CHAPTER 14

Geology and Mineral Resources

Civilization exists by geological consent, subject to change without notice.

WILL DURANT

Key Questions

14.1 What are the earth's major geological processes and what are mineral resources?

14.2 How long might supplies of nonrenewable mineral resources last?

14.3 What are the environmental effects of using nonrenewable mineral resources?

14.4 How can we use mineral resources more sustainably?

14.5 What are the earth's major geological hazards?

Open-pit copper mine in Utah. It is almost 5 kilometers (3 miles) wide and 1,200 meters (4,000 feet) deep, and is getting deeper.

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Core Case Study

The Real Cost of Gold

Mineral resources are extracted from the earth's crust through a variety of processes called **mining**. They are processed into an amazing variety of products that make life easier and provide economic benefits and jobs. However, extracting minerals from the ground and using them to manufacture products results in a number of harmful environmental and health effects.

For example, gold mining often involves digging up massive amounts of rock (Figure 14.1) containing only small concentrations of gold. Many newlyweds would be surprised to know that mining enough gold to make their wedding rings produces roughly enough mining waste to equal the total weight of more than three midsize cars. This waste is usually left piled near the mine site and can pollute the air and nearby surface water.

About 90% of the world's gold mining operations extract the gold by spraying a solution of highly toxic cyanide salts onto piles of crushed rock. The solution reacts with the gold and then drains off the rocks, pulling some gold with it, into settling ponds (Figure 14.1, foreground). After the solution is recirculated a number of times, the gold is removed from the ponds.

Until sunlight breaks down the cyanide, the settling ponds are extremely toxic to birds and mammals that go to them in search of water. These ponds can also leak or overflow, posing threats to underground drinking water supplies and to fish and other organisms in nearby lakes and streams. Special liners in the settling ponds can help prevent leaks, but some have failed. According to the U.S. Environmental Protection Agency (EPA), all such liners are likely to leak, eventually.

In 2000 snow and heavy rains washed out an earthen dam on one end of a cyanide leach pond at a gold mine in Romania. The dam's collapse released large amounts of water laced with cyanide and toxic metals into the Tisza and Danube Rivers, which flow through parts of Romania, Hungary, and Yugoslavia. Several hundred thousand people living along these rivers were told not to fish or to drink or withdraw water from them or from wells along the rivers. Businesses located there were shut down. Thousands of fish and other aquatic animals and plants were killed. This accident and another one that occurred in January 2001 could have been prevented if the mining company had installed a stronger containment dam and a backup collection pond to prevent leakage into nearby surface water.

In addition, in parts of Africa and Latin America, millions of poor miners have illegally cleared areas of tropical forest and dug huge pits to find gold. In these operations, they typically use toxic mercury to extract the gold from the *ore*, or the rock containing the gold. Many of these miners have been poisoned by mercury. Because these illegal mining operations pollute the air and water with mercury and its toxic compounds, they have become a regional and global threat.

In 2015 the world's top five gold-producing countries were, in order, China, Australia, Russia, the United States, and Canada. These countries vary in how they deal with the environmental impacts of gold mining.

In this chapter, we look at the earth's dynamic geological processes, the valuable minerals such as gold that some of these processes produce, and the potential supplies of these resources. We will also study the environmental impacts of extracting and processing these resources, and how people can use these resources more sustainably.

Larry Mayer/Getty Images

FIGURE 14.1 Gold mine in the Black Hills of the U.S. state of South Dakota with cyanide leach piles and settling ponds in foreground.

14.1 WHAT ARE THE EARTH'S MAJOR GEOLOGICAL PROCESSES AND WHAT ARE MINERAL RESOURCES?

CONCEPT 14.1A Dynamic processes within the earth and on its surface produce the mineral resources we depend on.

CONCEPT 14.1B Mineral resources are nonrenewable because it takes millions of years for the earth's rock cycle to produce or renew them.

The Earth Is a Dynamic Planet

Geology is the scientific study of dynamic processes taking place on the earth's surface and in its interior. Scientific evidence indicates that the earth formed about 4.6 billion years ago. As the primitive earth cooled over millions of years, its interior separated into three major concentric zones: the *core*, the *mantle*, and the *crust* (Figure 14.2). They make up the *geosphere* (Figure 3.2, p. 51), which is part of the earth's life-support system.

The **core** is the earth's innermost zone and is composed primarily of iron (Fe). The inner core is extremely hot and has a solid center. It is surrounded by the outer core, a thick layer of *molten rock*, or hot fluid rock, and semisolid material.

Surrounding the core is a thick zone called the **mantle**—a zone made mostly of solid rock that can be soft and pliable at very high temperatures. The outermost part of the mantle is entirely solid rock. Beneath it is the **asthenosphere**—a volume of hot, partly melted rock that flows.

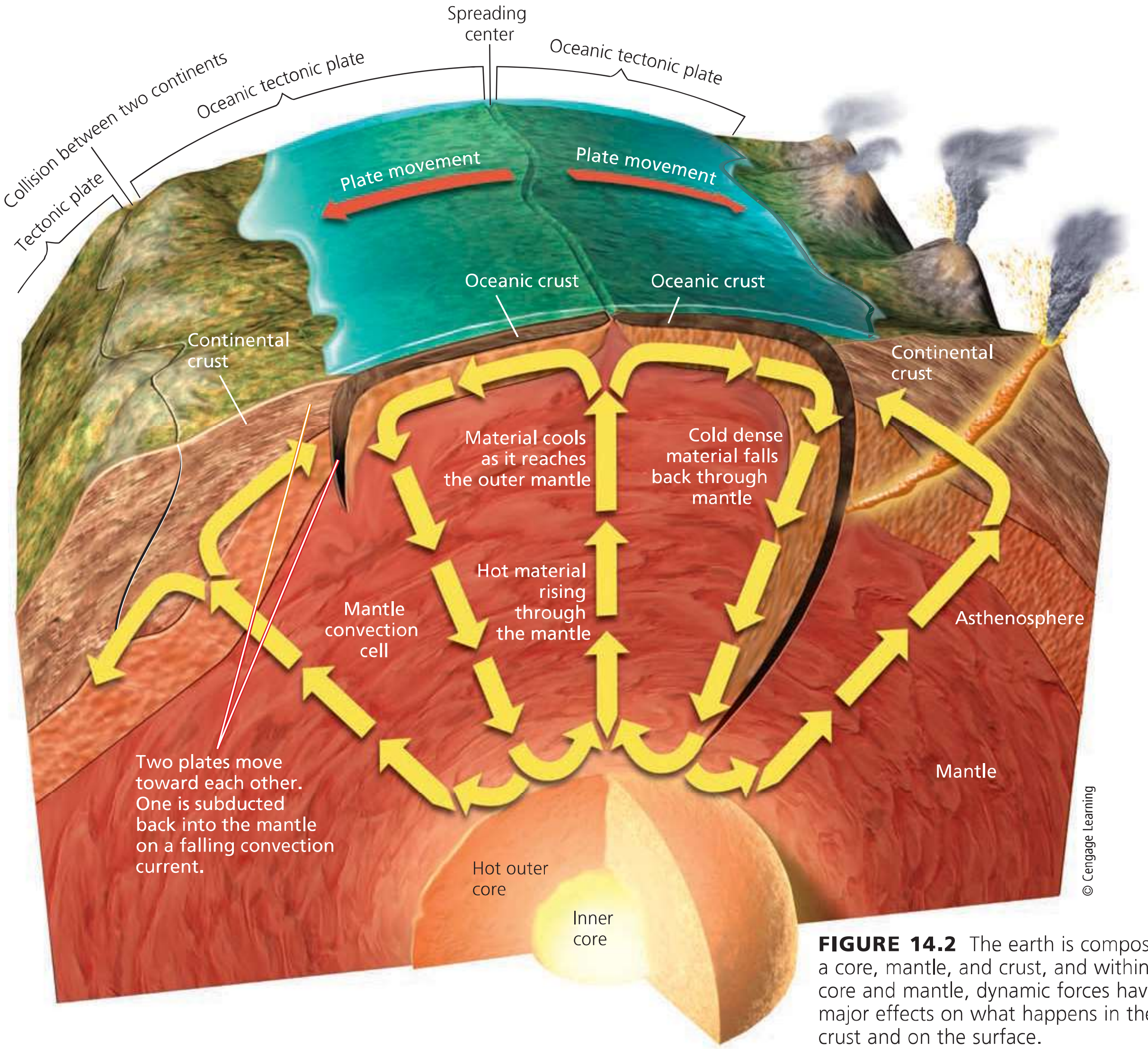

FIGURE 14.2 The earth is composed of a core, mantle, and crust, and within the core and mantle, dynamic forces have major effects on what happens in the crust and on the surface.

Tremendous heat within the core and mantle generates *convection cells*, or *currents*. The innermost material heats, rises, and begins to cool. As it cools, it becomes denser and sinks back toward the core where it is reheated, completing a huge loop of slowly moving material. These loops within the mantle operate like gigantic conveyer belts (Figure 14.2). Some of the molten rock in the asthenosphere flows upward into the crust, where it is called *magma*. When magma erupts onto the earth's surface, it is called *lava*. This cycling moves rock and minerals and transfers heat and energy within the earth and to its surface.

The outermost and thinnest zone of solid material is the earth's **crust.** It consists of the *continental crust,* which underlies the continents (including the continental shelves extending into the oceans), and the *oceanic crust,* which underlies the ocean basins and makes up 71% of the earth's crust. The combination of the crust and the rigid, outermost part of the mantle is called the **lithosphere.** This zone contains the mineral resources that we use (**Concept 14.1A**).

What Are Minerals and Rocks?

The earth's crust beneath our feet consists mostly of minerals and rocks. A **mineral** is a naturally occurring chemical element or inorganic compound that exists as a solid with a regularly repeating internal arrangement of its atoms or ions (a *crystalline solid*). A **mineral resource** is a concentration of one or more minerals in the earth's crust that we can extract and process into raw materials and useful products at an affordable cost. Because minerals take millions of year to form, they are *nonrenewable resources*, and their supplies can be depleted (**Concept 14.1B**).

A few minerals, such as mercury and gold (**Core Case Study** and Figure 2.3, p. 34), consist of a single chemical element. However, most of the more than 2,000 identified mineral resources that we use occur as inorganic compounds formed by various combinations of elements. Examples include salt (sodium chloride, or NaCl; see Figure 2.7, p. 36) and quartz (silicon dioxide, or SiO_2).

Rock is a solid combination of one or more minerals found in the earth's crust. Some kinds of rock, such as limestone (calcium carbonate, or $CaCO_3$) and quartzite (silicon dioxide, or SiO_2), contain only one mineral, but most rocks consist of two or more minerals. Granite, for example, is a mixture of mica, feldspar, and quartz crystals.

Based on the way they form, rocks are classified as sedimentary, igneous, or metamorphic. **Sedimentary rock** is made of *sediments*—dead plant and animal remains and particles of weathered and eroded rocks. These sediments are transported from place to place by water, wind, or gravity. Where they are deposited, they can accumulate in layers over time. Eventually, the increasing weight and pressure on the underlying layers transform the sedimentary layers to rock. Examples include *sandstone* and *shale* (formed from pressure created by deposited layers made mostly of sand or silt), *dolomite* and *limestone* (formed from the compacted shells, skeletons, and other remains of dead aquatic organisms), and *lignite* and *bituminous coal* (derived from compacted plant remains).

