Energy and Mineral Resources

CHAPTER

23

A large open pit copper mine at Morenci, Arizona. Copper mining at this site has been going on since the 1870s. (Photo by Michael Collier)

Materials that we extract from Earth are the basis of modern civilization (Figure 23.1). Mineral and energy resources from the crust are the raw materials from which the products used by society are made. Like most people who live in highly industrialized nations, you may not realize the quantity of resources needed to maintain your present standard of living. Figure 23.2 shows the annual per capita consumption of several important metallic and nonmetallic mineral resources for the United States. This is each person's prorated share of the materials required by industry to provide the vast array of homes, cars, electronics, cosmetics, packaging, and so on that modern society demands. Figures for other highly industrialized countries, such as Canada, Australia, and several nations in Western Europe are comparable.

The number of different mineral resources required by modern industries is large. Although some countries, including the United States, have substantial deposits of many important minerals, no nation is entirely self-sufficient. This reflects the fact that important deposits are limited in number and localized in occurrence. All countries must rely on international trade to fulfill at least some of their needs.

Renewable and Nonrenewable Resources

Resources are commonly divided into two broad categories—renewable and nonrenewable. **Renewable resources** can be replenished over relatively short time spans such as months, years, or decades. Common examples are plants and animals for food, natural fibers for clothing, and trees for lumber and paper. Energy from flowing water, wind, and the Sun are also considered renewable.

By contrast, **nonrenewable resources** continue to be formed in Earth, but the processes that create them are so slow that significant deposits take millions of years to

FIGURE 23.1 As this scene of Houston, Texas, reminds us, mineral and energy resources are the basis of modern civilization. (Photo by H. R. Bramaz/Peter Arnold, Inc.)

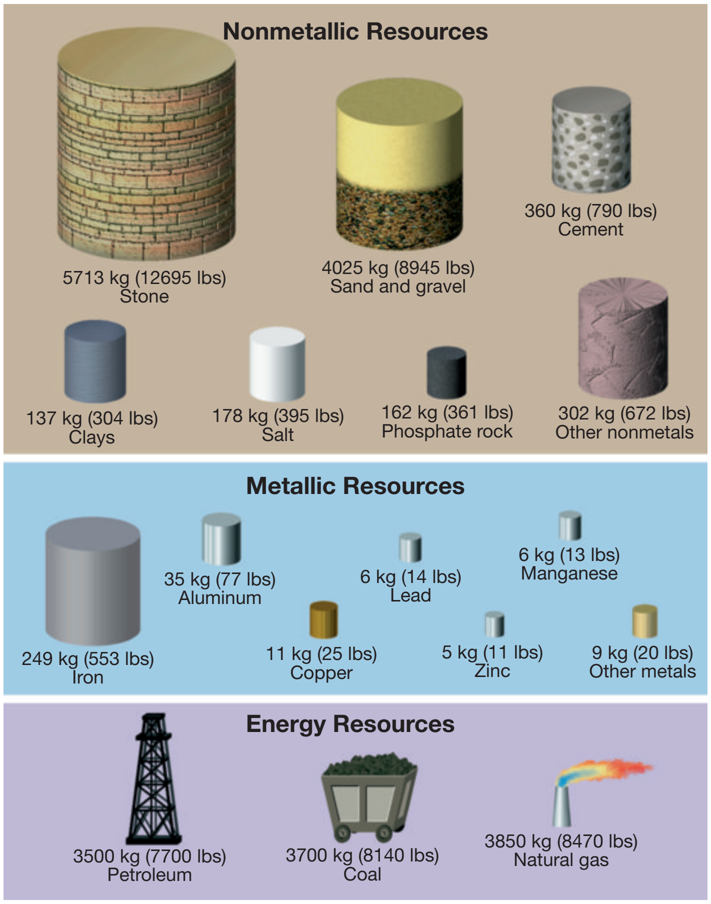


FIGURE 23.2 The annual per capita consumption of nonmetallic and metallic mineral resources for the United States is about 11,000 kilograms (12 tons)! About 97 percent of the materials used are nonmetallic. The per capita use of oil, coal, and natural gas exceeds 11,000 kilograms. (After U.S. Geological Survey)

