calcium. It is the dominant rock type in the crust of oceanic plates. Granitic rock is lighter-colored rock made up of the minerals feldspar, mica, and quartz, and contains elements such as silicon, aluminum, potassium, and calcium. It is the dominant rock type in the crust of continental plates. When granitic rock breaks down due to weathering, it forms sand. Soils that develop from granitic rock tend to be more permeable

Rock cycle The geologic cycle governing the constant formation, alteration, and destruction of rock material that results from tectonics, weathering, and erosion, among other processes.

Igneous rock Rock formed directly from magma.

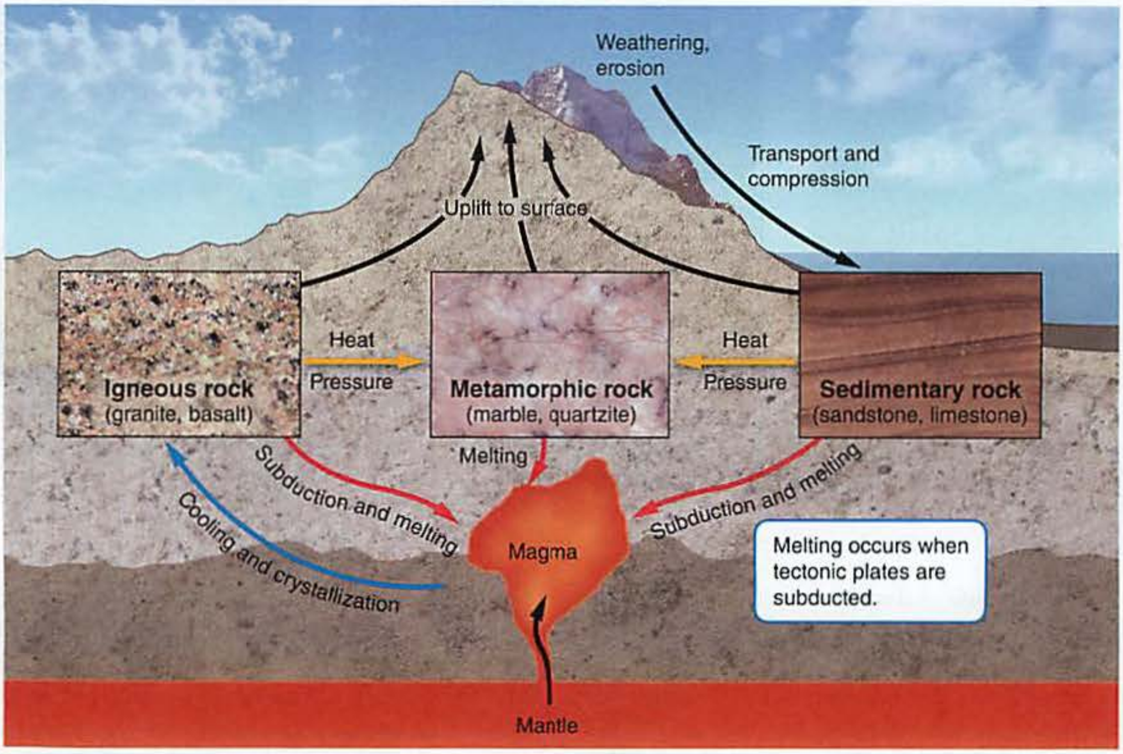


FIGURE 24.15 The rock cycle. The rock cycle slowly but continuously forms new rock and breaks down old rock. Three types of rock are created in the rock cycle: Igneous rock is formed from magma; sedimentary rock is formed by the compression of sedimentary materials; and metamorphic rock is created when rocks are subjected to high temperatures and pressures.

than those that develop from basaltic rock, but both types of rock can form fertile soil.

Intrusive igneous rocks form within Earth as magma rises up and cools in place underground. **Extrusive igneous rocks** form when magma cools above Earth's surface, such as when it is ejected from a volcano or released by seafloor spreading. Extrusive rocks cool rapidly, so their minerals have little time to expand into large individual crystals. The result is fine-grained, smooth types of rock such as obsidian. Both extrusive and intrusive rocks can be either granitic or basaltic in composition.

The formation of igneous rock often brings to the surface rare elements and metals that humans find economically valuable, such as the lanthanum described at the beginning of this chapter. When rock cools, it is subject to stresses that cause it to break. Cracks that occur when rock cools, known as **fractures,** can occur in any kind of rock. Water from the surface of Earth running through fractures may dissolve valuable metals, which may precipitate out in the fractures to form concentrated deposits called *veins*. These deposits are important sources of gold- and silver-bearing ores as well as rare metals such as tantalum, which is used to manufacture electronic components of cell phones.

Intrusive igneous rock Igneous rock that forms when magma rises up and cools in a place underground.

Extrusive igneous rock Rock that forms when magma cools above the surface of Earth.

Fracture In geology, a crack that occurs in rock as it cools.

Sedimentary rock Rock that forms when sediments such as muds, sands, or gravels are compressed by overlying sediments.

Metamorphic rock Rock that forms when sedimentary rock, igneous rock, or other metamorphic rock is subjected to high temperature and pressure.

Sedimentary Rocks

Sedimentary rocks form when sediments such as muds, sands, or gravels are compressed by overlying sediments. Sedimentary rock formation occurs over long periods when environments such as sand dunes, mudflats, lake beds, or areas prone to landslides are buried and the overlying materials create pressure on the materials below. The resulting rocks may be uniform in composition, such as sandstones and mudstones that formed from ancient oceanic or lake environments. Alternatively, they may be highly heterogeneous, such as conglomerate rocks formed from mixed cobbles, gravels, and sands.

Sedimentary rocks hold the fossil record that provides a window into our past. When layers of sediment containing plant or animal remains are compressed over eons, those organic materials may be preserved, as described in Chapter 5.

Metamorphic Rocks

Metamorphic rocks form when sedimentary rocks, igneous rocks, or other metamorphic rocks are subjected to high temperatures and pressures. The pressures that form metamorphic rock cause profound physical and chemical changes in the rock. These pressures can be exerted by overlying rock layers or by tectonic processes such as continental collisions, which cause extreme horizontal pressure and distortion. Metamorphic rocks include stones such as slate and marble as well as anthracite, a type of coal. Metamorphic rocks have long been important as building materials in human civilizations because they are structurally strong and visually attractive.

module
24

REVIEW

In this module, we looked at the formation of Earth and the distribution of minerals. After Earth formed, heavier elements sank to the core, which accounts for the distribution and abundance of elements we see at the surface of Earth. The plates that overlay Earth and move at different rates further distribute elements. Plates are in constant motion around the globe and the resulting seismic activity contributes to various environmental hazards and has led to the creation of different landforms such as mountain ranges. Minerals and rocks of various compositions result from the chemical composition of the material that forms them, and the geologic conditions under which they form. When rocks and minerals break down as a result of various environmental conditions, they release chemical elements and the precursors of soils. In the next module we will examine the conditions under which rocks break down and how that contributes to the variety of soils that form around the world.

Module 24 AP® Review Questions

1. Which layer of Earth is composed primarily of iron and nickel?
   (a) The core
   (b) The crust
   (c) The asthenophere
   (d) The mantle
   (e) The lithosphere

2. Subduction
   (a) is the reason similar fossils appear on both sides of the Atlantic.
   (b) is the result of a hot spot moving near a plate boundary.
   (c) occurs when one plate passes under another.
   (d) occurs when oceanic plates diverge and form volcanoes.
   (e) is the process in transform boundaries that results in earthquakes.

3. The Hawaiian islands were formed
   (a) at a divergent plate boundary.
   (b) at a hot spot.
   (c) at a convergent plate boundary.
   (d) at a transform fault.
   (e) at a mid-ocean ridge.

4. How far will a plate travel in 60,000 years if it moves at net rate of 25 mm/yr?
   (a) 24 m
   (b) 1,500 m
   (c) 3,000 m
   (d) 4,800 m
   (e) 12,000 m

5. Which rock is formed at high temperatures and pressures?
   (a) Extrusive igneous
   (b) Intrusive igneous
   (c) Basaltic
   (d) Sedimentary
   (e) Metamorphic

6. Earthquake epicenters are often at
   (a) divergent boundaries.
   (b) convergent boundaries.
   (c) transform boundaries.
   (d) hot spots.
   (e) subduction zones.

module

25

Weathering and Soil Science

Soil is a combination of geologic and organic material that forms a dynamic membrane over much of the surface of Earth. A variety of processes that occur in soil connect the overlying biology with the underlying geology. In this module we will explore the weathering of rocks that leads to the formation of soil and the development of specific soil horizons. We will discuss physical, chemical, and biological processes that take place in soils. Finally, we will examine human activities that degrade soils, including the process of mining.

Learning Objectives

After reading this module, you should be able to

- understand how weathering and erosion occur and how they contribute to element cycling and soil formation.
- explain how soil forms and describe its characteristics.
- describe how humans extract elements and minerals and the social and environmental consequences of these activities.

The processes of weathering and erosion contribute to the recycling of elements

We have seen that rock forms beneath Earth's surface under intense heat, pressure, or both heat and pressure. When rock is exposed at Earth's surface, it begins to break down through the processes of weathering and erosion. These processes are components of the rock cycle, returning chemical elements and rock fragments to the crust by depositing them as sediments through the hydrologic cycle. This physical breakdown and chemical alteration of rock begins the cycle all over again, as shown in Figure 24.15. Without this part of the rock cycle, elements would never be recycled and the precursors of soils would not be present.