Igneous rock forms below or on the earth's surface under intense heat and pressure when magma wells up from the earth's mantle and then cools and hardens. Examples include *granite* (formed underground) and *lava rock* (formed aboveground). Igneous rock forms the bulk of the earth's crust but is usually covered with layers of sedimentary rock.

Metamorphic rock forms when an existing rock is subjected to high temperatures (which may cause it to melt partially), high pressures, chemically active fluids, or a combination of these agents. Examples include *slate* (formed when shale and mudstone are heated) and *marble* (produced when limestone is exposed to heat and pressure).

The Earth's Rocks Are Recycled Slowly

The interaction of physical and chemical processes that change the earth's rocks from one type to another is called the **rock cycle** (Figure 14.3 and **Concept 14.1B**). Rocks are recycled over millions of years by three processes—*erosion*, *melting*, and *metamorphism*—which produce *sedimentary*, *igneous*, and *metamorphic* rocks, respectively.

In these processes, rocks are broken down, melted, fused together into new forms by heat and pressure, cooled, and sometimes recrystallized within the earth's interior and crust. The rock cycle is the slowest of the earth's cyclic processes and plays the major role in the formation of concentrated deposits of mineral resources.

We Depend on a Variety of Nonrenewable Mineral Resources

We know how to find and extract more than 100 different minerals from the earth's crust. According to the U.S. Geological Survey (USGS), the quantity of nonrenewable minerals extracted globally increased more than threefold between 1995 and 2014. To support its rapid economic growth, China used 45–55% of the world's iron ore, aluminum, steel, nickel, copper, and zinc in 2014.

An **ore** is rock that contains a large enough concentration of a mineral—often a metal—to make it profitable for mining and processing. A **high-grade ore** contains a high concentration of the mineral. A **low-grade ore** contains a low concentration.

Mineral resources are used for many purposes. Today, about 60 of the 118 chemical elements in the periodic table (see Figure 1, p. S6, Supplement 3) are used for

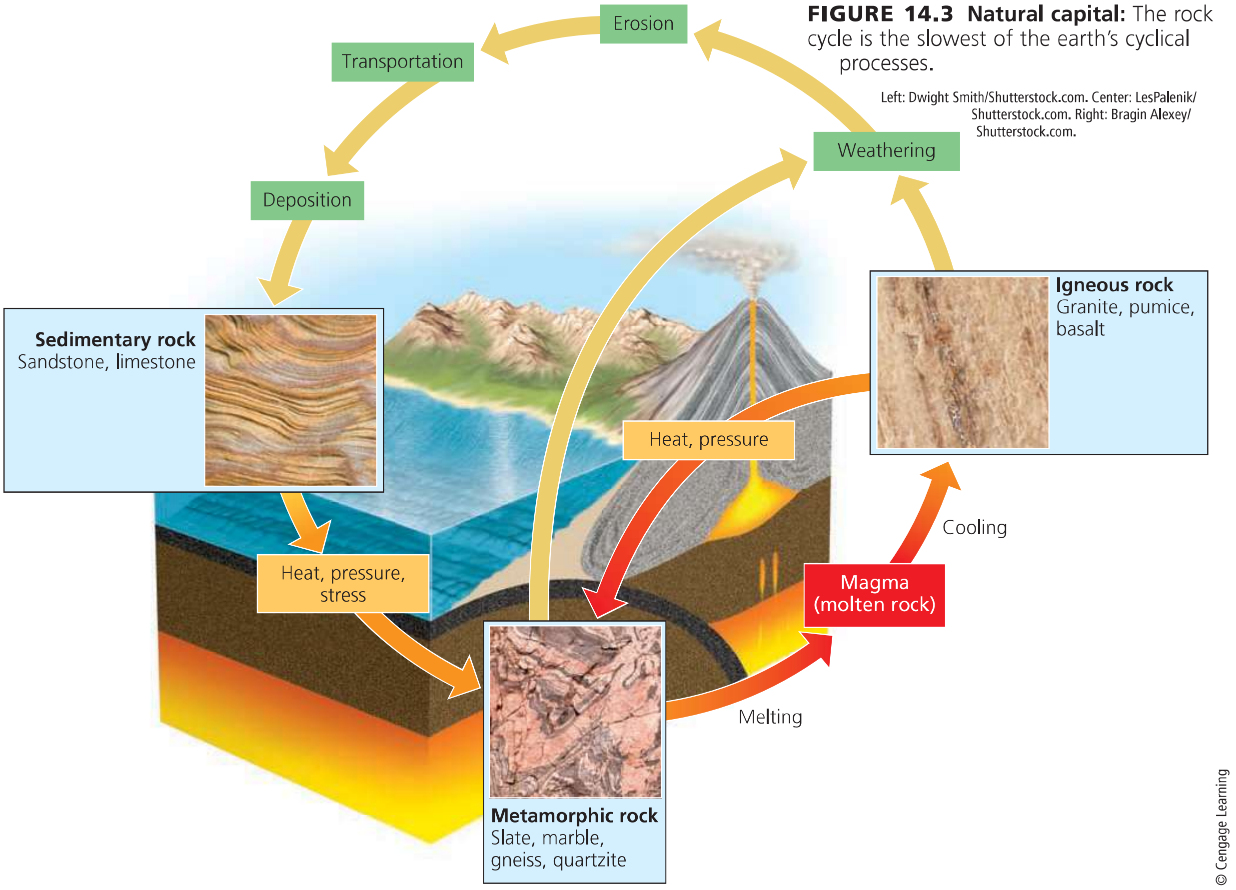

FIGURE 14.3 **Natural capital:** The rock cycle is the slowest of the earth's cyclical processes.

Left: Dwight Smith/Shutterstock.com. Center: LesPalenik/Shutterstock.com. Right: Bragin Alexey/Shutterstock.com.

making computer chips. *Aluminum* (Al) is used as a structural material in beverage cans, motor vehicles, aircraft, and buildings. *Steel*, an essential material used in buildings, machinery, and motor vehicles, is a mixture (or *alloy*) of iron (Fe) and other elements that gives it certain physical properties. *Manganese* (Mn), *cobalt* (Co), and *chromium* (Cr) are widely used in steel alloys. *Copper* (Cu), a good conductor of electricity, is used to make electrical and communications wiring and plumbing pipes. *Gold* (Au) (**Core Case Study**) is a component of electrical equipment, tooth fillings, jewelry, coins, and some medical implants. *Molybdenum* (Mo) is widely used to harden steel and to make it more resistant to corrosion.

There are several widely used nonmetallic mineral resources. *Sand*, which is mostly silicon dioxide (SiO_2), is used to make glass, bricks, and concrete for the construction of roads and buildings. *Gravel* is used for roadbeds and to make concrete. Another common nonmetallic mineral is *limestone* (mostly calcium carbonate, or $CaCO_3$), which is crushed to make concrete and cement. Still another is *phosphate*, used to make inorganic fertilizers and certain detergents.

14.2 HOW LONG MIGHT SUPPLIES OF NONRENEWABLE MINERAL RESOURCES LAST?

CONCEPT 14.2A Nonrenewable mineral resources exist in finite amounts and can become economically depleted when it costs more than it is worth to find, extract, and process the remaining deposits.

CONCEPT 14.2B There are several ways to extend supplies of mineral resources, but each of them is limited by economic and environmental factors.

Supplies of Nonrenewable Mineral Resources Can Be Economically Depleted

Most published estimates of the supply of a given nonrenewable mineral resource refer to its **reserves:** identified deposits from which we can extract the mineral profitably at current prices. Reserves can be expanded when we find new, profitable deposits or when higher prices or improved mining technologies make it profitable to extract deposits that previously were too expensive to remove.

The future supply of any nonrenewable mineral resource depends on the actual or potential supply of the mineral and the rate at which we use it. We have never completely run out of a nonrenewable mineral resource, but a mineral becomes *economically depleted* when it costs more than it is worth to find, extract, transport, and process the remaining deposits (**Concept 14.2A**). At that point, there are five choices: *recycle or reuse existing supplies*, *waste less*, *use less*, *find a substitute*, or *do without*.

Depletion time is the time it takes to use up a certain proportion—usually 80%—of the reserves of a mineral at a given rate of use. When experts disagree about depletion times, it is often because they are using different assumptions about supplies and rates of use (Figure 14.4).

The shortest depletion-time estimate assumes no recycling or reuse and no increase in the reserve (curve A, Figure 14.4). A longer depletion-time estimate assumes that recycling will stretch the existing reserve and that better mining technology, higher prices, or new discoveries will increase the reserve (curve B). The longest depletion-time estimate (curve C) makes the same assumptions as A and B, but also assumes that people will reuse and reduce consumption to expand the reserve further. Finding a substitute for a resource leads to a new set of depletion curves for the new mineral.

The earth's crust contains abundant deposits of nonrenewable mineral resources such as iron and aluminum.

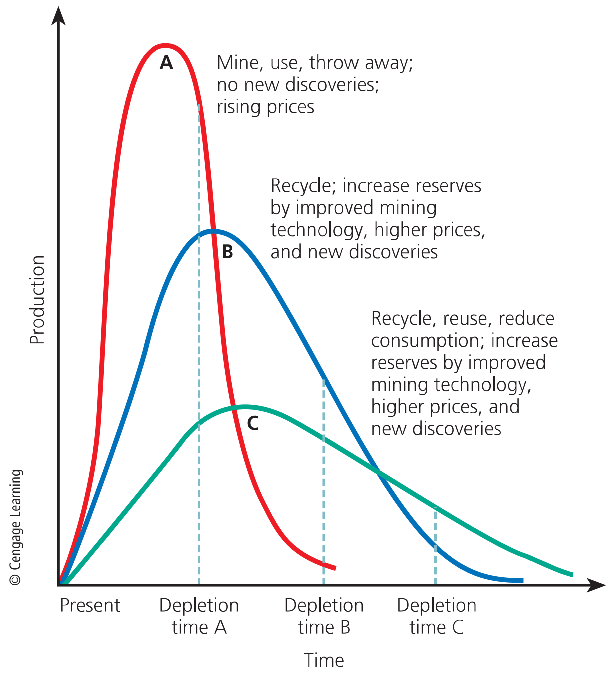

FIGURE 14.4 Natural capital depletion: Each of these *depletion curves* for a mineral resource is based on a different set of assumptions. Dashed vertical lines represent the times at which 80% depletion occurs.

But concentrated deposits of important mineral resources such as manganese, chromium, cobalt, platinum, and *rare earth elements* (see the Case Study that follows) are relatively scarce. In addition, deposits of many mineral resources are not distributed evenly among countries. Five nations—the United States, Canada, Russia, South Africa, and Australia—supply most of the nonrenewable mineral resources that modern societies use.

Since 1900, and especially since 1950, there has been a sharp rise in the total and per capita use of mineral resources in the United States. According to the USGS, each American uses an average of 22 metric tons (24 tons) of mineral resources per year.