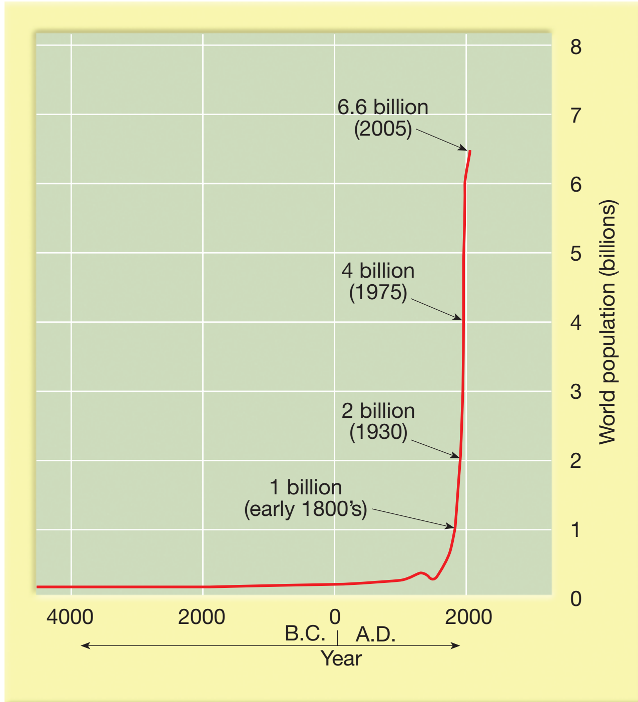


FIGURE 23.3 Growth of world population. It took until 1800 for the number to reach 1 billion. By the year 2015, more than 7 billion people may inhabit the planet. The demand for basic resources is growing faster than the rate of population increase. (Data from the Population Reference Bureau)

accumulate. For human purposes, Earth contains fixed quantities of these substances. When the present supplies are mined or pumped from the ground, there will be no more. Examples are fuels (coal, oil, natural gas) and many important metals (iron, copper, uranium, gold). Some of these nonrenewable resources, such as aluminum, can be used over and over again; others, such as oil, cannot be recycled.

Occasionally some resources can be placed in either category, depending on how they are used. Groundwater is one such example. Where it is pumped from the ground at a rate that can be replenished, groundwater can be classified as a renewable resource. However, in places where groundwater is withdrawn faster than it is replenished, the water table drops steadily. In this case, the groundwater is being "mined" just like other nonrenewable resources.*

Figure 23.3 shows that the population of our planet is growing rapidly. Although the number did not reach 1 billion until the beginning of the 19th century, just 130 years later the population doubled to 2 billion. Between 1930 and 1975 the figure doubled again to 4 billion, and by 2015 more than 7 billion people may inhabit the planet. Clearly, as population grows, the demand for resources expands as well. However, the rate of mineral-and-energy resource usage has climbed faster than population growth. This results from an increasing standard of living. In the United States only 6 percent of the world's population uses approximately 30 percent of the world's annual production of mineral and energy resources!

How long can our remaining resources sustain the rising standard of living in today's industrialized countries and still provide for the growing needs of developing regions? How much environmental deterioration are we willing to accept in pursuit of resources? Can alternatives be found? If we are to cope with an increasing per capita demand and a growing world population, we must understand our resources and their limits.

*The problem of declining water-table levels is discussed in Chapter 17.

Energy Resources

Coal, petroleum, and natural gas are the primary fuels of our modern industrial economy (Figure 23.4). About 86 percent of the energy consumed in the United States today comes from these basic fossil fuels. Although major shortages of oil and gas will not occur for many years, proven reserves are declining. Despite new exploration, even in very remote regions and severe environments, new sources are not keeping pace with consumption.