Physical weathering The mechanical breakdown of rocks and minerals.

Weathering

Weathering occurs when rock is exposed to air, water, certain chemical compounds, or biological agents such as plant roots, lichens, and burrowing animals. There are two major categories of weathering—*physical* and *chemical*—that work in combination to degrade rocks.

Physical weathering is the mechanical breakdown of rocks and minerals, shown in FIGURE 25.1. Physical

(a)

(b)

FIGURE 25.1 Physical weathering. (a) Water can work its way into cracks in rock, where it can wash away loose material. When the water freezes and expands, it can widen the cracks. (b) Growing plant roots can force rock sections apart.

weathering can be caused by water, wind, or variations in temperature such as seasonal freeze-thaw cycles. When water works its way into cracks or fissures in rock, it can remove loose material and widen the cracks, as illustrated in Figure 25.1a. When water freezes in the cracks, the water expands, and the pressure of its expansion can force rock to break. Different responses to temperature can cause two minerals within a rock to expand and contract differently, which also results in splitting or cracking. Coarse-grained rock formed by slow cooling or metamorphism tends to weather more quickly than fine-grained rock formed by rapid cooling or metamorphism.

Biological agents can also cause physical weathering. Plant roots can work their way into small cracks in rocks and pry them apart, as illustrated in Figure 25.1b. Burrowing animals may also contribute to the breakdown of rock material, although their contributions are usually minor. However it occurs, physical weathering exposes more surface area and makes rock more vulnerable to further degradation. By producing more surface area for weathering processes to act on, physical weathering increases the rate of *chemical weathering*. **Chemical weathering** is the breakdown of rocks and minerals by chemical reactions, the dissolving of chemical elements from rocks, or both these processes. It releases essential nutrients from rocks, making them available for use by plants and other organisms.

Chemical weathering occurs most rapidly on newly exposed minerals, known as primary minerals. It alters primary minerals to form secondary minerals and the ionic forms of their constituent chemical elements. For example, when feldspar—a mineral found in granitic rock—is exposed to natural acids in rain, it forms clay particles and releases ions such as potassium, an essential nutrient for plants. Lichens can break down rock in a similar way by producing weak acids. Their effects can commonly be seen on soft gravestones and masonry. Rocks that contain compounds that dissolve easily, such as calcium carbonate, tend to weather quickly. Rocks that contain compounds that do not dissolve readily are often the most resistant to chemical weathering. In examining element cycles in Chapter 3, we noted that weathering of rocks is an important part of the phosphorus cycle.

Recall from Chapter 2 that solutions can be basic or acidic. Depending on the starting chemical composition of rock and the pH of the water that comes in contact with it, hundreds of different chemical reactions can take place. For example, as we saw in Chapter 2, carbon dioxide in the atmosphere dissolves in water vapor to create a weak acid, called carbonic acid. When waters containing carbonic acid flow into geologic regions that are rich in limestone, they dissolve the limestone (which is composed of calcium carbonate) and create spectacular cave systems (**FIGURE 25.2**).

Some chemical weathering is the result of human activities. For example, sulfur emitted into the atmosphere from fossil fuel combustion combines with oxygen to form sulfur dioxide. That sulfur dioxide reacts with water vapor in the atmosphere to form sulfuric acid, which then causes *acid precipitation*. **Acid precipitation,** also called **acid rain,** is precipitation high in sulfuric acid and nitric acid from reactions between water vapor and sulfur and nitrogen oxides in the atmosphere. Acid precipitation is responsible for the rapid degradation of certain old statues and gravestones and other limestone and marble structures. When acid precipitation falls on soil, it can promote

Chemical weathering The breakdown of rocks and minerals by chemical reactions, the dissolving of chemical elements from rocks, or both.

Acid precipitation Precipitation high in sulfuric acid and nitric acid from reactions between water vapor and sulfur and nitrogen oxides in the atmosphere. *Also known as* **Acid rain.**

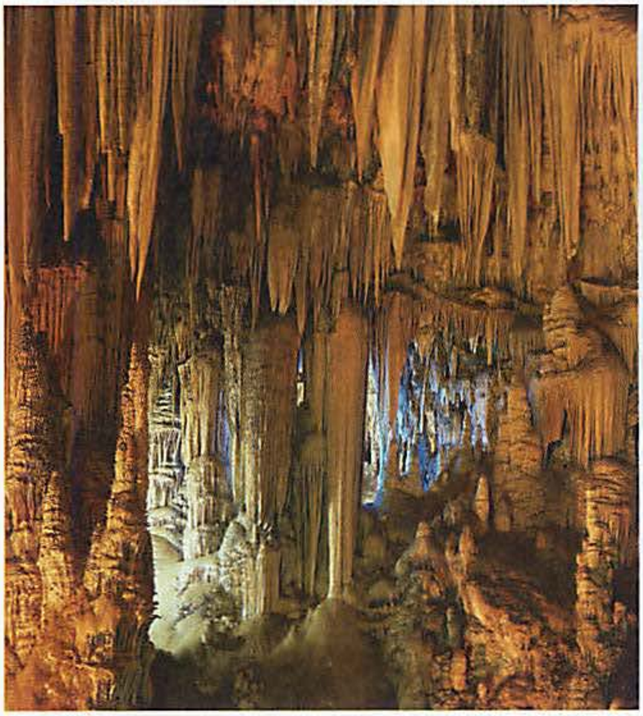


FIGURE 25.2 **Chemical weathering.** Water that contains carbonic acid wears away limestone, sometimes forming spectacular caves. *(Mauritius/SuperStock)*

FIGURE 25.3 **Erosion.** Some erosion, such as the erosion that created these formations in the Badlands of South Dakota, occurs naturally as a result of the effects of water, glaciers, or wind. The Badlands are the result of the erosion of softer sedimentary rock types, such as shales and clays. Harder rocks, including many types of metamorphic and igneous rocks, are more resistant to erosion. *(welcomia/Shutterstock)*

chemical weathering of certain minerals in the soil, releasing elements that may then be taken up by plants or leached from the soil into groundwater and streams.

Chemical weathering, due to either natural processes or acid precipitation, can contribute additional elements to an ecosystem. Knowing the rate of weathering helps researchers assess how rapidly soil fertility can be renewed in an ecosystem. In addition, because the chemical reactions involved in the weathering of certain granitic rocks consume carbon dioxide from the atmosphere, weathering can actually reduce atmospheric carbon dioxide concentrations.

Erosion

We have seen that physical and chemical weathering results in the breakdown and chemical alteration of rock. **Erosion** is the physical removal of rock fragments (sediment, soil, rock, and other particles) from a landscape or ecosystem. Erosion is usually the result of two mechanisms. In one, wind, water, and ice move soil and other materials by downslope creep under the force of gravity. In the other, living organisms, such as animals that burrow under the soil, cause erosion. After eroded material has traveled a certain distance from its source, it accumulates. Deposition is the accumulation or depositing of eroded material such as sediment, rock fragments, or soil.

Erosion The physical removal of rock fragments from a landscape or ecosystem.

Erosion is a natural process: Streams, glaciers, and wind-borne sediments continually carve, grind, and scour rock surfaces (FIGURE 25.3). In many places, however, human land use contributes substantially to the rate of erosion. Poor land use practices such as deforestation, overgrazing, unmanaged construction activity, and road building can create and accelerate erosion problems. Furthermore, erosion usually leads to deposition of the eroded material somewhere else, which may cause additional environmental problems. We discuss human-caused erosion further in Chapters 10 and 11.

Soil links the rock cycle and the biosphere

Soil has a number of functions that benefit organisms and ecosystems. As you can see in FIGURE 25.4, soil is a medium for plant growth. It also serves as the primary filter of water as water moves from the atmosphere into rivers, streams, and groundwater. Soil contributes greatly to biodiversity by providing habitat for a wide variety of living organisms—from bacteria, algae, and fungi to insects and other animals. Soil and the organisms within it filter chemical compounds deposited by air pollution and by household sewage systems; some of these materials remain in the soil and some are released to the atmosphere or into groundwater.