The United States has economically depleted some of its once-rich deposits of metals such as lead, aluminum, and iron. Currently, the United States imports all of its supplies of 24 key nonrenewable mineral resources. Most of these imports come from reliable and politically stable countries. However, there are serious concerns about access to adequate supplies of four *strategic metal resources*—manganese, cobalt, chromium, and platinum—that are essential for the country's economic and military strength. The United States has little or no reserves of these metals.

CASE STUDY

The Crucial Importance of Rare Earth Metals

Some mineral resources are familiar, such as gold, copper, aluminum, sand, and gravel. Less well known are the *rare earth metals and oxides*, which are crucial to the technologies that support modern lifestyles and economies.

The 17 rare earth metals, also known as *rare earths*, include scandium, yttrium, and 15 lanthanide chemical elements, including lanthanum (see the Periodic Table, Figure 1 of Supplement 3, p. S6). Because of their superior magnetic strength and other unique properties, these elements and their compounds are important for a number of widely used technologies.

Rare earths are used to make LCD flat screens for computers and television sets, energy-efficient compact fluorescent and LED light bulbs, solar cells, fiber-optic cables, cell phones, and digital cameras. They are also used to manufacture batteries and motors for electric and hybrid-electric cars (Figure 14.5), solar cells, catalytic converters in car exhaust systems, jet engines, and the powerful magnets in wind turbine generators. Rare earths also go into missile guidance systems, jet engines, smart bombs, aircraft electronics, and satellites.

Without affordable supplies of these metals, industrialized nations could not develop the current versions of cleaner energy technology and other high-tech products that will be major sources of economic growth during this century. Many nations also need these metals to maintain their military strength.

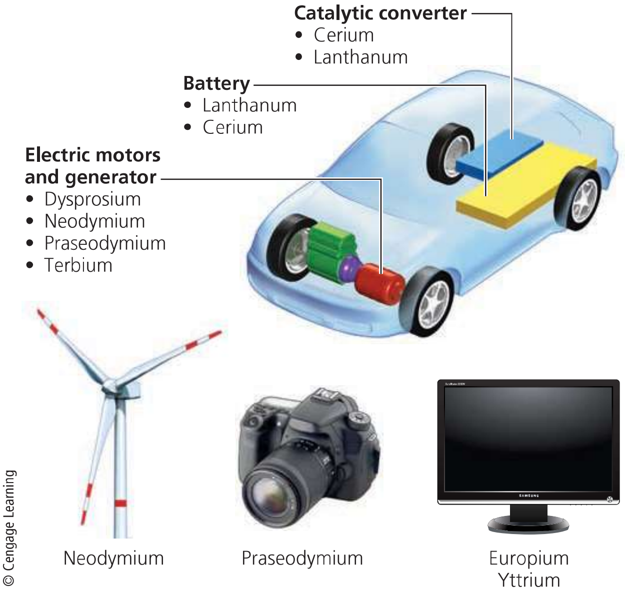

FIGURE 14.5 Rare-earth metals are used to manufacture all-electric and hybrid-electric cars and many other products.

Most rare earth elements are not actually rare, but they are hard to find in concentrations high enough to extract and process at an affordable price. According to the USGS, in 2014 China had roughly 42% of the world's known rare earth reserves, Brazil had the second largest share with 17%, and the United States, with the fifth largest share, had 1.4% of the global reserves.

In 2015 China produced about 90% of the world's rare earth metals and oxides, down from 97% in 2013. Australia and Chile are beginning to increase their shares of global production. China still holds the lead, partly because it does not strictly regulate the environmentally disruptive mining and processing of rare earths. This means that Chinese companies have lower production costs than do companies in countries with stricter regulations. China can thus afford to sell its rare earths at a lower price.

The United States and Japan are heavily dependent on rare earths and their oxides. Japan has no rare earth reserves. In the United States, the only rare earth mine, located in California, was once the world's largest supplier of rare earth metals. However, it closed down because of the expense of meeting pollution regulations, and because China had driven the prices of rare earth metals down to a point where the mine was too costly to operate. In 2015 the company that owns the mine declared bankruptcy.

Market Prices Affect Supplies of Mineral Resources

Geological processes determine the quantity and location of a mineral resource in the earth's crust, but economics determines what part of the known supply is extracted and used. According to standard economic theory, in a competitive market system when a resource becomes scarce, its price rises. Higher prices can encourage exploration for new deposits, stimulate development of better mining technology, and make it profitable to mine lower-grade ores. It can also promote resource conservation and a search for substitutes, but there are limits to these effects (**Concept 14.2B**).

CONSIDER THIS . . .

CONNECTIONS High Metal Prices and Thievery

Resource scarcity can promote theft. For example, copper prices have risen sharply in recent years because of increasing demand. As a result, in many U.S. communities, thieves have been stealing copper to sell it. They strip abandoned houses of copper pipe and wiring and steal outdoor central air conditioning units for their copper coils. They also steal wiring from beneath city streets and copper piping from farm irrigation systems. In 2015 thieves stole copper wiring from New York City's subway system, temporarily shutting down two of the city's busiest lines.

According to some economists, the standard effect of supply and demand on the market prices of mineral resources may no longer apply completely in most more-developed countries. Governments in such countries often use subsidies, tax breaks, and import tariffs to control the supply, demand, and prices of key mineral resources. In the United States, for instance, mining companies get various types of government subsidies, including *depletion allowances*—which allow the companies to deduct the costs of developing and extracting mineral resources from their taxable incomes. These allowances amount to 5–22% of their gross income gained from selling the mineral resources.

Generally, the mining industry maintains that they need subsidies and tax breaks to keep the prices of minerals low for consumers. They also claim that, without subsidies and tax breaks, they might move their operations to other countries where they would not have to pay taxes or comply with strict mining and pollution control regulations.

Can We Expand Reserves by Mining Lower-Grade Ores?

Some analysts contend that we can increase supplies of some minerals by extracting them from lower-grade ores. They point to the development of new earth-moving equipment, improved techniques for removing impurities from ores, and other technological advances in mineral extraction and processing that can make lower-grade ores accessible, sometimes at lower costs.

For example, shortly after World War II, rich deposits of high-grade iron ore in northern Minnesota (USA) were economically depleted. By the 1960s, a new process had been developed for mining *taconite*, a low-grade and plentiful ore that had been viewed as waste rock in the iron mining process. This improvement in mining technology expanded Minnesota's iron reserves and supported a taconite mining industry long after the high-grade iron ore reserves there had been tapped out. Similarly, in 1900 the copper ore mined in the United States was typically 5% copper by weight. Today, it is typically 0.5%, yet copper costs less (when prices are adjusted for inflation).

Several factors can limit the mining of lower-grade ores (**Concept 14.2B**). For example, it requires mining and processing larger volumes of ore, which takes much more energy and costs more. Another factor is the dwindling supplies of freshwater needed for the mining and processing of some minerals, especially in dry areas. A third limiting factor is the growing environmental impacts of land disruption, along with waste material and pollution produced during mining and processing.

One way to improve mining technology and reduce its environmental impact is to use a biological approach, sometimes called *biomining*. Miners use naturally occurring or genetically engineered bacteria to remove desired metals from ores through wells bored into the deposits. This leaves the surrounding environment undisturbed and reduces the air and water pollution associated with removing the metal from metal ores. On the downside, biomining is slow. It can take decades to remove the same amount of material that conventional methods can remove within months or years. So far, biomining methods are economically feasible only for low-grade ores for which conventional techniques are too expensive.

Can We Get More Minerals from the Oceans?

Most of the minerals found in seawater occur in such low concentrations that recovering them takes more energy and money than they are worth. Currently, only magnesium, bromine, and sodium chloride are abundant enough to be extracted profitably from seawater. On the other hand, sediments along the shallow continental shelf and adjacent shorelines contain significant deposits of minerals such as sand, gravel, phosphates, copper, iron, silver, titanium, and diamonds.

Another potential ocean source of some minerals is *hydrothermal ore deposits* that form when superheated, mineral-rich water shoots out of vents in volcanic regions of the ocean floor. When the hot water comes into contact with cold seawater, black particles of various metal sulfides precipitate out and accumulate as chimney-like structures, called *black smokers*, near the hot water vents (Figure 14.6). These deposits are especially rich in minerals such as copper, lead, zinc, silver, gold, and some of the rare earth metals. A variety of more than 300 exotic forms of life—including giant clams, six-foot tubeworms, and eyeless shrimp—live in the dark depths around black smokers.

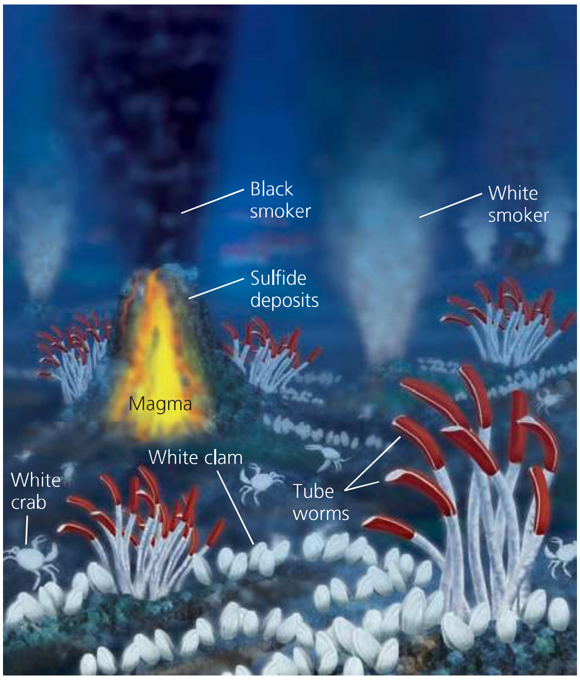

FIGURE 14.6 Natural capital: *Hydrothermal deposits*, or *black smokers*, are rich in various minerals.

Because of the rapidly rising prices of many of these metals, there is growing interest in deep-sea mining. Companies from Australia, the United States, and China have been exploring the possibility of mining black smokers in several areas. In 2012 the U.S. government issued its first-ever approval of large-scale deep-sea mining, proposed for a large area between Hawaii and Mexico. In 2015 the Center for Biological Diversity sued the government to try to prevent the project, arguing that it could damage important habitat for whales, sharks, and sea turtles by destroying seafloor ecosystems.

According to some analysts, seafloor mining is less environmentally harmful than mining on land. Other scientists, however, are concerned because seafloor mining stirs up sediment that can harm or kill organisms that feed by filtering seawater. Supporters of seafloor mining say that the number of potential mining sites, and thus the overall environmental impact, will be small.

Another possible source of metals is the potato-size *manganese nodules* that cover large areas of the Pacific Ocean floor and smaller areas of the Atlantic and Indian Ocean floors. They also contain low concentrations of various rare earth minerals. These modules could be sucked up through vacuum pipes or scooped up by underwater mining machines.

To date, mining on the ocean floor has been hindered by the high costs involved, the potential threat to marine ecosystems, and arguments over rights to the minerals in deep ocean areas that do not belong to any specific country.