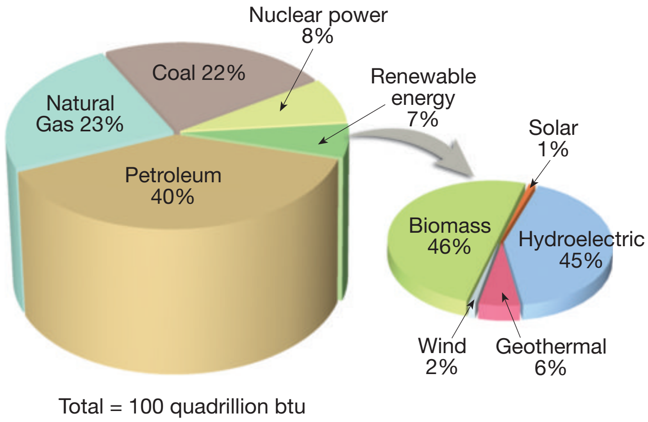


FIGURE 23.4 U.S. energy consumption, 2004. The total was 100 quadrillion Btu. A quadrillion, by the way, is 10 raised to the 12th power, or a million million—a quadrillion Btu is a convenient unit for referring to U.S. energy use as a whole. (Source: U.S. Department of Energy, Energy Information Administration)

Unless large, new petroleum reserves are discovered (which is possible, but not likely), a greater share of our future needs will have to come from coal and from alternative energy sources such as nuclear, geothermal, solar, wind, tidal, and hydroelectric power (see Box 23.1). Two fossil-fuel alternatives—oil sands and oil shale—are sometimes mentioned as promising sources of liquid fuels. In the following sections, we will briefly examine the fuels that have traditionally supplied our energy needs, as well as sources that will provide an increasing share of our future requirements.

Students Sometimes Ask . . .

Figure 23.4 shows biomass as a form of renewable energy. What exactly is biomass?

Biomass refers to organic matter that can be burned directly as fuel or converted into a different form and then burned. Biomass is a relatively new name for some of the oldest human fuels. Examples include firewood, charcoal, crop residues, and animal waste. These fuels are especially important in countries with emerging economies. More modern biomass fuels include such products as ethanol (a type of alcohol produced from corn and other crops that is added to gasoline) and biodiesel (a diesel-equivalent fuel derived from natural renewable sources such as vegetable oils).

Coal

Along with oil and natural gas, coal is commonly called a **fossil fuel.** Such a designation is appropriate because each time we burn coal we are using energy from the Sun that was stored by plants many millions of years ago. We are indeed burning a "fossil."

Coal has been an important fuel for centuries. In the 19th and early 20th centuries, cheap and plentiful coal powered the Industrial Revolution. By 1900 coal was providing 90 percent of the energy used in the United States. Although still important, coal currently accounts for about 22 percent of the nation's energy needs (Figure 23.4).

Until the 1950s, coal was an important domestic heating fuel as well as a power source for industry. However, its direct use in the home has been largely replaced by oil, natural gas, and electricity. These fuels are preferred because they are more readily available (delivered via pipes, tanks, or wiring) and cleaner to use.

Nevertheless, coal remains the major fuel used in power plants to generate electricity, and it is therefore indirectly an important source of energy for our homes. More than 70 percent of present-day coal usage is for the generation of electricity. As oil reserves gradually diminish in the years to come, the use of coal may increase. Expanded coal production is possible because the world has enormous reserves and the technology to mine coal efficiently. In the United States, coal fields are widespread and contain supplies that should last for hundreds of years (Figure 23.5).

Although coal is plentiful, its recovery and use present a number of problems. Surface mining can turn the countryside into a scarred wasteland if careful (and costly) reclamation is not carried out to restore the land. (Today all U.S. surface mines must reclaim the land.) Although underground mining does not scar the landscape to the same degree, it has been costly in terms of human life and health.

Moreover, underground mining long ago ceased to be a pick-and-shovel operation and is today a highly mechanized and computerized process (Figure 23.6). Strong federal safety regulations have made U.S. mining quite safe. However, the hazards of collapsing roofs, gas explosions, and working with heavy equipment remain.