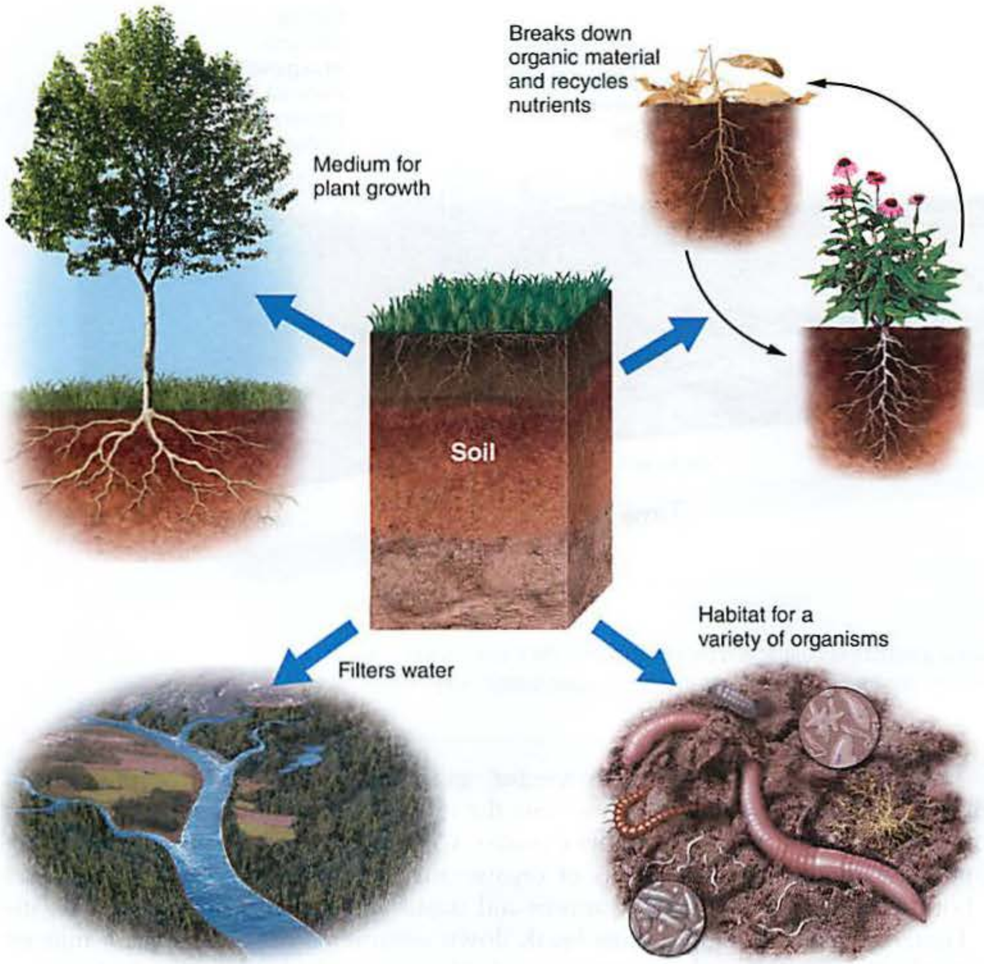


FIGURE 25.4 Ecosystem services provided by soil. Soil serves as a medium for plant growth, as a habitat for other organisms, and as a recycling system for organic wastes. Soil also helps to filter and purify water.

In this section we will look at the formation and properties of soil.

The Formation of Soil

In order to appreciate the role of soil in ecosystems, we need to understand how and why soil forms and what happens to soil when humans alter it. It takes hundreds to thousands of years for soil to form. Soil is the result of physical and chemical weathering of rocks and the gradual accumulation of detritus from the biosphere. We can determine the specific properties of a soil if we know its parent rock type, the amount of time it has been forming, and its associated biotic and abiotic components.

FIGURE 25.5 shows the stages of soil development from rock to mature soil. The processes that form soil work in two directions simultaneously. The breakdown of rocks and primary minerals by weathering provides the raw material for soil from below. The deposition of organic matter from organisms and their wastes contributes to soil formation from above. What we normally think of as "soil" is a mix of these mineral and organic components. A poorly developed (young) soil has substantially less organic matter and fewer nutrients than a more developed (mature) soil. Very old soils may also be nutrient poor because over time plants remove many essential nutrients and water leaches away others. Five factors simultaneously determine the properties of soils: *parent material,* climate, topography, organisms, and time.

Parent Material

A soil's **parent material** is the underlying rock material from which a soil's inorganic components are derived. Different soil types arise from different parent materials. For example, a quartz sand (made up of silicon dioxide) parent material will give rise to a soil that is nutrient poor, such as those along the Atlantic coast of the United States. By contrast, a soil that has calcium carbonate as its parent material will contain an abundant supply of calcium, have a high pH, and may also support high agricultural productivity. Such soils are found in the area surrounding Lake Champlain in Vermont and northern New York, as well as in many other locations.

Parent material The rock material from which the inorganic components of a soil are derived.

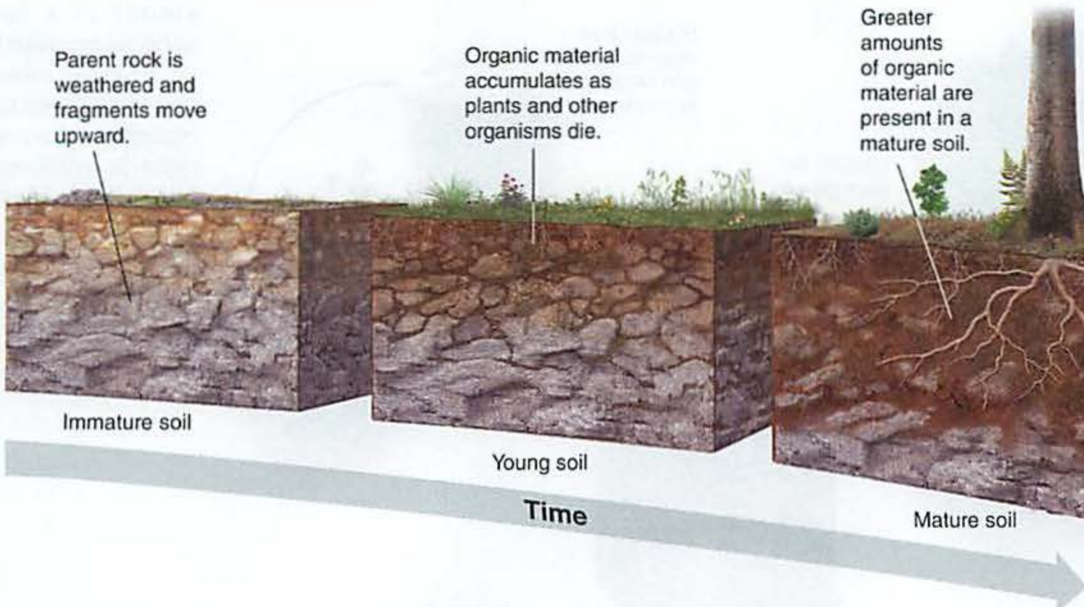


FIGURE 25.5 Soil formation. Soil is a mixture of organic and inorganic matter. The breakdown of rock and primary minerals from the parent material provides the inorganic matter. The organic matter comes from organisms and their wastes.

Climate

Climate influences soil formation in a number of ways. Soils do not develop well when temperatures are below freezing because decomposition of organic matter and water movement are both extremely slow in frozen or nearly frozen soils. Therefore, soils at high latitudes of the Northern Hemisphere are composed largely of organic material in an undecomposed state, as we saw in Chapter 4. In contrast, soil development in the humid tropics is accelerated by rapid weathering of rock and soil minerals, leaching of nutrients, and decomposition of organic detritus. Climate also has an indirect effect on soil formation because it affects the type of vegetation that develops, and therefore the type of detritus left after the vegetation dies.

Topography

Topography—the surface slope and arrangement of a landscape—is another factor in soil formation. Soils that form on steep slopes are constantly subjected to erosion and, on occasion, more drastic mass movements of material as happens in landslides. In contrast, soils that form at the bottoms of steep slopes may continually accumulate material from higher elevations and become quite deep.

Organisms

Many organisms influence soil formation. Plants remove nutrients from soil and excrete organic acids that speed chemical weathering. Animals that tunnel or burrow—for example, earthworms, gophers, and voles—mix the soil, uniformly distributing organic and mineral matter. Collectively, soil organisms act as recyclers of organic matter. In the process of using dead organisms and wastes as an energy source, soil organisms break down organic detritus and release mineral nutrients and other materials that benefit plants.

Human activity has dramatic effects on soils. For centuries, the use and overuse of land for agriculture, forestry, and other human activities has led to significant **soil degradation**: the loss of some or all of the ability of soils to support plant growth. One of the major causes of soil degradation is soil erosion, which occurs when topsoil is disturbed—for example, by plowing—or when vegetation is removed. As we saw in Chapter 3, these activities lead to erosion by water or wind (**FIGURE 25.6**).

Soil degradation The loss of some or all of a soil's ability to support plant growth.

FIGURE 25.6 Erosion from human activity. Erosion in this cornfield in Tennessee is obvious after a brief rainstorm. *(Tim McCabe/ USDA Natural Resources Conservation Service)*

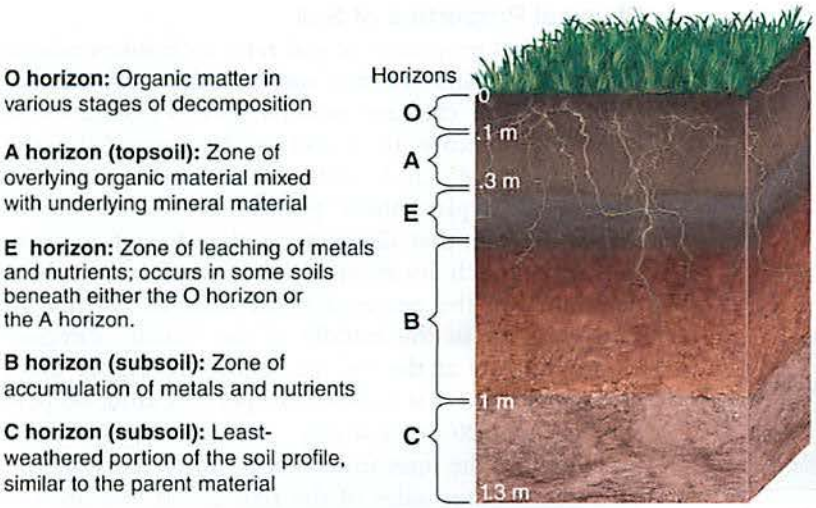


FIGURE 25.7 Soil horizons. All soils have horizons, or layers, which vary depending on soil-forming factors such as climate, organisms, and parent material. Most soils have either an O or A horizon and usually not both. Some soils that have an O horizon also have an E horizon.