14.3 WHAT ARE THE ENVIRONMENTAL EFFECTS OF USING NONRENEWABLE MINERAL RESOURCES?

CONCEPT 14.3 Extracting minerals from the earth's crust and converting them to useful products can disturb the land, erode soils, produce large amounts of solid waste, and pollute the air, water, and soil.

Extracting Minerals Can Have Harmful Environmental Effects

Every metal product has a *life cycle* that includes mining the mineral, processing it, manufacturing the product, and disposal or recycling of the product (Figure 14.7). This process makes use of large amounts of energy and water, and produces pollution and waste at every step of the life cycle (**Concept 14.3**).

The environmental impacts of mining a metal ore are determined partly by the ore's percentage of metal content, or *grade*. The more accessible higher-grade ores are usually exploited first. Mining lower-grade ores takes more money, energy, water, and other resources, and leads to more land disruption, mining waste, and pollution.

Several mining techniques are used to remove mineral deposits. Shallow mineral deposits are removed by **surface mining,** in which vegetation, soil, and rock overlying a mineral deposit are cleared away. This waste material is called **overburden** and is usually deposited in piles called **spoils** (Figure 14.8). Surface mining is used to extract about 90% of the nonfuel mineral resources and 60% of the coal used in the United States.

Different types of surface mining can be used, depending on two factors: the resource being sought and the local topography. In **open-pit mining,** machines are used to dig large pits and remove metal ores containing copper (see chapter-opening photo), gold (**Core Case Study**), or other metals, or sand, gravel, or stone.

LianeM/Shutterstock.com

FIGURE 14.8 Natural capital degradation: This spoils pile in Zielitz, Germany, is made up of waste material from the mining of potassium salts used to make fertilizers.

9 million

Number of people who could sit in Bingham Copper Mine (see chapter-opening photo) if it were a stadium

Strip mining involves extracting mineral deposits that lie in large horizontal beds close to the earth's surface. In **area strip mining,** used on flat terrain, a gigantic earthmover strips away the overburden, and a power shovel—which can be as tall as a 20-story building—removes a mineral resource such as gold (Figure 14.9). The resulting trench is filled with overburden, and a new cut is

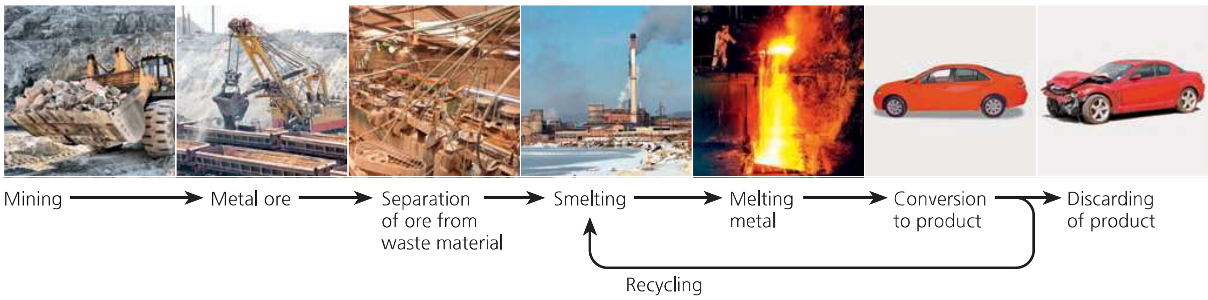

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FIGURE 14.7 Each metal product that we use has a *life cycle*.

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FIGURE 14.9 Natural capital degradation: Area strip mining for gold in Yukon Territory, Canada.

made parallel to the previous one. This process is repeated over the entire site.

Contour strip mining (Figure 14.10) is used mostly to mine coal and various mineral resources on hilly or mountainous terrain. Huge power shovels and bulldozers cut a series of terraces into the side of a hill. Then, earthmovers remove the overburden, an excavator or power shovel extracts the coal, and the overburden from each new terrace is dumped onto the one below. Unless the land is restored, this leaves a series of spoils banks and a highly erodible hill of soil and rock called a *highwall*.

Another surface mining method is **mountaintop removal,** in which explosives are used to remove the top of a mountain to expose seams of coal (Figure 14.11). This method is commonly used in the Appalachian Mountains of the United States. After a mountaintop is blown apart, enormous machines plow waste rock and dirt into valleys below. This destroys forests, buries mountain streams, and increases the risk of flooding. Wastewater and toxic sludge, produced when the coal is

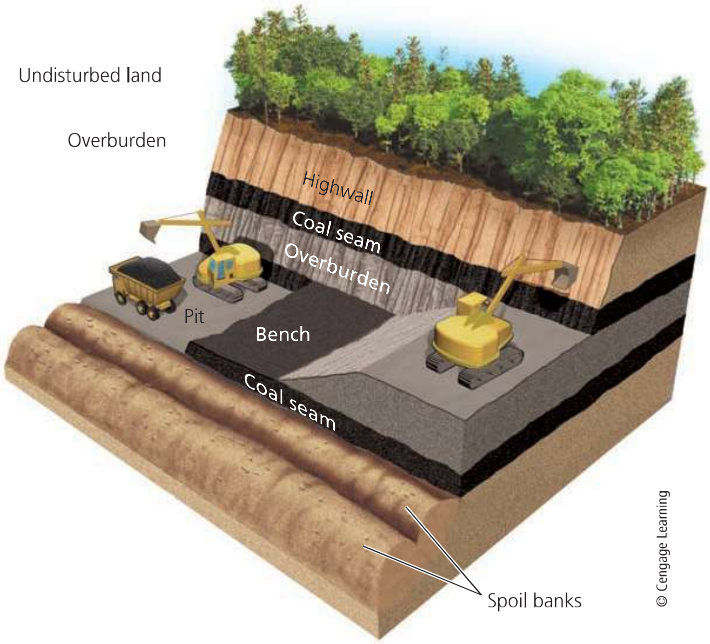

FIGURE 14.10 Natural capital degradation: Contour strip mining is used in hilly or mountainous terrain.

Jim West/Age Fotostock

FIGURE 14.11 Natural capital degradation: Mountaintop removal coal mining near Whitesville, West Virginia.

processed, are often stored behind dams in these valleys. Such dams have been known to overflow or collapse and release toxic substances such as arsenic and mercury.

In the United States, more than 500 mountaintops in West Virginia and other Appalachian states have been removed to extract coal. According to the U.S. Environmental Protection Agency (EPA), the resulting spoils have buried more than 1,100 kilometers (700 miles) of streams—a total roughly equal in length to the distance between the two U.S. cities of New York and Chicago.

The U.S. Department of the Interior estimates that at least 500,000 surface-mined sites dot the U.S. landscape, mostly in the West. Such sites can be cleaned up and restored. The U.S. Surface Mining Control and Reclamation Act of 1977 requires the restoration of surface-mined sites. However, the program is underfunded and many mines have not been reclaimed.

Deep deposits of minerals are removed by **subsurface mining,** in which underground mineral resources are removed through tunnels and shafts (Figure 14.12). This method is used to remove metal ores and coal that are too deep to be extracted by surface mining. Miners dig a deep, vertical shaft and blast open subsurface tunnels and chambers to reach the deposit. Then they use machinery to remove the resource and transport it to the surface.

Subsurface mining disturbs less than one-tenth as much land as surface mining, and usually produces less waste material. However, it can lead to other hazards such as cave-ins, explosions, and fires for miners. Miners often get lung diseases caused by prolonged inhalation of mineral or coal dust in subsurface mines. Another problem is *subsidence*—the collapse of land above some underground mines. It can damage houses, crack sewer lines, break natural gas mains, and disrupt groundwater systems.

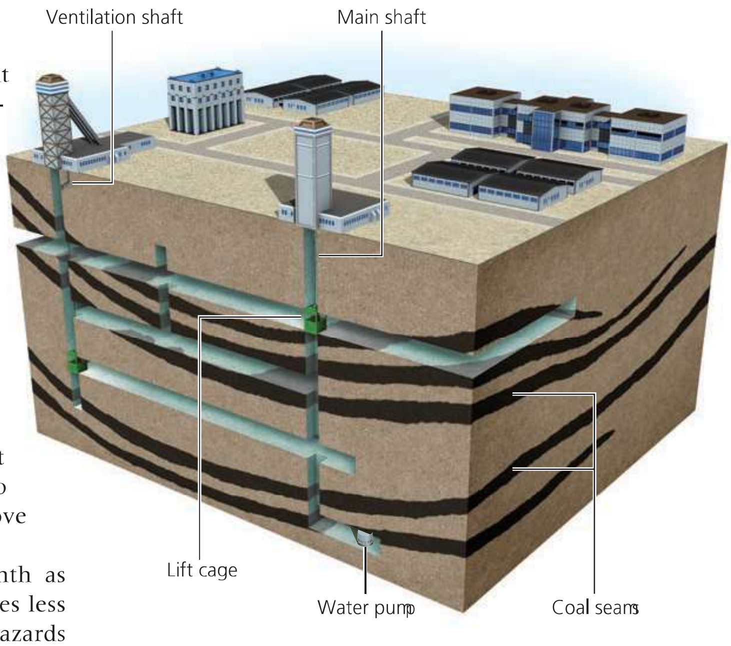

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FIGURE 14.12 Subsurface mining of coal.

Surface and subsurface mining operations also produce large amounts of solid waste—three-fourths of all U.S. solid waste—and cause major water and air pollution. For example, *acid mine drainage* occurs when rainwater that seeps through an underground mine or a spoils pile from a surface mine carries sulfuric acid (H_2SO_4) produced when aerobic bacteria act on remaining minerals to nearby streams and groundwater. This is one of the problems often associated with gold mining (**Core Case Study**).

According to the EPA, mining has polluted mountain streams in 40% of the western watersheds in the United States. It accounts for 50% of all the country's emissions of toxic chemicals into the atmosphere. In fact, the mining industry produces more of such toxic emissions than any other U.S. industry.

Where environmental regulations and enforcement are lax, mining is even more harmful to the environment. In China, for instance, the mining and processing of rare earth metals and oxides has stripped land of its vegetation and topsoil. It also has polluted the air, acidified streams, and left toxic and radioactive waste piles.

Removing Metals from Ores Has Harmful Environmental Effects

Ore extracted by mining typically has two components: the ore mineral, containing the desired metal, and waste material. Removing the waste material from ores produces **tailings**—rock wastes that are left in piles or put into ponds where they settle out. Particles of toxic metals in tailings piles can be blown by the wind or washed out by rain, or can leak from holding ponds and contaminate surface water and groundwater.

After the waste material is removed, heat or chemical solvents are used to extract the metals from mineral ores. Heating ores to release metals is called **smelting** (Figure 14.6). Without effective pollution control equipment, a smelter emits large quantities of air pollutants, including sulfur dioxide and suspended toxic particles that damage vegetation and acidify soils in the surrounding area. Smelters also cause water pollution and produce liquid and solid hazardous wastes that require safe disposal. A 2012 study found that lead smelting is the world's second most toxic industry after the recycling of lead-acid batteries.