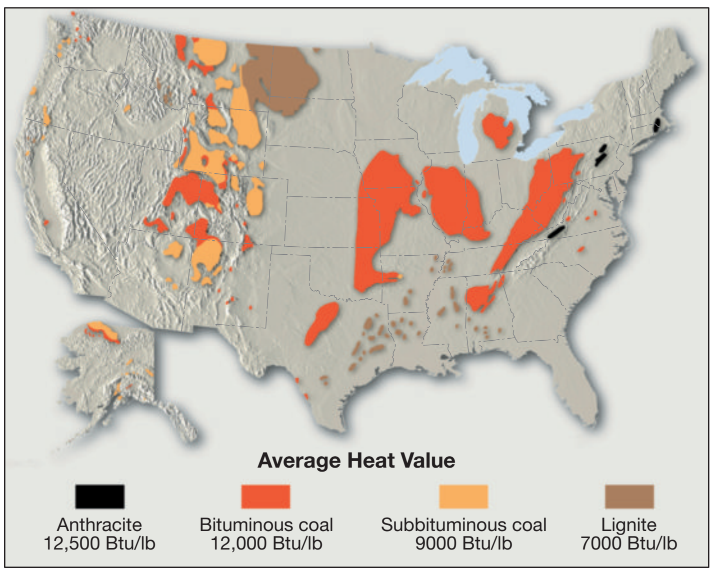


FIGURE 23.5 Coal fields of the United States. (Data from the Bureau of Mines, U.S. Department of the Interior)

Air pollution is a major problem associated with the burning of coal. Much coal contains significant quantities of sulfur. Despite efforts to remove sulfur before the coal is burned, some remains; when the coal is burned, the sulfur is converted into noxious sulfur oxide gases. Through a series of complex chemical reactions in the atmosphere, the sulfur oxides are converted to sulfuric acid, which then falls to Earth's surface as rain or snow. This acid precipitation can have adverse ecological effects over widespread areas (see Box 6.2, p. 174).

As is the case when other fossil fuels are burned, the combustion of coal produces carbon dioxide. This major "greenhouse gas" plays a significant role in the heating of our atmosphere. Chapter 21, "Global Climate Change," examines this issue in some detail.

Oil and Natural Gas

Petroleum and natural gas are found in similar environments and frequently occur together. Both consist of various hydrocarbon compounds (compounds consisting of hydrogen and carbon) mixed together. They may also contain small quantities of other elements, such as sulfur, nitrogen, and oxygen. Like coal, petroleum and natural gas are biological products derived from the remains of organisms. However, the environments in which they form are very different, as are the organisms. Coal is formed mostly from plant material that accumulated in a swampy environment above sea level. Oil and gas are derived from the remains of both plants and animals having a marine origin.

Petroleum Formation

Petroleum formation is complex and not completely understood. Nonetheless, we know that it begins with the accumulation of sediment in ocean areas that are rich in plant and animal remains. These accumulations must occur where biological activity is high, such as in nearshore areas. However, most marine environments are oxygen-rich, which leads to the decay of organic remains before they can be buried by other sediments. Therefore, accumulations of oil and gas are not as widespread as are the marine environments that support abundant biological activity. This limiting factor notwithstanding, large quantities of organic matter are buried and protected from oxidation in many offshore sedimentary basins. With increasing burial over millions of years, chemical reactions gradually transform some of the original organic matter into the liquid and gaseous hydrocarbons we call petroleum and natural gas.

Unlike the organic matter from which they formed, the newly created petroleum and natural gas are mobile. These fluids are gradually squeezed from the compacting, mud-rich layers where they originate into adjacent permeable beds such as sandstone, where openings between sediment grains are larger. Because this occurs under water, the rock layers containing the oil and gas are saturated with water. But oil and gas are less dense than water, so they migrate upward through the water-filled pore spaces of the enclosing rocks. Unless something halts this upward migration, the fluids will eventually reach the surface, at which point the volatile components will evaporate.

FIGURE 23.6 **A.** Modern underground coal mining is highly mechanized and relatively safe. (Photo by Melvin Grubb/Grubb Photo Services, Inc.) **B.** Strip mining of coal at Black Mesa, Arizona. Surface mining is common when coal seams are near the surface. (Photo by Richard W. Brooks/Photo Researchers, Inc.)

A.

B.