While topsoil loss can happen rapidly—in as little as a single growing season—it takes centuries for the lost topsoil to be replaced. Compaction of soil by machines, humans, and livestock can alter its properties and reduce its ability to retain moisture. Compaction and drying of soil can, in turn, reduce the amount of vegetation that grows in the soil and thereby increase erosion. Intensive agricultural use and irrigation can deplete soil nutrients, and the application of agricultural pesticides can pollute the soil. In Chapters 11 and 14 we will return to the ways in which human activity affects the soil.

Time

The final factor that determines the properties of a soil is the amount of time during which the soil has developed. As soils age, they develop a variety of characteristics. The grassland soils that support much of the food crop and livestock feed production in the United States are relatively old soils. Because they have had continual inputs of organic matter for hundreds of thousands of years from the grassland and prairie vegetation growing above them, they have become deep and fertile. Other soils that are equally old, but with less productive communities above them and perhaps greater quantities of water moving through them, can become relatively infertile.

Soil Horizons

As soils form, they develop characteristic **horizons,** which are horizontal layers with distinct physical features such as color or texture, shown in FIGURE 25.7. The specific composition of those horizons depends largely on climate, vegetation, and parent material. At the surface of many soils is a layer known as the **O horizon,** composed of organic detritus such as leaves, needles, twigs, and even animal bodies, all in various stages of decomposition. The O horizon is most pronounced in forest soils and is also found in some grasslands. Organic matter is sometimes called humus (pronounced "hu-mus," but often mispronounced by beginning students as hummus, the delicious food made from chickpeas, olive oil, and garlic). In actuality, only the most decomposed organic matter at the lowest part of the organic horizon is truly humus.

In a soil that is mixed, either naturally or by human agricultural practices, the top layer is the **A horizon,** also known as **topsoil,** a zone of organic material and minerals that have been mixed together. In some acidic soils, an **E horizon**—a zone of leaching, or eluviation—forms under the O horizon or, less often, the A horizon. When an E horizon is present, iron, aluminum, and dissolved organic acids from the overlying horizons are transported through and removed from the E horizon and then deposited in the B horizon, where they accumulate. When an E horizon is present, it always occurs above the *B horizon.* The **B horizon,** commonly known as subsoil, is composed primarily of mineral material with very little organic matter. If nutrients are present in the soil, they will be in the B horizon. The **C horizon**—the least weathered soil horizon—occurs beneath the B horizon and is similar to the parent material.

Horizon A horizontal layer in a soil defined by distinctive physical features such as texture and color.

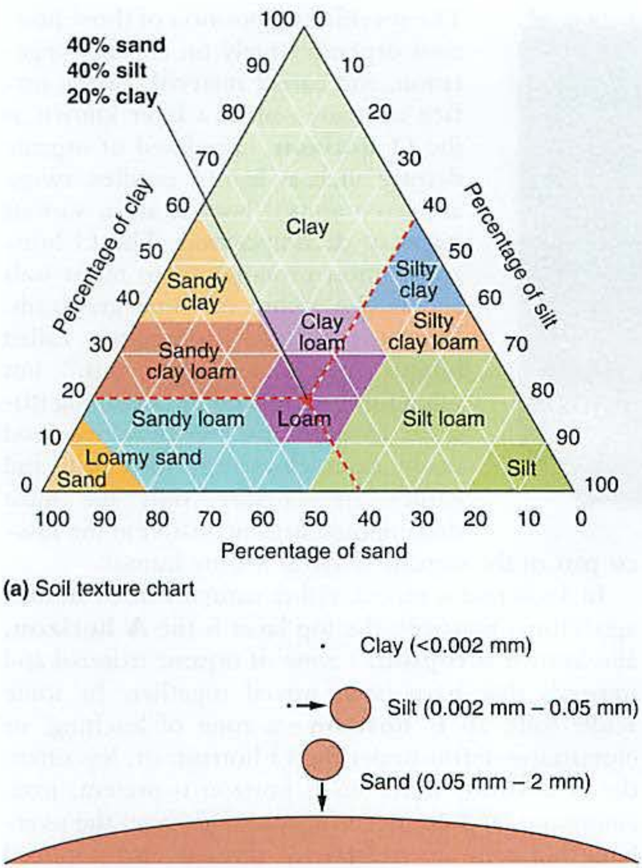
O horizon The organic horizon at the surface of many soils, composed of organic detritus in various stages of decomposition.

A horizon Frequently the top layer of soil, a zone of organic material and minerals that have been mixed together. *Also known as* **Topsoil.**

E horizon A zone of leaching, or eluviation, found in some acidic soils under the O horizon or, less often, the A horizon.

B horizon A soil horizon composed primarily of mineral material with very little organic matter.

C horizon The least-weathered soil horizon, which always occurs beneath the B horizon and is similar to the parent material.



(a) Soil texture chart

(b) Relative soil particle sizes (magnified approximately 100 times)

FIGURE 25.8 Soil properties. (a) Soils consist of a mixture of clay, silt, and sand. The relative proportions of these particles determine the texture of the soil. (b) The relative sizes of sand, silt, and clay.

Properties of Soil

Soils with different properties serve different functions for humans. For example, some soil types are good for growing crops and others are more suited for building a housing development. Therefore, to understand and classify soil types, we need to understand the physical, chemical, and biological properties of soils.

Physical Properties of Soil

The physical properties of soil refer to features related to physical characteristics such as size and weight. Sand, silt, and clay are mineral particles of different sizes. The texture of a soil is determined by the percentages of sand, silt, and clay it contains. FIGURE 25.8a plots those percentages on a triangle-shaped diagram that allows us to identify and compare soil types. Each location on the diagram has three determinants: the percentages of sand, of silt, and of clay. A point in the middle of the "loam" category (approximately at the "a" in "loam" in Figure 25.8) represents a soil that contains 40 percent sand, 40 percent silt, and 20 percent clay. We can determine this by following the lines from that point to the scales on each of the three sides of the triangle. If you are not certain which line to follow from a given point, always follow the line that leads to the lower value. For example, if you want to determine the percentage of sand in a sample represented by the red dot in Figure 25.8, you might follow the line out to either 60 percent sand or 40 percent sand; however, since you should always follow the line to the lower value, in this case the percentage of sand is 40 percent. The sum of sand, silt, and clay will always be 100 percent. Conversely, in the laboratory, a soil scientist can determine the percentage of each component in a soil sample and then plot the results. The name for the soil, for example "silty clay loam," follows from the percentage of the components in the soil.

The permeability of soil—how quickly soil drains—depends on its texture, shown in FIGURE 25.9. Sand particles—the largest of the three components—pack together loosely. Water can move easily between the particles, making sand quick to drain and quick to dry out. Soils with a high proportion of sand are also easy for roots to penetrate, making sandy soil somewhat advantageous for growing plants such as carrots and potatoes. Clay particles—the smallest of the three components—pack together much more tightly than sand particles. As a result, there is less pore space in a soil dominated by clay, and water and roots cannot easily move through it. Silt particles are intermediate both in size and in their ability to drain or retain water.

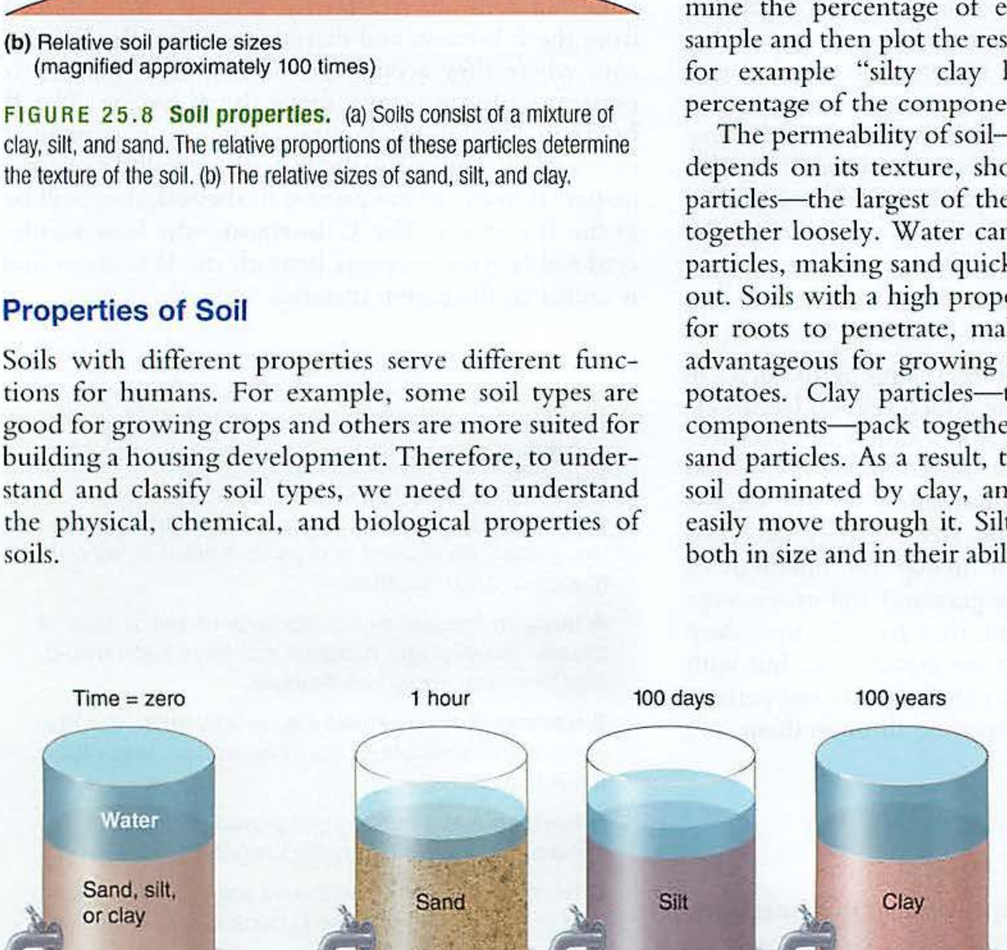


FIGURE 25.9 Soil permeability. The permeability of soil depends on its texture. Sand, with its large, loosely packed particles, drains quickly. Clay drains much more slowly.