Using chemicals to extract metals from their ores can also create numerous problems, as noted in the **Core Case Study**. Even on a smaller scale, this is the case. For example, millions of poverty-stricken miners in less-developed countries have gone into tropical forests in search of gold (Figure 14.13). They have cleared trees to get access to gold, and such illegal deforestation has increased rapidly, especially in parts of the Amazon Basin. The miners use toxic mercury to separate gold from its ore. They heat the

FIGURE 14.13 Illegal gold mining on the banks of the Pra River in Ghana, Africa.

Randy Olson/National Geographic Creative mixture of gold and mercury to vaporize the mercury and leave the gold, causing dangerous air and water pollution. Many of these miners and villagers living near the mines eventually inhale toxic mercury vapor, drink mercury-laden water, or eat fish contaminated with mercury.

14.4 HOW CAN WE USE MINERAL RESOURCES MORE SUSTAINABLY?

CONCEPT 14.4 We can try to find substitutes for scarce resources, reduce resource waste, and recycle and reuse minerals.

Find Substitutes for Scarce Mineral Resources

Some analysts believe that even if supplies of key minerals become too expensive or too scarce due to unsustainable use, human ingenuity will find substitutes (**Concept 14.4**). They point to the current *materials revolution* in which silicon and other materials are replacing some metals for common uses. They also point out the possibilities of finding substitutes for scarce minerals through nanotechnology (Science Focus 14.1), as well as through other emerging technologies.

For example, fiber-optic glass cables that transmit pulses of light are replacing copper and aluminum wires in telephone cables, and nanowires may eventually replace fiber-optic glass cables. High-strength plastics and materials, strengthened by lightweight carbon, hemp, and glass fibers, are beginning to transform the automobile and aerospace industries. These new materials do not need painting (which reduces pollution and costs) and can be molded into any shape. Use of such materials in manufacturing motor vehicles and airplanes could greatly increase vehicle fuel efficiency by reducing vehicle weights. Such new materials are even being used to build bridges. Two such possible breakthrough materials are graphene and phosphorene (see the Case Study that follows).

CONSIDER THIS . . .

LEARNING FROM NATURE

Without using toxic chemicals, spiders rapidly build their webs by producing threads of silk that are capable of capturing insects flying at high speeds. Learning how spiders do this could revolutionize the production of high-strength fibers with a very low environmental impact.

However, resource substitution is not a cure-all. For example, platinum is currently unrivaled as a catalyst and is used in industrial processes to speed up chemical reactions, and chromium is an essential ingredient of stainless steel. We can try to find substitutes for such scarce resources, but this may not always be possible.

CASE STUDY

Graphene and Phosphorene: New Revolutionary Materials

Graphene is made from graphite—a form of carbon that occurs as a mineral in some rocks. Ultrathin graphene consists of a single layer of carbon atoms packed into a two-dimensional hexagonal lattice (somewhat like chicken wire) that can be applied as a transparent film to surfaces (Figure 14.14).

Graphene is one of the world's thinnest and strongest materials and is light, flexible, and stretchable. A single layer of graphene is 150,000 times thinner than a human hair and 100 times stronger than structural steel. A sheet of this amazing material stretched over a coffee mug could support the weight of a car. It is also a better conductor of electricity than copper and conducts heat better than any known material.

The use of graphene could revolutionize the electric car industry by leading to the production of batteries that can be recharged 10 times faster and hold 10 times more power than current car batteries. Graphene composites can also be used to make stronger and lighter plastics, lightweight aircraft and motor vehicles, flexible computer tablets, and TV screens as thin as a magazine. Within 5 years, it might also be used to make flexible, more efficient, less costly solar cells that can be attached to almost anything. Engineers also hope to make advances in desalination by using graphene to make the membrane used in reverse osmosis (see Science Focus 13.2, p. 339).

Researchers are looking into possible harmful effects of graphene production and use. A 2014 study led by Sharon Walker at the University of California–Riverside found graphene oxide in lakes and drinking water storage tanks. This could increase the chances that animals and humans could ingest the chemical, which was found in some early studies to be toxic to mice and human lung cells.

Graphene is made from very high purity and expensive graphite. According to the USGS, in 2013 China controlled about 68% of the world's high-purity graphite production. The United States mines very little natural graphite and imports most of its graphite from Mexico and China, which could restrict U.S. product exports as the use of graphene grows.

Geologists are looking for deposits of graphite in the United States. However, in 2011 a team of Rice University chemists, led by James M. Tour, found ways to make large sheets of high-quality graphene from inexpensive materials found in garbage and from dog feces. If such a process becomes economically feasible, concern over supplies of graphite could vanish, along with any harmful environmental effects of the mining and processing of graphite.

In 2014 a team of researchers at Purdue University was able to isolate a single layer of black phosphorus atoms—a

SCIENCEFOCUS 14.1

The Nanotechnology Revolution

Nanotechnology uses science and engineering to manipulate and create materials out of atoms and molecules at the ultra-small scale of less than 100 nanometers. The diameter of the period at the end of this sentence is about a half million nanometers.

At the nanometer level, conventional materials have unconventional and unexpected properties. For example, scientists have learned to link carbon atoms together to form one-atom-thick sheets of carbon called *graphene* (see Case Study, p. 369). These sheets can be shaped into tubes called *carbon nanotubes* that are 60 times stronger than high-grade steel. A nearly invisible thread of this material is strong enough to suspend a pickup truck. Using carbon nanotubes to build cars would make them stronger and safer and would improve gas mileage by making them up to 80% lighter.

Currently, nanomaterials are used in more than 1,300 consumer products and the number is growing. Such products include certain batteries, stain-resistant and wrinkle-free clothes, self-cleaning glass surfaces, self-cleaning sinks and toilets, sunscreens, waterproof coatings for cell phones, some cosmetics, some foods, and food containers that release nanosilver ions to kill bacteria, molds, and fungi.

Nanotechnologists envision innovations such as a supercomputer smaller than a grain of rice, thin and flexible solar cell films that could be attached to or painted onto almost any surface, biocomposite materials that would make our bones and tendons super strong, and nanomolecules specifically designed to seek out and kill cancer cells. Nanotechnology allows us to make materials from the bottom up, using atoms of abundant elements (primarily hydrogen, oxygen, nitrogen, carbon, silicon, and aluminum) as substitutes for scarcer elements, such as copper, cobalt, and tin.

Nanotechnology has many potential environmental benefits. Designing and building products on the molecular level would greatly reduce the need to mine many materials. It would also require less matter and energy and it would reduce waste production. We may be able to use nanoparticles to remove industrial pollutants from contaminated air, soil, and groundwater. Nanofilters might someday be used to desalinate and purify seawater at an affordable cost, thereby helping to increase drinking water supplies. **GREEN CAREER: Environmental nanotechnology**

What's the catch? The main problem is serious concerns about the possible harmful health effects of nanotechnology. Because of the large combined surface area of the huge number of nanoparticles involved in any application, they are more chemically reactive and potentially more toxic to humans and other animals than are conventional materials.

Laboratory studies involving mice and other test animals reveal that nanoparticles can be inhaled deeply into the lungs and absorbed into the bloodstream. This can result in lung damage similar to that caused by mesothelioma, a deadly cancer resulting from the inhalation of asbestos particles. Nanoparticles can also penetrate cell membranes, including those in the brain, and move across the placenta from a mother to her fetus. A 2015 study led by Gary Cherr of the University of California–Davis found that nanoparticles from sunscreens, boat paints, and other consumer products can harm the embryonic development of certain marine organisms.

A panel of experts from the U.S. National Academy of Sciences has said that the U.S. government is not doing enough to evaluate the potential health and environmental risks of using nanomaterials. For example, the U.S. Food and Drug Administration does not maintain a list of the food products and cosmetics that contain nanomaterials. By contrast, the European Union takes a precautionary approach to the use of nanomaterials, requiring that manufacturers demonstrate the safety of their products before they can enter the marketplace.

Many analysts say that, before unleashing nanotechnology more broadly, we should ramp up research on the potential harmful health effects of nanoparticles and develop regulations to control its growing applications until we know more about its possible harmful health effects. Many are also calling for the labeling of all products that contain nanoparticles.

CRITICAL THINKING

Do you think the potential benefits of nanotechnology products outweigh their potentially harmful effects? Explain.

new material known as *phosphorene*. As a semiconductor, it is more efficient than silicon transistors that are used as chips in computers and other electronic devices. Replacing them with phosphorene transistors could make almost any electronic device run much faster while using less power. This could revolutionize computer technology. However, phosphorene must be sealed in a protective coating because it breaks down when exposed to air.

Use Mineral Resources More Sustainably

Figure 14.15 lists several ways to use mineral resources more sustainably. One strategy is to focus on recycling and reuse of nonrenewable mineral resources, especially valuable or scarce metals such as gold, iron, copper, aluminum, and platinum (**Concept 14.4**). Recycling, an application of the chemical cycling **principle of sustainability** (see Inside

INDIVIDUALS MATTER 14.1

Yu-Guo Guo: Designer of Nanotechnology Batteries and National Geographic Explorer

Yu-Guo Guo is a professor of chemistry and a nanotechnology researcher at the Chinese Academy of Sciences in Beijing. He has invented nanomaterials that can be used to make lithium-ion battery packs smaller, more powerful, and less costly, which makes them more useful for powering electric cars and electric bicycles. This is an important scientific advance, because the battery pack is the most important and expensive part of any electric vehicle.

Guo's innovative use of nanomaterials has greatly increased the power of lithium-ion batteries by enabling electric current to flow more efficiently through what he calls "3-D conducting nanonetworks." With this promising technology, lithium-ion battery packs in electric vehicles can be fully charged in a few minutes. They also have twice the energy storage capacity of today's batteries, and thus will extend the range of electric vehicles by enabling them to run longer. Guo is also interested in developing nanomaterials for use in solar cells and fuel cells that could be used to generate electricity and to power vehicles.

FIGURE 14.14 Graphene, which consists of a single layer of carbon atoms linked together in a hexagonal lattice, is a revolutionary new material.

Solutions

Sustainable Use of Nonrenewable Minerals

- Reuse or recycle metal products whenever possible
- Redesign manufacturing processes to use less mineral resources
- Reduce mining subsidies
- Increase subsidies for reuse, recycling, and finding substitutes

FIGURE 14.15 We can use nonrenewable mineral resources more sustainably (**Concept 14.4**). ***Critical thinking:*** Which two of these solutions do you think are the most important? Why?

Back Cover), has a much lower environmental impact than that of mining and processing metals from ores. For example, recycling aluminum beverage cans and scrap aluminum produces 95% less air pollution and 97% less water pollution, and uses 95% less energy, than mining and processing aluminum ore. We can also extract and recycle valuable gold (**Core Case Study**) from discarded cell phones. Cleaning up and reusing items instead of recycling them has an even lower environmental impact.

Using mineral resources more sustainably is a major challenge in the face of rising demand for many minerals. For example, one way to increase supplies of rare earths is to extract and recycle them from the massive amounts of electronic wastes that are being produced. So far, however, less than 1% of rare earth metals are recovered and recycled.