BOX 23.1 ▸ UNDERSTANDING EARTH

Gas Hydrates—A Fuel from Ocean-Floor Sediments

Gas hydrates are unusually compact chemical structures made of water and natural gas. The most common type of natural gas is methane, which produces *methane hydrate.* Gas hydrates occur beneath permafrost areas on land and under the ocean floor at depths below 525 meters (1720 feet).

Most oceanic gas hydrates are created when bacteria break down organic matter trapped in seafloor sediments, producing methane gas with minor amounts of ethane and propane. These gases combine with water in deep-ocean sediments (where pressures are high and temperatures are low) in such a way that the gas is trapped inside a latticelike cage of water molecules.

Vessels that have drilled into gas hydrates have retrieved cores of mud mixed with chunks or layers of gas hydrates (Figure 23.A) that fizzle and evaporate quickly when they are exposed to the relatively warm, low-pressure conditions at the ocean surface. Gas hydrates resemble chunks of ice but ignite when lit by a flame because methane and other flammable gases are released as gas hydrates vaporize (Figure 23.B).

Some estimates indicate that as much as 20 quadrillion cubic meters (700 quadrillion cubic feet) of methane are locked up in sediments containing gas hydrates. This is equivalent to about *twice* as much carbon as Earth's coal, oil, and conventional gas reserves combined, so gas hydrates have great potential. One major drawback in exploiting reserves of gas hydrate is that they rapidly decompose at surface temperatures and pressures. In the future, however, these vast seafloor reserves of energy may help power modern society.

FIGURE 23.A This sample retrieved from the ocean floor shows layers of white icelike gas hydrate mixed with mud. (Photo courtesy of GEOMAR Research Center, Kiel, Germany)

FIGURE 23.B Gas hydrates evaporate when exposed to surface conditions and release natural gas, which can be ignited. (Photo courtesy of GEOMAR Research Center, Kiel, Germany)

Oil Traps

Sometimes the upward migration is halted. A geologic environment that allows for economically significant amounts of oil and gas to accumulate underground is termed an **oil trap.** Several geologic structures may act as oil traps, but all have two basic conditions in common: a porous, permeable **reservoir rock** that will yield petroleum and natural gas in sufficient quantities to make drilling worthwhile; and a **cap rock,** such as shale, that is virtually impermeable to oil and gas. The cap rock halts the upwardly mobile oil and gas and keeps the oil and gas from escaping at the surface (Figure 23.7).