The best agricultural soil is a mixture of sand, silt, and clay. This mixture promotes balanced water drainage and retention. In natural ecosystems, however, various herbaceous and woody plants have adapted to growing in wet, intermediate, and dry environments, so there are plants that thrive in soils of virtually all textures.

Soil texture can have a strong influence on how the physical environment responds to environmental pollution. For example, the ground water of western Long Island in New York State has been contaminated over the years by toxic chemicals discharged from local industries. One major reason for the contamination is that Long Island is dominated by sandy soils that readily allow surface water to drain into the groundwater. While soil usually serves as a filter that removes pollutants from the water moving through it, sandy soils are so permeable that pollutants move through them quickly and therefore are not filtered effectively.

Clay is particularly useful where a potential contaminant needs to be contained. Many modern landfills are lined with clay, which helps keep the contaminants in solid waste from leaching into the soil and groundwater beneath the landfill.

Chemical Properties of Soil

Chemical properties are also important in determining how a soil functions. Clay particles contribute the most to the chemical properties of a soil because of their ability to attract positively charged mineral ions, referred to as cations. Because clay particles have a negative electrical charge, cations are adsorbed—held on the surface—by the particles. The cations can be subsequently released from the particles and used as nutrients by plants.

The ability of a particular soil to adsorb and release cations is called its **cation exchange capacity (CEC),** sometimes referred to as the nutrient holding capacity. The overall CEC of a soil is a function of the amount and types of clay particles present. Soils with high CECs have the potential to provide essential cations to plants and therefore are desirable for agriculture. If a soil is more than 20 percent clay, however, its water retention becomes too great for most crops as well as many other types of plants. In such waterlogged soils, plant roots are deprived of oxygen. Thus there is a trade off between CEC and permeability.

The relationship between soil bases and soil acids is another important soil chemical property. Calcium, magnesium, potassium, and sodium are collectively called soil bases because they can neutralize or counteract soil acids such as aluminum and hydrogen. Soil acids are generally detrimental to plant nutrition, while soil bases tend to promote plant growth. With the exception of sodium, all the soil bases are essential for plant nutrition. **Base saturation** is the proportion of soil bases to soil acids, expressed as a percentage.

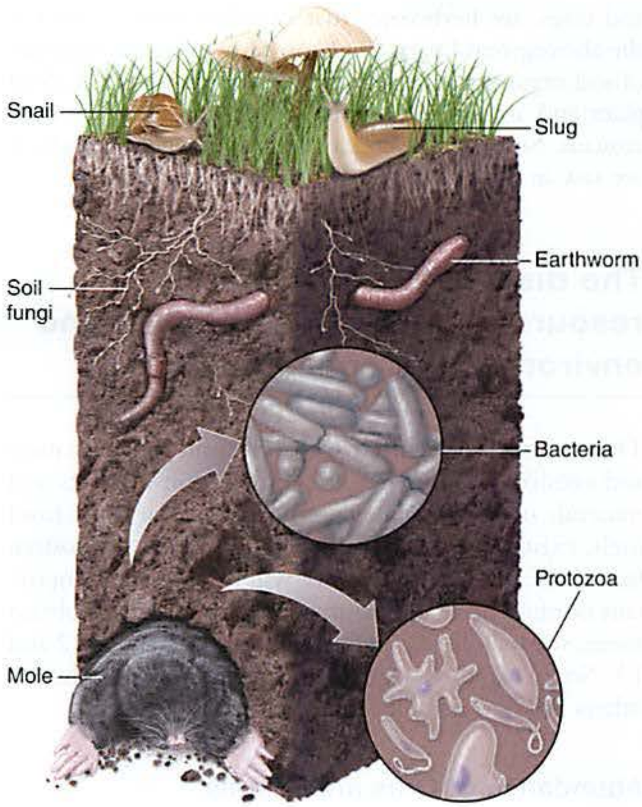


FIGURE 25.10 Soil organisms. Bacteria, fungi, and protozoans account for 80 to 90 percent of soil organisms. Also present are snails, slugs, insects, earthworms, and rodents.

Because of the way they affect nutrient availability to plants, CEC and base saturation are important determinants of overall ecosystem productivity. If a soil has a high CEC, it can retain and release plant nutrients. If it has a relatively high base saturation, its clay particles will hold important plant nutrients such as calcium, magnesium, and potassium. A soil with both high CEC and high base saturation is likely to support high productivity.

Biological Properties of Soil

As we have seen, a diverse group of organisms populates the soil. FIGURE 25.10 shows a representative sample. Three groups of organisms account for 80 to 90 percent of the biological activity in soils: fungi, bacteria, and protozoans (a diverse group of single-celled organisms). Rodents and earthworms contribute to soil mixing and the breakdown of large organic materials into smaller pieces. Earthworms are responsible for abundant humus formation in soils. Some soil organisms, such as snails

Cation exchange capacity (CEC) The ability of a particular soil to absorb and release cations.

Base saturation The proportion of soil bases to soil acids, expressed as a percentage.

and slugs, are herbivores that eat plant roots as well as the aboveground parts of plants. However, the majority of soil organisms are detritivores, which consume dead plant and animal tissues and recycle the nutrients they contain. Some soil bacteria also fix nitrogen, which, as we saw in Chapter 3, is essential for plant growth.

The distribution of mineral resources on Earth has social and environmental consequences

The tectonic cycle, the rock cycle, and soil formation and erosion all influence the distribution of rocks and minerals on Earth. These resources, along with fossil fuels, exist in finite quantities, but are vital to modern human life. In this section we will discuss some important nonfuel mineral resources and how humans obtain them; we will discuss fuel resources in Chapters 12 and 13. Some of these resources are abundant, whereas others are rare and extremely valuable.

Abundance of Ores and Metals

As we saw at the beginning of this chapter, early Earth cooled and differentiated into distinct vertical zones. Heavy elements sank toward the core, and lighter elements rose toward the crust. **Crustal abundance** is the average concentration of an element in Earth's crust. Looking at FIGURE 25.11, we can see that four elements—oxygen, silicon, aluminum, and iron—constitute over 88 percent of the crust. However, the chemical composition of the crust is highly variable from one location to another.

Environmental scientists and geologists study the distribution and types of mineral resources around the planet in order to locate them and to manage their extraction or conservation. **Ores** are concentrated accumulations of minerals from which economically valuable materials can be extracted. Ores are typically characterized by the presence of valuable metals, but accumulations of other valuable materials, such as salt or sand, can also be considered ores. **Metals** are elements with properties that allow them to conduct electricity and heat energy and to perform other important functions. Copper, nickel, and aluminum are common examples of metals. They exist in varying concentrations in rock, usually in association with elements such as sulfur, oxygen, and silicon. Some metals, such as gold, exist naturally in a pure form.

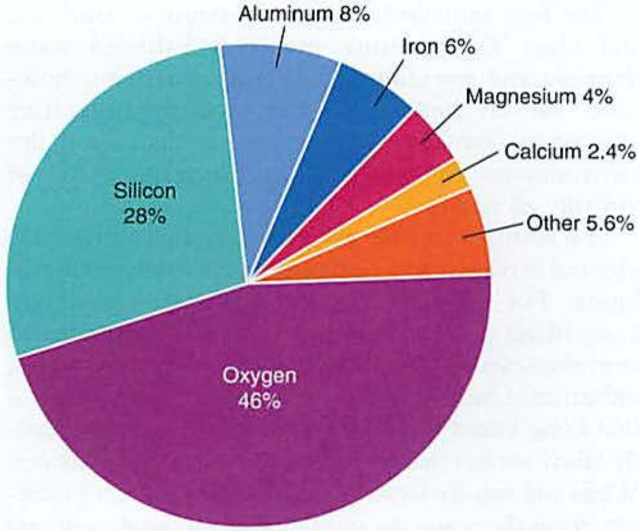


FIGURE 25.11 Elemental composition of Earth's crust. Oxygen is the most abundant element in the crust. Silicon, aluminum, and iron are the next three most abundant elements.