Another way to use minerals more sustainably is to find substitutes for rare minerals, ideally, substitutes without heavy environmental impacts (**Concept 14.4**). For example, electric car battery makers are beginning to switch from making nickel-metal-hydride batteries, which require the rare earth metal lanthanum, to manufacturing lighter-weight lithium-ion batteries, which researchers are now trying to improve (Individuals Matter 14.1).

Lithium (Li), the world's lightest metal, is a vital component of lithium-ion batteries, which are used in cell phones, iPads, laptop computers, and a growing number of other products. The problem is that some countries, including the United States, do not have large supplies of lithium. The South American countries of Bolivia, Chile, and Argentina have about 80% of the global reserves of lithium. Bolivia alone has about 50% of these reserves, whereas the United States holds only about 3%.

Japan, China, South Korea, and the United Arab Emirates are buying up access to global lithium reserves to ensure their ability to sell lithium or batteries to the rest of the world. Within a few decades, the United States may be heavily dependent on expensive imports of lithium and lithium batteries. However, in 2014 the company Simbol, Inc. began building a plant in California that is designed to extract lithium from brine waste produced by geothermal power plants. If it is successful, this process could lessen some U.S. dependence on imported lithium.

Scientists are also searching for substitutes for rare earth metals that are used to make increasingly important powerful magnets and related devices. In Japan and the United States, researchers are developing a variety of such devices that require no rare earth minerals, are light and compact, and can deliver more power with greater efficiency at a reduced cost.

14.5 WHAT ARE THE EARTH'S MAJOR GEOLOGICAL HAZARDS?

CONCEPT 14.5 Dynamic processes move matter within the earth and on its surface and can cause volcanic eruptions, earthquakes, tsunamis, erosion, and landslides.

The Earth Beneath Your Feet Is Moving

We tend to think of the earth's crust as solid and unmoving. However, the flows of energy and heated material within the earth's convection cells (Figure 14.2) are so powerful that they have caused the lithosphere to break up into a dozen or so huge rigid plates, called **tectonic plates,** which move extremely slowly atop the asthenosphere (Figure 14.16).

These gigantic plates are somewhat like the world's largest and slowest-moving surfboards on which we ride without noticing their movement. Their typical speed is about the rate at which your fingernails grow. Throughout the earth's history, landmasses have split apart and joined together as tectonic plates shifted around, changing the size, shape, and location of the earth's continents (Figure 4.B, p. 90). The slow movement of the continents across Earth's surface is called **continental drift.**

Much of the geological activity at the earth's surface takes place at the boundaries between tectonic plates as they separate, collide, or grind along against each other. The boundary that occurs where two plates move away from each other is called a **divergent boundary** (Figure 14.16). At such boundaries, magma flows up where the plates separate, sometimes hardening and forming new crust and sometimes breaking to the surface and causing volcanic eruptions. Earthquakes can also occur because of divergence of plates, and superheated water can erupt as geysers.

Another type of boundary is the **convergent boundary** (Figure 14.16), where two tectonic plates are colliding. This super-slow-motion collision causes one or both plate edges to buckle and rise, forming mountain ranges. In most cases, one plate slides beneath the other, melting and making new magma that can rise through cracks and form volcanoes near the boundary. The overriding plate is pushed up and made into mountainous terrain.

The third major type of boundary is the **transform plate boundary** (Figure 14.16), where two plates grind along in opposite directions next to each other. The tremendous forces produced at these boundaries can form mountains or deep cracks (Figure 14.17) and cause earthquakes and volcanic eruptions.

Volcanoes Release Molten Rock from the Earth's Interior

An active **volcano** occurs where magma rising in a plume through the lithosphere reaches the earth's surface through a central vent or a long crack, called a *fissure* (Figure 14.18). Magma or molten rock that reaches the earth's surface is called *lava*.

A *volcanic eruption* releases chunks of lava rock, liquid lava, glowing hot ash, and gases (including water vapor, carbon dioxide, and sulfur dioxide) (**Concept 14.5**). Eruptions can be explosive and extremely destructive, causing loss of life and obliterating ecosystems and human communities. They can also be slow and much less destructive with lava gurgling up and spreading slowly across the land or sea floor. It is this slower form of eruption that builds the cone-shaped mountains so commonly associated with volcanoes, as well as layers of rock made of cooled lava on the earth's surface.

While volcanic eruptions can be destructive, they can also form majestic mountain ranges and lakes, and the weathering of lava contributes to fertile soils. Hundreds of volcanoes have erupted on the ocean floor, building cones that have reached the ocean's surface, eventually to form islands that have become suitable for human settlement, such as the Hawaiian Islands.

We can reduce the loss of human life and some of the property damage caused by volcanic eruptions by using historical records and geological measurements to identify high-risk areas, so that people can avoid living in those areas. We also use monitoring devices that warn us when volcanoes are likely to erupt, and in some areas that are prone to volcanic activity, evacuation plans have been developed.

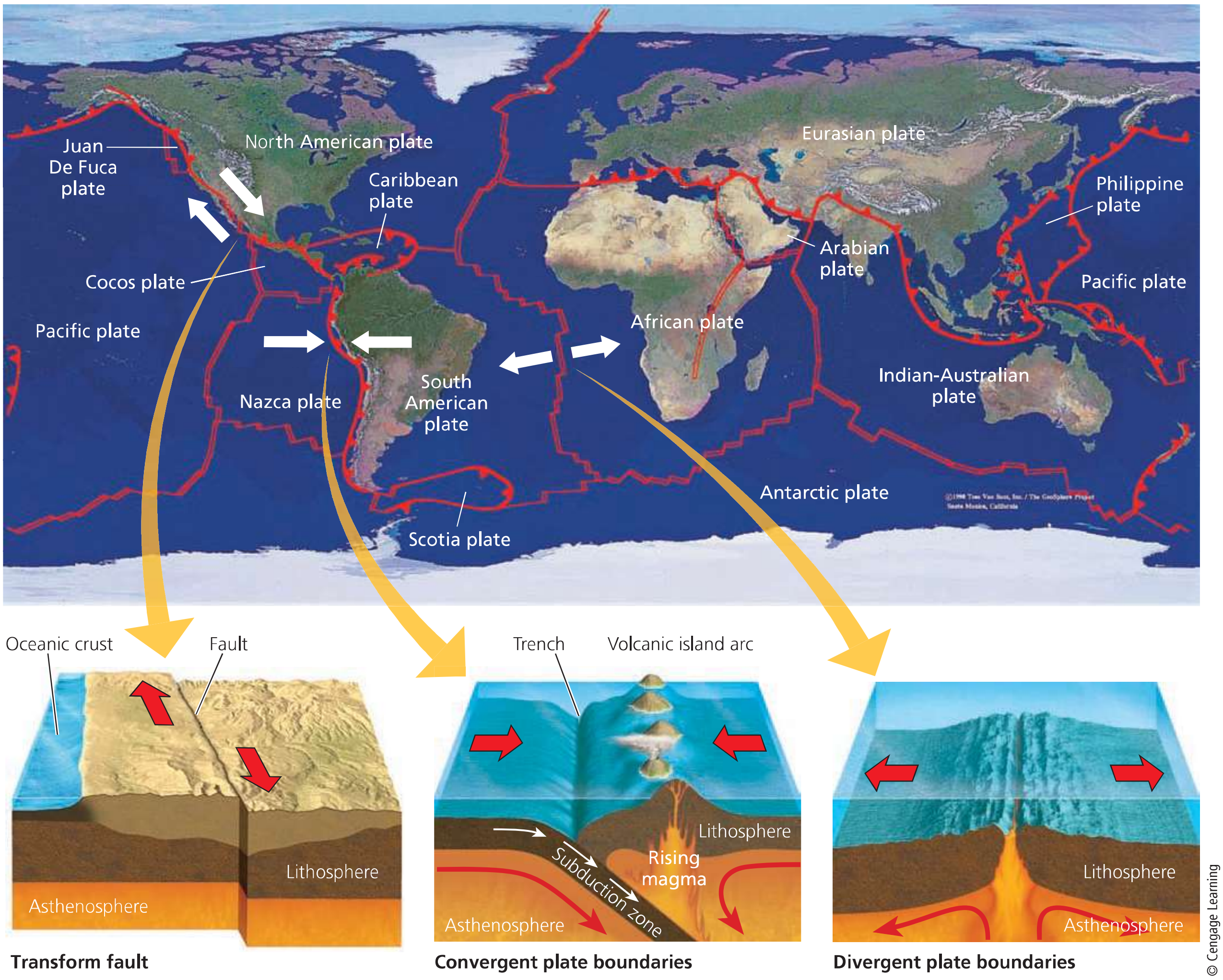

FIGURE 14.16 The earth's crust has been fractured into several major tectonic plates. White arrows indicate examples of where plates are colliding, separating, or grinding along against each other in opposite directions. ***Question:*** Which plate are you riding on?

Earthquakes Are Geological Rock-and-Roll Events

Forces inside the earth's mantle put tremendous stress on rock within the crust. Such stresses can be great enough to cause sudden breakage and shifting of the rock, producing a *fault*, or fracture in the earth's crust (Figure 14.17). When a fault forms, or when there is abrupt movement on an existing fault, energy that has accumulated over time is released in the form of vibrations, called *seismic waves*, which move in all directions through the surrounding rock—an event called an **earthquake** (Figure 14.19 and **Concept 14.5**). Most earthquakes occur at the boundaries of tectonic plates (Figures 14.16 and 14.17).

Seismic waves move upward and outward from the earthquake's *focus* like ripples in a pool of water. Scientists measure the severity of an earthquake by the *magnitude* of its seismic waves. The magnitude is a measure of ground motion (shaking) caused by the earthquake, as indicated by the *amplitude*, or size of the seismic waves when they reach a recording instrument, called a *seismograph*.

Scientists use the *Richter scale*, on which each unit has an amplitude 10 times greater than the next smaller unit. *Seismologists*, or people who study earthquakes, rate earthquakes

FIGURE 14.17 The San Andreas Fault, created by the North American Plate and the Pacific Plate sliding very slowly past each other, runs almost the full length of California (see map). It is responsible for earthquakes of various magnitudes, which have caused rifts on the land surface in some areas (photo).