Ores are formed by a variety of geologic processes. Some ores form when magma comes into contact with water, heating the water and creating a solution from which metals precipitate, while others form after the deposition of igneous rock. Some ores occur in relatively small areas of high concentration, such as veins, and others, called disseminated deposits, occur in much larger areas of rock, although often in lower concentrations. Still other ores, such as copper, can be deposited both throughout a large area and in veins. Nonmetallic mineral resources, such as clay, sand, salt, limestone, and phosphate, typically occur in concentrated deposits. These deposits occur as a result of their chemical or physical separation from other materials by water, in conjunction with the tectonic and rock cycles. Some ores, such as bauxite—the ore in which aluminum is most commonly found—are formed by intense chemical weathering in tropical regions.

The global supply of mineral resources is difficult to quantify. Because private companies hold the rights to extract certain mineral resources, information about the exact quantities of resources is not always available to the public. The publicly known estimate of how much of a particular resource is available is based on its **reserve**: the known quantity of the resource that can be economically recovered.

Crustal abundance The average concentration of an element in Earth's crust.

Ore A concentrated accumulation of minerals from which economically valuable materials can be extracted.

Metal An element with properties that allow it to conduct electricity and heat energy, and to perform other important functions.

Reserve In resource management, the known quantity of a resource that can be economically recovered.

TABLE 25.1 Approximate Supplies of Metal Reserves Remaining

Metal	Global reserves remaining (years)	U.S. reserves remaining (years)
Iron (Fe)	120	40
Aluminum (Al)	330	2
Copper (Cu)	65	40
Lead (Pb)	20	40
Zinc (Zn)	30	25
Gold (Au)	30	20
Nickel (Ni)	75	0
Cobalt (Co)	50	0
Manganese (Mn)	70	0
Chromium (Cr)	85	0

Sources: Data from S. Marshak, *Earth: Portrait of a Planet*, 3rd ed. (W. W. Norton, 2007); U.S. Geological Survey Mineral Commodity Summaries 2013, http://minerals.er.usgs.gov/minerals/pubs/mcs/.

TABLE 25.1 lists the estimated number of years of remaining supplies of some of the most important metal resources commonly used in the United States, assuming that rates of use do not change. Some important metals, such as tantalum, have never existed in the United States. The United States has used up all of its reserves of some other metals, such as nickel, and must now import those metals from other countries.

Mining Techniques

Mineral resources are extracted from Earth by mining the ore and separating any other minerals, elements, or residual rock away from the sought-after element or mineral. As illustrated in FIGURE 25.12, two kinds of mining take place on land: surface mining and *subsurface mining*. Each method has different benefits and costs in terms of environmental, human, and social perspectives.

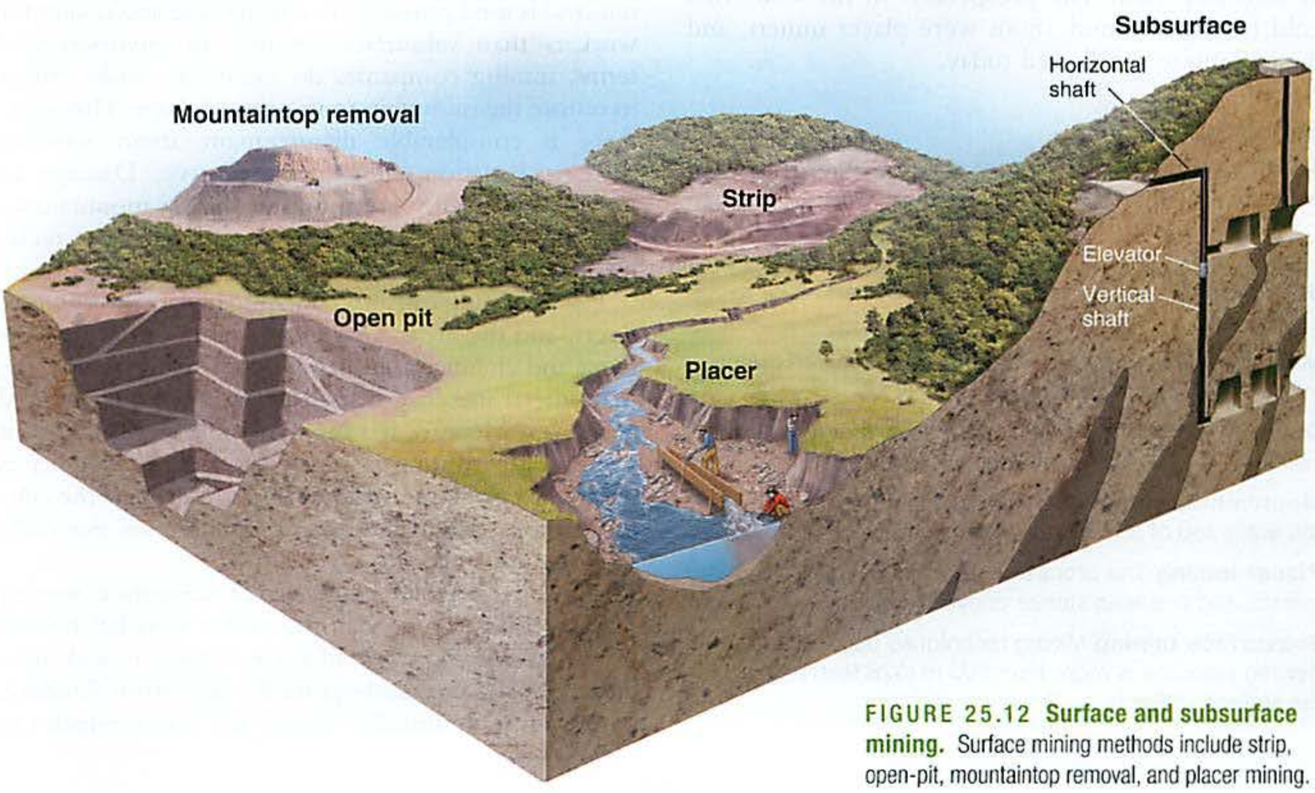


FIGURE 25.12 Surface and subsurface mining. Surface mining methods include strip, open-pit, mountaintop removal, and placer mining.

Surface Mining

A variety of surface mining techniques can be used to remove a mineral or ore deposit that is close to the surface of Earth. **Strip mining,** or the removal of "strips" of soil and rock to expose the underlying ore, is used when the ore is relatively close to Earth's surface and runs parallel to it, which is often the case for deposits of sedimentary materials such as coal and sand. In these situations, miners remove a large volume of material, extract the resource, and return the unwanted waste material, called **mining spoils** or **tailings,** to the hole created during the mining. A variety of strategies can be used to restore the affected area to something close to its original condition.

Open-pit mining, a mining technique that creates a large visible pit or hole in the ground, is used when the resource is close to the surface but extends beneath the surface both horizontally and vertically. Copper mines are usually open-pit mines. One of the largest open-pit mines in the world is the Kennecott Bingham Canyon mine near Salt Lake City, Utah. This copper mine is 4.4 km (2.7 miles) across and 1.1 km (0.7 miles) deep.

In **mountaintop removal,** miners remove the entire top of a mountain with explosives. Large earth-moving equipment removes the resource and deposits the tailings in lower-elevation regions nearby, often in or near rivers and streams.

Placer mining is the process of looking for metals and precious stones in river sediments. Miners use the river water to separate heavier items, such as diamonds, tantalum, and gold, from lighter items, such as sand and mud. The prospectors in the California gold rush in the mid 1800s were placer miners, and the technique is still used today.

Subsurface Mining

When the desired resource is more than 100 m (328 feet) below Earth's surface, miners must turn to **subsurface mining,** which is mining that occurs below the surface of Earth. Typically, a subsurface mine begins with a horizontal tunnel dug into the side of a mountain or other feature containing the resource. From this horizontal tunnel, vertical shafts are drilled, and elevators are used to bring miners down to the resource and back to the surface. The deepest mines on Earth are up to 3.5 km (2.2 miles) deep. Coal, diamonds, and gold are some of the resources removed by subsurface mining.

Strip mining The removal of strips of soil and rock to expose ore.

Mining spoils Unwanted waste material created during mining. *Also known as* **Tailings.**

Open-pit mining A mining technique that uses a large visible pit or hole in the ground.

Mountaintop removal A mining technique in which the entire top of a mountain is removed with explosives.

Placer mining The process of looking for minerals, metals, and precious stones in river sediments.

Subsurface mining Mining techniques used when the desired resource is more than 100 m (328 feet) below the surface of Earth.

The Environment and Safety

The extraction of mineral resources from Earth's crust has a variety of environmental impacts on water, soil, biodiversity, and other areas. In addition, mineral resource extraction can have human health consequences that affect the miners directly as well as other individuals who are affected by the mining process.

Mining and the Environment

As you can see in **TABLE 25.2,** all forms of mining affect the environment. Mining almost always requires the construction of roads, which can result in soil erosion, damage to waterways, and habitat fragmentation. In addition, all types of mining produce tailings, the residue that is left behind after the desired metal or ore is removed, and some tailings contaminate land and water with acids and metals.

In mountaintop removal, the mining spoils are typically deposited in the adjacent valleys, sometimes blocking or changing the flow of rivers. Mountaintop removal is used primarily in coal mining and is safer for workers than subsurface mining. In environmental terms, mining companies do sometimes make efforts to restore the mountain to its original shape. However, there is considerable disagreement about whether these reclamation efforts are effective. Damage to streams and nearby groundwater during mountaintop removal cannot be completely rectified by the reclamation process.

Placer mining can also contaminate large portions of rivers, and the areas adjacent to the rivers, with sediment and chemicals. In certain parts of the world, the toxic metal mercury is used in placer mining of gold and silver. Mercury is a highly *volatile* metal; that is, it moves easily among air, soil, and water. Mercury is harmful to plants and animals and can damage the central nervous system in humans; children are especially sensitive to its effects.

The environmental impacts of subsurface mining may be less apparent than the visible scars left behind by surface mining. One of these impacts is acid mine drainage. To keep underground mines from flooding, pumps must continually remove the water, which can

TABLE 25.2 Types of Mining Operations and Their Effects					
Type of operation	Effects on air	Effects on water	Effects on soil	Effects on biodiversity	Effects on humans
Surface mining	Significant dust from earth-moving equipment	Contamination of water that percolates through tailings	Most soil removed from site; may be replaced if reclamation occurs	Habitat alteration and destruction over the surface areas that are mined	Minimal in the mining process, but air quality and water quality can be adversely affected near the mining operation
Subsurface mining	Minimal dust at the mining site, but emissions from fossil fuels used to power mining equipment can be significant	Acid mine drainage as well as contamination of water that percolates through tailings		Road construction to mines fragments habitat	Occupational hazards in mine; possibility of death or chronic respiratory diseases such as black lung disease

have an extremely low pH. Drainage of this water lowers the pH of nearby soils and streams and can cause damage to the ecosystem.

Mining Safety and Legislation

Subsurface mining is a dangerous occupation. Hazards to miners include accidental burial, explosions, and fires. In addition, the inhalation of gases and particles over long periods can lead to a number of occupational respiratory diseases, including black lung disease and asbestosis, a form of lung cancer. In the United States, between 1900 and 2006, more than 11,000 coal miners died in underground coal mine explosions and fires. A much larger number died from respiratory diseases. Today, there are relatively few deaths per year in coal mines in the United States, in part because of improved work safety standards and in part because there is much less subsurface mining. In other countries, especially China, mining accidents remain fairly common.

As human populations grow and developing nations continue to industrialize, the demand for mineral resources continues to increase. But as the most easily mined mineral resources are depleted, extraction efforts become more expensive and environmentally destructive. The ores that are easiest to reach and least expensive to remove are always recovered first. When these sources are exhausted, mining companies must turn to deposits that are more difficult to reach. These extraction efforts result in greater amounts of mining spoils and more of the environmental problems we have already noted. Learning to use and reuse limited mineral resources more efficiently will help protect the environment as well as human health and safety.

Governments have sought to regulate the mining process for many years. Early mining legislation was primarily focused on promoting economic development, but later legislation became concerned with worker safety as well as environmental protection. The effectiveness of these mining laws has varied.

Congress passed the Mining Law of 1872 to regulate the mining of silver, copper, and gold ores as well as fuels, including natural gas and oil, on federal lands. This law, also known as the General Mining Act, allowed individuals and companies to recover ores or fuels from federal lands. The law was written primarily to encourage development and settlement in the western United States and, as a result, it contains very few provisions for environmental protection.

The Surface Mining Control and Reclamation Act of 1977 regulates surface mining of coal and the surface effects of subsurface coal mining. The act mandates that land be minimally disturbed during the mining process and reclaimed after mining is completed. Mining legislation does not regulate all of the mining practices that can have harmful effects on air, water, and land. In later chapters we will learn about other U.S. legislation that does, to some extent, address these issues, including the Clean Air Act, Clean Water Act, and Superfund Act.

module

25

REVIEW

In this module, we saw that rocks and minerals undergo physical and chemical weathering and become products that are precursors for soil. Weathered materials are subject to erosion, which is a natural process that can be enhanced by human activity. Erosion also influences the precursors to soil. Soil forms from geologic material as well as biological material. Soil properties result from physical, chemical, and biological processes and are influenced by five soil forming factors. Concentrated accumulations of elements and minerals in and below soils that are economically valuable are called ores. When ores are extracted, a variety of consequences affect humans and the environment.

Module 25 AP® Review Questions

1. Acid precipitation directly causes
   I. erosion.
   II. physical weathering.
   III. chemical weathering.

   (a) I only
   (b) I and II only
   (c) I and III only
   (d) III only
   (e) I, II, and III

2. What are the five primary soil formation factors?
   (a) Altitude, climate, parent material, latitude, organisms
   (b) Climate, parent material, pH, organisms, topography
   (c) Parent material, topography, organisms, time, latitude
   (d) Parent material, climate, pH, latitude, altitude
   (e) Climate, parent material, topography, organisms, time

3. Which is the correct order of soil horizons starting at the surface?
   (a) A, B, C, E, O
   (b) O, A, B, C, E
   (c) O, E, A, B, C
   (d) O, A, E, B, C
   (e) E, A, B, O, C

4. What type of soil would be best for a man-made pond, where the goal is to have as little leakage of water as possible?
   (a) Mostly clay
   (b) Mostly silt
   (c) Mostly sand
   (d) Equal amounts of sand, silt, and clay
   (e) Equal amounts of silt and sand

5. Which of the following, if added to soil, would lower the base saturation?
   (a) Sodium
   (b) Potassium
   (c) Magnesium
   (d) Calcium
   (e) Aluminum

6. Tailings are
   (a) minerals found in metamorphic rock.
   (b) magma ore resulting from seafloor spreading.
   (c) the remaining supply of metals on Earth.
   (d) the nutrients that leach downward in soil.
   (e) the waste material from mining.

working toward sustainability

Mine Reclamation and Biodiversity

One of the environmental impacts of surface mining is the amount of land surface it disturbs. Once a mining operation is finished, the mining company may try to restore it to its original condition. In the United States, the Surface Mining Control and Reclamation Act of 1977 requires coal mining companies to restore the lands they have mined. Regulations also require other types of mining operations to do some level of restoration.

A disturbed ecosystem can return to a state similar to its original condition only if the original physical, chemical, and biological properties of the land are re-created. Therefore, reclamation after mining involves several steps. First, the mining company must fill in the hole or depression it has created in the landscape. Second, the fill material must be shaped to follow the original contours of the land that existed before the mining began.

The mining company usually scrapes off the topsoil that was on the land and puts it aside at the beginning of the mining operation. This topsoil must be returned and spread over the landscape after mining is completed. Finally, the land must be replanted. In order to re-create the communities of organisms that inhabited the area before mining, the vegetation planted on the site must be native to the area and foster the process of natural succession. Properly completed reclamation makes the soils physically stable so that erosion does not occur and water infiltration and retention can proceed as they did before mining. The materials used in the reclamation must be relatively free of metals, acids, and other compounds that could potentially leach into nearby bodies of water.

Many former mining areas have not been reclaimed properly. However, there are an increasing number of reclamation efforts that have achieved conditions that equal those that existed prior to the mining operation. The Trapper Mine in Craig, Colorado, and other mines like it illustrate reclamation success stories.

The Trapper Mine produces about 2 million tons of coal per year that is sold to a nearby electricity generation plant. Although all coal mining operations are required to save excavated rock and topsoil, managers at the Trapper Mine have stated that they are meticulous about saving all the topsoil they remove. The rock they save is used to fill the lower portions of excavated holes. Workers then install drainage pipes and other devices to ensure proper drainage of water. The topsoil that has been set aside is spread over the top of the restored ground and contoured as it was before mining. Trapper Mine reclamation staff then replant the site with a variety of native species of grasses and shrubs, including the native sagebrush commonly found in the high plateaus of northwestern Colorado.

Government officials, and even the Colorado branch of the Sierra Club, have expressed approval of the Trapper Mine reclamation process. But

Mining and reclamation. At a strip mine operation in Colorado, not far from the Trapper Mine: (a) active mining underway; (b) restored native habitat after reclamation. *(Courtesy of Seneca Coal Company)*

(b)

(a)

perhaps the strongest evidence of its success is the wildlife that now inhabits the formerly mined areas. The Columbian sharp-tailed grouse (*Tympanuchus phasianellus columbianus*), a threatened bird species, has had higher annual survival and fertility rates on the reclaimed mine land than it has on native habitat in other parts of Colorado. Populations of elk, mule deer, and antelope have all increased on reclaimed mine property.

Reclamation issues must be addressed for each particular area where mining occurs. As we have seen, subsurface and surface water runoff in certain locations can contain high concentrations of toxic metals and acids. In other situations, although certain native species may increase in abundance after reclamation, other native species may decrease. Nevertheless, with supervision, skill, and enough money to pay for the proper reclamation techniques, a reclaimed mining area can become a satisfactory or even an improved habitat for many species.

Critical Thinking Questions

1. If you were on a committee asked to determine if a mine reclamation project had been successful, what three measures or conditions would you want to consider in your evaluation?
2. Identify two environmental problems that might occur in the area where you live if a mining site was not reclaimed.

References

Department of the Interior, Office of Surface Mining Reclamation and Enforcement. http://www.osmre.gov/.

Raabe, S. 2002. Nature's Comeback: Trapper Mine reclamation attracts wildlife, wins praise. *Denver Post*, November 12, p. C01.

chapter 8 REVIEW

In this chapter, we have examined how geologic processes such as plate tectonics, earthquakes, and volcanism have led to the differential distribution of elements and minerals on the surface of Earth. These geologic processes, which have occurred at different rates over long periods of time, have led to the formation of different rocks and minerals on or near the surface of Earth. Rocks and minerals have undergone weathering at different rates and have been eroded and deposited elsewhere on Earth. This has been one of the contributors to soil formation. Soils are a membrane that covers much of the land surface on Earth and these soils contain a mixture of geologic material from below and organic material from plants and animals from above. We have also examined how the actions involved in removal of valuable mineral resources from on top and below the surface of Earth have affected a number of environmental processes.