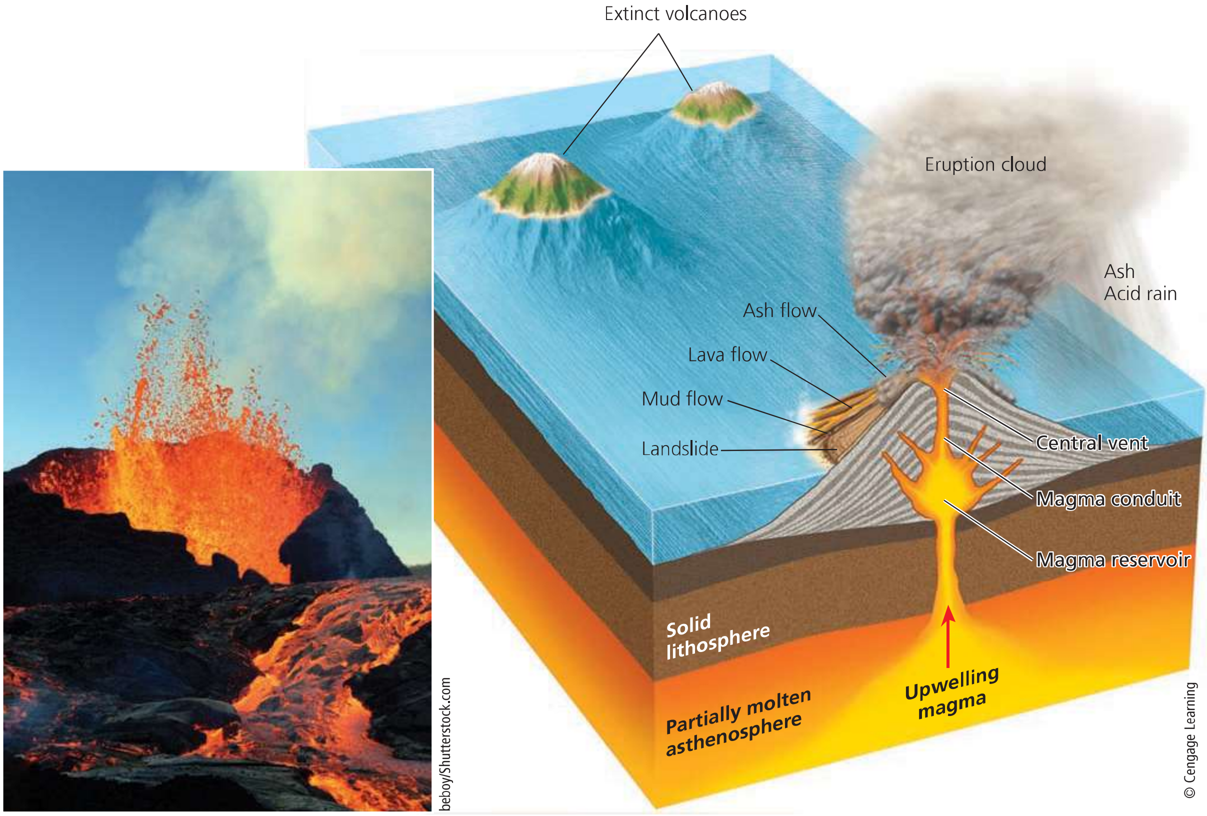

FIGURE 14.18 Sometimes, the internal pressure in a volcano is high enough to cause lava, ash, and gases to be ejected into the atmosphere (photo) or to flow over land, causing considerable damage.

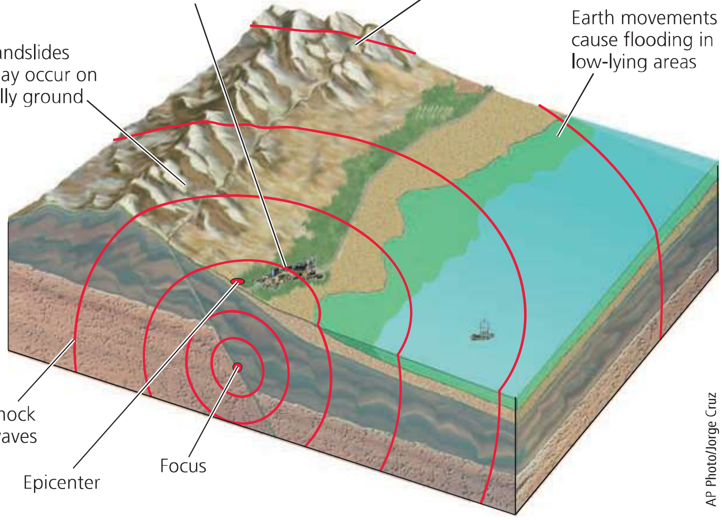

FIGURE 14.19 An *earthquake* (left) is one of nature's most powerful events. The photo shows damage from a 2010 earthquake in Port-au-Prince, Haiti.

as *insignificant* (less than 4.0 on the Richter scale), *minor* (4.0–4.9), *damaging* (5.0–5.9), *destructive* (6.0–6.9), *major* (7.0–7.9), and *great* (over 8.0). The largest recorded earthquake occurred in Chile on May 22, 1960, and measured 9.5 on the Richter scale. Each year, scientists record the magnitudes of more than 1 million earthquakes, most of which are too small to feel.

The primary effects of earthquakes include shaking and sometimes a permanent vertical or horizontal displacement of a part of the crust. These effects can have serious consequences for people and for buildings, bridges, freeway overpasses, dams, and pipelines. A major earthquake is a large rock-and-roll geological event.

One way to reduce the loss of life and property damage from earthquakes is to examine historical records and make geological measurements to locate active fault zones. We can then map high-risk areas and establish building codes that regulate the placement and design of buildings in such areas. Then people can evaluate the risk and factor it into their decisions about where to live. In addition, engineers know how to make homes, large buildings, bridges, and freeways more earthquake resistant, although this is costly.

See Figure 12, p. S27, in Supplement 4, for a map comparing earthquake risks in various areas of the United States, and Figure 13, p. S28, in Supplement 4 for a map of such areas throughout the world.

Earthquakes on the Ocean Floor Can Cause Tsunamis

A **tsunami** is a series of large waves generated when part of the ocean floor suddenly rises or drops (Figure 14.20). Most large tsunamis are caused when certain types of faults in the ocean floor move up or down because of a large underwater earthquake. Other causes are landslides generated by earthquakes and volcanic eruptions (**Concept 14.5**).

Tsunamis are often called *tidal waves*, although they have nothing to do with tides. They can travel across the ocean at the speed of a jet airliner. In deep water the waves are very far apart—sometimes hundreds of kilometers—and their crests are not very high. As a tsunami approaches a coast with its shallower waters, it slows down, its wave crests squeeze closer together, and their heights grow rapidly. It can hit a coast as a series of towering walls of water that can level buildings.

The largest recorded loss of life from a tsunami occurred in December 2004 when a great underwater earthquake in the Indian Ocean with a magnitude of 9.15 caused a tsunami that killed more than 230,000 people and devastated many coastal areas of Indonesia (Figure 14.21 and map in Figure 14.20), Thailand, Sri Lanka, South India, and eastern Africa. It also displaced about 1.7 million people (1.3 million of them in India and Indonesia), and destroyed or damaged about 470,000 buildings and houses. There

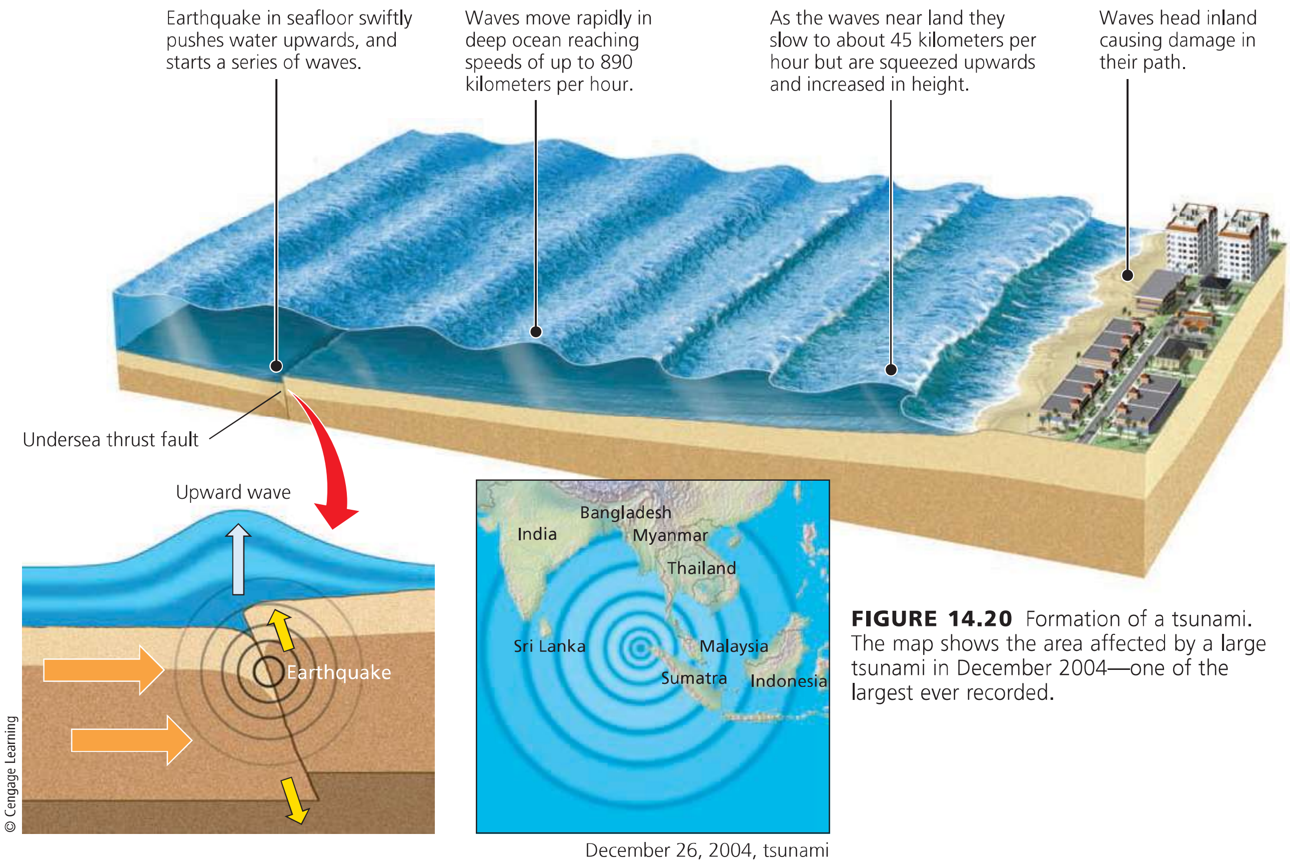

FIGURE 14.20 Formation of a tsunami. The map shows the area affected by a large tsunami in December 2004—one of the largest ever recorded.