Key Terms

Core
Mantle
Magma
Asthenosphere
Lithosphere
Crust
Hot spot
Plate tectonics
Tectonic cycle
Subduction
Volcano
Divergent plate boundary
Seafloor spreading
Convergent plate boundary
Transform fault boundary
Fault
Seismic activity
Fault zone
Earthquake
Epicenter
Richter scale
Rock cycle
Igneous rock
Intrusive igneous rock
Extrusive igneous rock
Fracture
Sedimentary rock
Metamorphic rock
Physical weathering
Chemical weathering
Acid precipitation
Acid rain
Erosion
Parent material
Soil degradation
Horizon

O horizon
A horizon
Topsoil
E horizon
B horizon
C horizon
Cation exchange capacity (CEC)
Base saturation
Crustal abundance
Ore
Metal
Reserve
Strip mining
Mining spoils
Tailings
Open-pit mining
Mountaintop removal
Placer mining
Subsurface mining

Learning Objectives Revisited

Module 24 Mineral Resources and Geology

- **Describe the formation of Earth and the distribution of critical elements on Earth.**

  Earth formed from cosmic dust in the solar system. As it cooled, heavier elements, such as iron, sank toward the core, while lighter elements, such as silica, floated toward the surface. These processes have led to an uneven distribution of elements and minerals throughout the planet.

- **Define the theory of plate tectonics and discuss its relevance to the study of the environment.**

  Earth is overlain by a series of plates that move at rates of a few millimeters per year. Plates can move away from each other, move toward each other, or slide past each other. One plate can be subducted under another. These tectonic processes create mountains, earthquakes, and volcanoes.

- **Describe the rock cycle and discuss its importance in environmental science.**

  Rocks are made up of minerals, which are formed from the various chemical elements in Earth's crust. The processes of the rock cycle lead to the formation, breakdown, and recycling of rocks.

Module 25 Weathering and Soil Science

- **Understand how weathering and erosion occur and how they contribute to element cycling and soil formation.**

  Physical weathering is the mechanical breakdown of rocks and minerals while chemical weathering is a result of chemical reactions. Both occur as a result of natural processes and can be accelerated by human activities. Erosion is the physical removal of rock fragments and weathering products that are subsequently deposited elsewhere.

- **Explain how soil forms and describe its characteristics.**

  Soil forms as the result of physical and chemical weathering of rocks and the gradual accumulation of organic detritus from the biosphere. The factors that determine soil properties are parent material, climate, topography, soil organisms, and time. The relative abundances of sand, silt, and clay in a soil determine its texture.

- **Describe how humans extract elements and minerals and the social and environmental consequences of these activities.**

  Concentrated accumulations of minerals from which economically valuable materials can be extracted are called ores. Ores are removed by surface or subsurface mining operations. Surface mining generally results in greater environmental impacts, whereas subsurface mining is more dangerous to miners. With the exception of coal mining, legislation directly related to mining does not address most environmental considerations.

Chapter 8 AP® Environmental Science Practice Exam

Section 1: Multiple-Choice Questions

Choose the best answer for questions 1–13.

1. As Earth slowly cooled
   - (a) lighter elements sank to the core and heavier elements moved to the surface.
   - (b) lighter elements mixed with heavier elements and sank to the core.
   - (c) lighter elements mixed with heavier elements and moved to the surface.
   - (d) lighter elements moved to the surface and heavier elements sank to the core.
   - (e) lighter and heavier elements dispersed evenly from the core to the surface.

2. The correct vertical zonation of Earth above the core is
   - (a) asthenosphere-mantle-soil-lithosphere.
   - (b) asthenosphere-lithosphere-mantle-soil.
   - (c) mantle-asthenosphere-lithosphere-soil.
   - (d) mantle-lithosphere-soil-asthenosphere.
   - (e) soil-mantle-lithosphere-asthenosphere.

3. Evidence for the theory of plate tectonics includes
   - I. deposits of copper ore around the globe.
   - II. identical rock formations on both sides of the Atlantic.
   - III. fossils of the same species on distant continents.

   - (a) I only
   - (b) I and III only
   - (c) II and III only
   - (d) I and II only
   - (e) I, II, and III

4. Which type of mining is usually most directly harmful to miners?
   - (a) Mountaintop removal
   - (b) Open-pit mining
   - (c) Placer mining
   - (d) Strip mining
   - (e) Subsurface mining

5. Measured on the Richter scale, an earthquake with a magnitude of 7.0 is ____ times greater than an earthquake with a magnitude of 2.0.
   - (a) 10
   - (b) 100
   - (c) 1,000
   - (d) 10,000
   - (e) 100,000

For questions 6 to 9, select from the following choices:

- (a) Seismic activity center
- (b) Divergent plate boundary
- (c) Convergent plate boundary
- (d) Transform fault boundary
- (e) Epicenter

6. At which type of boundary do tectonic plates move sideways past each other?

7. At which type of boundary does subduction occur?

8. At which type of boundary does seafloor spreading occur?

9. Which term refers to the point on Earth's surface directly above an earthquake?

10. Fossil records are found in
    - (a) intrusive rock.
    - (b) extrusive rock.
    - (c) igneous rock.
    - (d) metamorphic rock.
    - (e) sedimentary rock.

11. Where would you expect to find extrusive igneous rock?
    - (a) Along a transform fault
    - (b) In the Himalayas
    - (c) Along the ocean floor
    - (d) On the coast of a continent
    - (e) At a continental subduction zone

12. Which of the following statements about soil is NOT correct?
    - (a) Soil is fairly static and does not change.
    - (b) Soil is the medium for plant growth.
    - (c) Soil is a primary filter of water.
    - (d) A wide variety of organisms live in soil.
    - (e) Soil plays an important role in biogeochemical cycles.

13. The soil horizon commonly known as subsoil is the
    - (a) A horizon.
    - (b) O horizon.
    - (c) B horizon.
    - (d) C horizon.
    - (e) E horizon.

Section 2: Free-Response Questions

Write your answer to each part clearly. Support your answers with relevant information and examples. Where calculations are required, show your work.

1. The rock cycle plays an important role in the recycling of Earth's limited amounts of mineral resources.
   (a) The mineral composition of rock depends on how it is formed. Name the *three* distinct rock types, explain how each rock type is formed, and give one specific example of a rock of each type. (6 points)
   (b) Explain either the physical *or* the chemical weathering process that leads to the breakdown of rocks. (2 points)
   (c) Describe the natural processes that can lead to the formation of soil, and discuss how human activities can accelerate the loss of soil. (2 points)

2. Read the following articles that appeared on the website of the organization "Eatwild," at http://www.eatwild.com/environment.html, and answer the questions that follow.

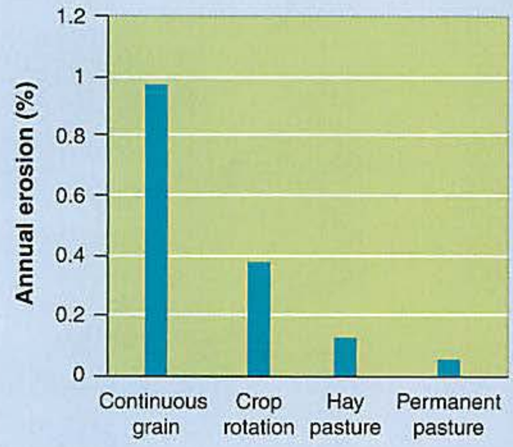
Grass Farming Benefits the Environment

Grazing better for the soil than growing grain
Six Minnesota pasture-based ranchers asked researchers to compare the health of their soil with soil from neighboring farms that produced corn, soybean, oats, or hay. At the end of four years of monitoring, researchers concluded that the carefully managed grazed land had

- 53% greater soil stability
- 131% more earthworms
- Substantially more organic matter
- Less nitrate pollution of groundwater
- Improved stream quality
- Better habitat for grassland birds and other wildlife

Depending on the way that cattle are managed, they can either devastate a landscape or greatly improve the health of the soil. ["Managed Grazing as an Alternative Manure Management Strategy," Jay Dorsey, Jodi Dansingburg, Richard Ness, USDA-ARS, Land Stewardship Project.]

Pasture reduces topsoil erosion by 93 percent
Currently, the United States is losing three billion tons of nutrient-rich topsoil each year. Growing corn and soy for animal feed using conventional methods causes a significant amount of this soil loss. Compared with row crops, pasture reduces soil loss by as much as 93 percent. [Ontario Ministry of Agriculture and Food, Robert P. Stone and Neil Moore, Fact Sheet 95-089.]



(a) Explain the consequences of the observations in the studies described and comment on the long-term sustainability of each agricultural practice.

   (i) What roles do earthworms play in maintaining soil stability? (1 point)
   (ii) How does the presence of organic matter benefit the soil? (1 point)
   (iii) Suggest why there is less nitrate contamination of groundwater from the permanent pastures. (1 point)
   (iv) In what ways could the stream quality have improved? (1 point)

(b) Discuss one negative consequence of grazing cattle on pastureland instead of feeding them grain. (3 points)

(c) Describe one potential negative effect on rivers and streams of grazing cattle on pastureland. (3 points)