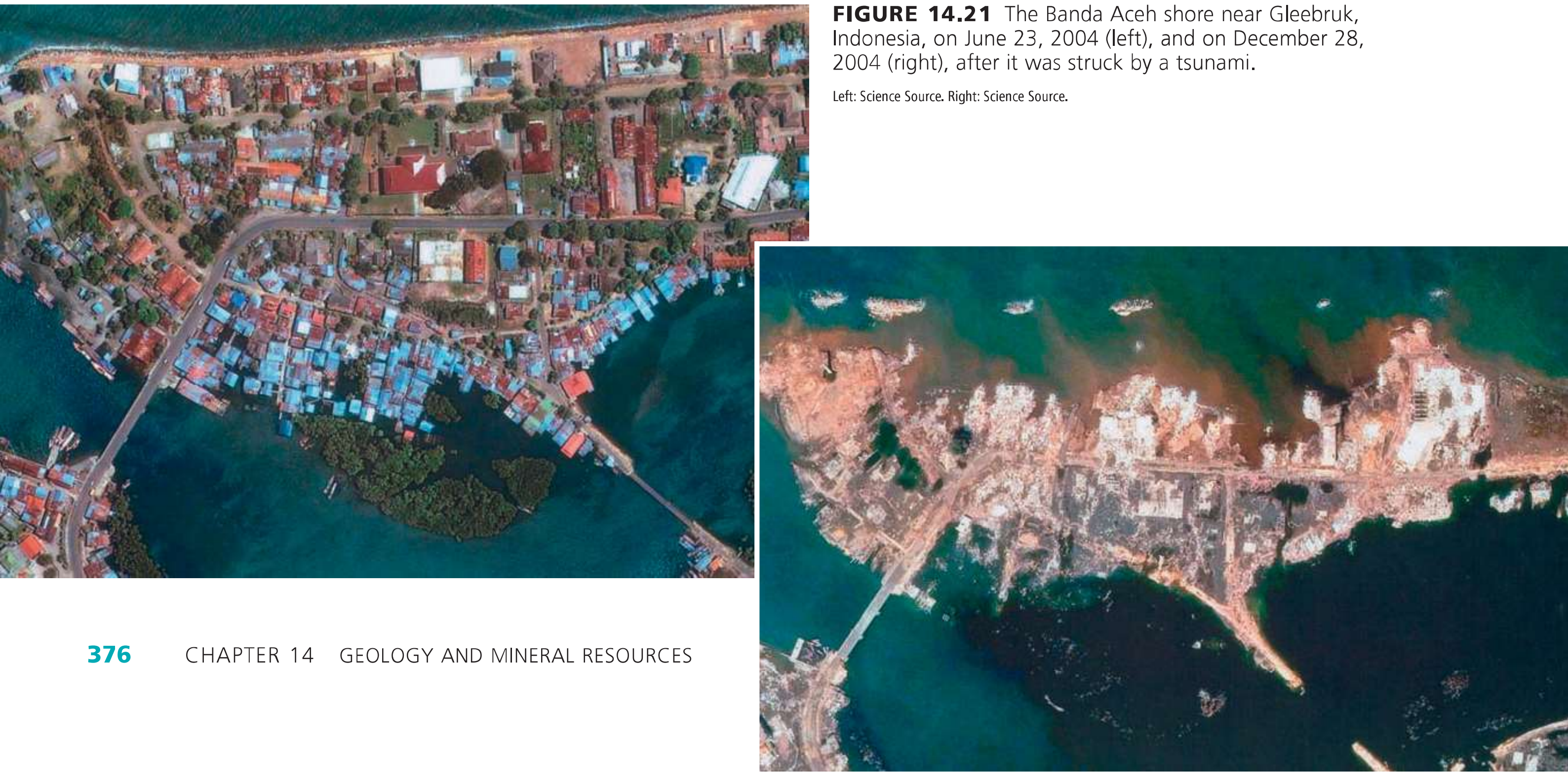

FIGURE 14.21 The Banda Aceh shore near Gleebruk, Indonesia, on June 23, 2004 (left), and on December 28, 2004 (right), after it was struck by a tsunami.

Left: Science Source. Right: Science Source.

were no recording devices in place to provide an early warning of this tsunami.

In 2011 a large tsunami caused by a powerful earthquake off the coast of Japan generated 3-story high waves that killed almost 19,000 people, displaced more than 300,000 people, and destroyed or damaged 125,000 buildings. It also heavily damaged three nuclear reactors, which then released dangerous radioactivity into the surrounding environment.

In some areas, scientists have built networks of ocean buoys and pressure recorders on the ocean floor to collect data that can be relayed to tsunami emergency warning centers. However, these networks are not widespread.

BIG IDEAS

- Dynamic forces that move matter within the earth and on its surface recycle the earth's rocks, form deposits of mineral resources, and cause volcanic eruptions, earthquakes, and tsunamis.
- The available supply of a mineral resource depends on how much of it is in the earth's crust, how fast we use it, the mining technology used to obtain it, its market prices, and the harmful environmental effects of removing and using it.
- We can use mineral resources more sustainably by trying to find substitutes for scarce resources, reducing resource waste, and reusing and recycling nonrenewable minerals.

Tying It All Together

The Real Cost of Gold and Sustainability

In this chapter's Core Case Study, we considered the harmful effects of gold mining as an example of the impacts of our extraction and use of mineral resources. We saw that these effects make gold much more costly, in terms of environmental and human health costs, than is reflected in the price of gold.

In this chapter, we looked at technological developments that could help us to expand supplies of mineral resources and to use them more sustainably. For example, if we develop it safely, we could use nanotechnology to make new materials that could replace scarce mineral resources and greatly reduce the environmental impacts of mining and processing such resources. For example, we might use graphene to produce more efficient and affordable solar cells to generate electricity—an application of the solar energy **principle of sustainability**.

We can also use mineral resources more sustainably by reusing and recycling them, and by reducing unnecessary resource use and waste—applying the chemical cycling **principle of sustainability**. In addition, industries can mimic nature by using a diversity of ways to reduce the harmful environmental impacts of mining and processing mineral resources, thus applying the biodiversity **principle of sustainability**.

Matt Benoit/Shutterstock.com

Chapter Review

Core Case Study

1. Explain why the real cost of gold is more than what most people pay for it. What are some examples of costs not accounted for?

Section 14.1

2. What are the two key concepts for this section? Define **geology**, **core**, **mantle**, **asthenosphere**, **crust**, and **lithosphere**. Define **mineral**, **mineral resource**, and **rock**. Define and distinguish among **sedimentary rock**, **igneous rock**, and **metamorphic rock** and give an example of each. What is the **rock cycle**? Explain its importance. Define **ore** and distinguish between a **high-grade ore** and a **low-grade ore**. List five important nonrenewable mineral resources and their uses.

Section 14.2

3. What are the two key concepts for this section? What are the **reserves** of a mineral resource and how can they be expanded? What two factors determine the future supply of a nonrenewable mineral resource? Explain how the supply of a nonrenewable mineral resource can be economically depleted and list the five choices we have when this occurs. What is **depletion time** and what factors affect it?

4. What five nations supply most of the world's nonrenewable mineral resources? How dependent is the United States on other countries for important nonrenewable mineral resources? Explain the concern over U.S. access to rare earth mineral resources. Describe the conventional view of the relationship between the supply of a mineral resource and its market price. Explain why some economists believe this relationship no longer applies in some countries. Summarize the pros and cons of providing government subsidies and tax breaks for mining companies.

5. Summarize the opportunities and limitations of expanding mineral supplies by mining lower-grade ores. What are the advantages and disadvantages of biomining? Describe the opportunities and possible problems that could result from deep-sea mining.

Section 14.3

6. What is the key concept for this section? Summarize the life cycle of a metal product.

7. What is **surface mining**? Define **overburden** and **spoils**. Define **open-pit mining** and **strip mining**, and distinguish among **area strip mining**, **contour strip mining**, and **mountaintop removal mining**. Describe three harmful environmental effects of surface mining. What is **subsurface mining**? What is acid mine drainage? Define **tailings** and explain why they can be hazardous. What is **smelting** and what are its major harmful environmental effects?

Section 14.4

8. What is the key concept for this section? Give two examples of promising substitutes for key mineral resources. What is **nanotechnology** and what are some of its potential environmental and other benefits? What are some problems that could arise from the widespread use of nanotechnology? Describe the potential of using graphene and phosphorene as new resources. Explain the benefits of recycling and reusing valuable metals. List five ways to use nonrenewable mineral resources more sustainably. What are two examples of research into substitutes for rare earth metals? Explain why uneven distribution of lithium among various countries is a concern.

Section 14.5

9. What is the key concept for this section? What are **tectonic plates**? What is **continental drift**? Define and distinguish among **divergent**, **convergent**, and **transform plate boundaries**. Define **volcano** and describe the nature and major effects of a volcanic eruption. Define **earthquake** and describe its nature and major effects. What is a **tsunami** and what are its major effects?

10. What are this chapter's three big ideas? Explain how we can apply the three **scientific principles of sustainability** to obtain and use gold and other nonrenewable mineral resources in more sustainable ways.

Note: Key terms are in bold type.

Critical Thinking

1. Do you think that the benefits we get from gold—its uses in jewelry, dentistry, electronics, and other uses—are worth the real cost of gold (**Core Case Study**)? If so, explain your reasoning. If not, explain your argument for cutting back on or putting a stop to the mining of gold.

2. You are an igneous rock. Describe what you experience as you move through the rock cycle. Repeat this exercise, assuming you are a sedimentary rock and again assuming you are a metamorphic rock.

3. What are three ways in which you benefit from the rock cycle?

4. Suppose your country's supply of rare earth metals was cut off tomorrow. How would this affect your life? Give at least three examples. How would you adjust to these changes? Explain.

5. Use the second law of thermodynamics (see Chapter 2, p. 42) to analyze the scientific and economic feasibility of each of the following processes:
   a. Extracting certain minerals from seawater
   b. Mining increasingly lower-grade deposits of minerals
   c. Continuing to mine, use, and recycle minerals at increasing rates

6. Suppose you were told that mining deep-ocean mineral resources would mean severely degrading ocean bottom habitats and life forms such as giant tubeworms and giant clams (Figure 14.6). Do you think that such information should be used to prevent ocean bottom mining? Explain.

7. List three ways in which a nanotechnology revolution could benefit you and three ways in which it could harm you. Do you think the benefits outweigh the harms? Explain.

8. What are three ways to reduce the harmful environmental impacts of the mining and processing of nonrenewable mineral resources? What are three aspects of your lifestyle that contribute to these harmful impacts?

Doing Environmental Science

Do research to determine which mineral resources go into the manufacture of each of the following items and how much of each of these resources are required to make each item: **(a)** a cell phone, **(b)** a wide-screen TV, and **(c)** a large pickup truck. Pick three of the lesser-known mineral materials that you have learned about in this exercise and do more research to find out where in the world most of the reserves for that mineral are located. For each of the three minerals you chose, try to find out what kinds of environmental effects have resulted from the mining of the mineral in at least one of the places where it is mined. You might also find out about steps that have been taken to deal with those effects. Write a report summarizing all of your findings.

Global Environment Watch Exercise

Go to your MindTap course to access the GREENR database. Using the "Basic Search" box at the top of the page, search for an article that deals with rare earth metal supplies (**Core Case Study**). Summarize the conclusions expressed in the article. Is there scientific information cited in the article to support the author's conclusions? Give specific examples. Do you think there are any types of supporting scientific data not mentioned in the article that would strengthen the author's conclusions? For example, would you add statistical data to support a point, or data in a graph indicating possible cause-and-effect relationships? Be specific and give reasons for your suggestions.

Data Analysis

Rare earth metals are widely used in a variety of important products (Case Study, p. 362). According to the U.S. Geological Survey, China has about 42% of the world's reserves of rare earth metals. Use this information to answer the following questions.

1. In 2014 China had 55 million metric tons of rare earth metals in its reserves and produced 95,000 metric tons of these metals. At this rate of production, how long will China's rare earth reserves last?

2. In 2014 the global demand for rare earth metals was about 136,000 metric tons. At this annual rate of use, if China were to produce all of the world's rare earth metals, how long would their reserves last?

3. The annual global demand for rare earth metals is projected to rise to at least 182,000 metric tons by 2020. At this rate, if China were to produce all of the world's rare earth metals, how long would its reserves last?