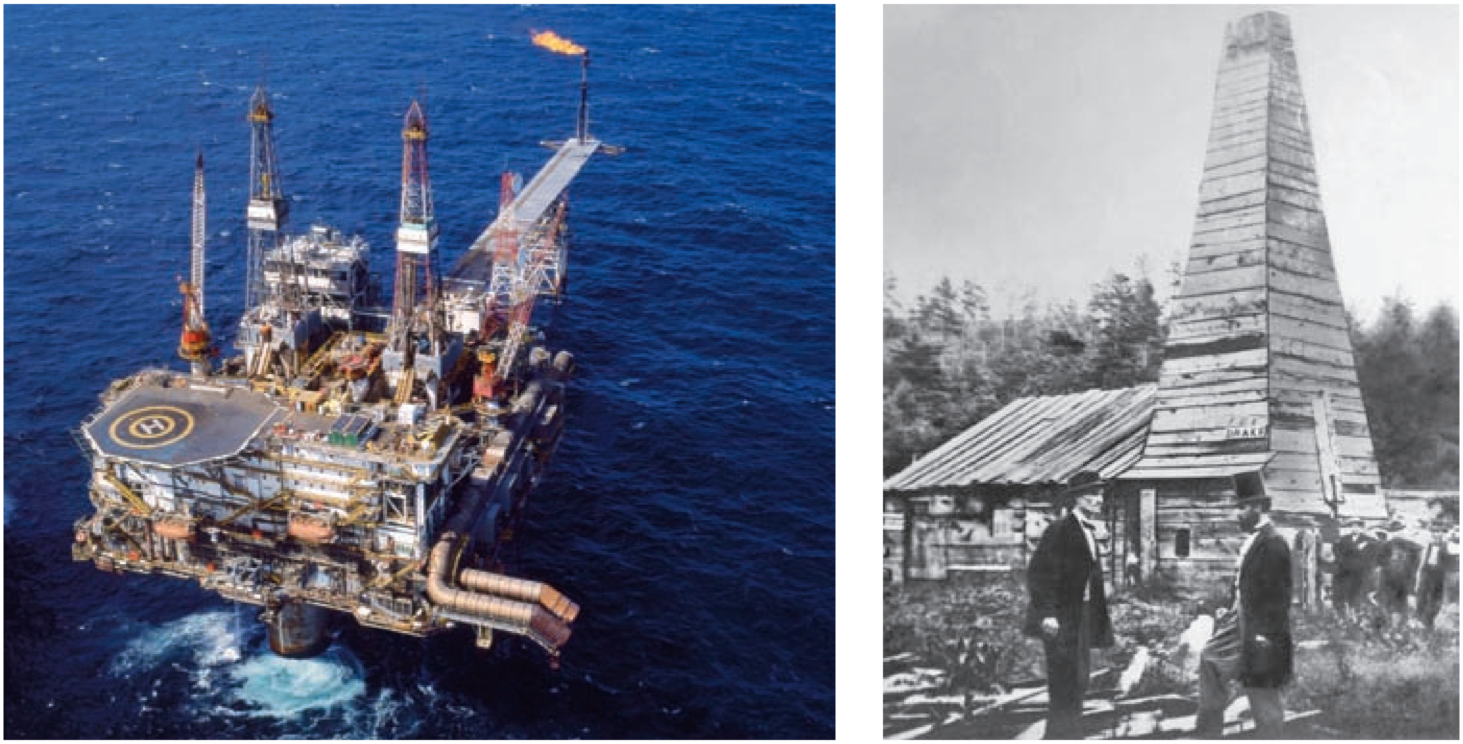
Figure 23.8 illustrates some common oil and natural-gas traps. One of the simplest traps is an *anticline,* an uparched series of sedimentary strata (Figure 23.8A). As the strata are bent, the rising oil and gas collect at the apex (top) of the fold. Because of its lower density, the natural gas collects above the oil. Both rest upon the denser water that saturates the reservoir rock. One of the world's largest oil fields, El Nala in Saudi Arabia, is the result of an anticlinal trap, as is the famous Teapot Dome in Wyoming.

Fault traps form when strata are displaced in such a manner as to bring a dipping reservoir rock into position opposite an impermeable bed, as shown in Figure 23.8B. In this case the upward migration of the oil and gas is halted where it encounters the fault.

In the Gulf coastal plain region of the United States, important accumulations of oil occur in association with *salt domes.* Such areas have thick accumulations of sedimentary strata, including layers of rock salt. Salt occurring at great depths has been forced to rise in columns by the pressure of overlying beds. These rising salt columns gradually deform the overlying strata. Because oil and gas migrate to the highest level possible, they accumulate in the upturned sandstone beds adjacent to the salt column (Figure 23.8C).

Yet another important geologic circumstance that may lead to significant accumulations of oil and gas is termed a *stratigraphic trap.* These oil-bearing structures result primarily from the original pattern of sedimentation rather than structural deformation. The stratigraphic trap illustrated in Figure 23.8D exists because a sloping bed of sandstone thins to the point of disappearance.

When the lid created by the cap rock is punctured by drilling, the oil and natural gas, which are under pressure, migrate from the pore spaces of the reservoir rock to the drill hole. On rare occasions, when fluid pressure is great, it



A. **B.**

FIGURE 23.7 Oil accumulates in oil traps that consist of porous, permeable *reservoir rock* overlain by an impermeable *cap rock.* **A.** Modern offshore oil production platform in the North Sea. (Photo by Peter Bowater/Photo Researchers, Inc.) **B.** The first successful oil well was completed by Edwin Drake (right) on August 27, 1859, near Titusville, Pennsylvania. The oil-bearing reservoir rock was encountered at a depth of 21 meters (69 feet). (Photo by CORBIS/Bettman)

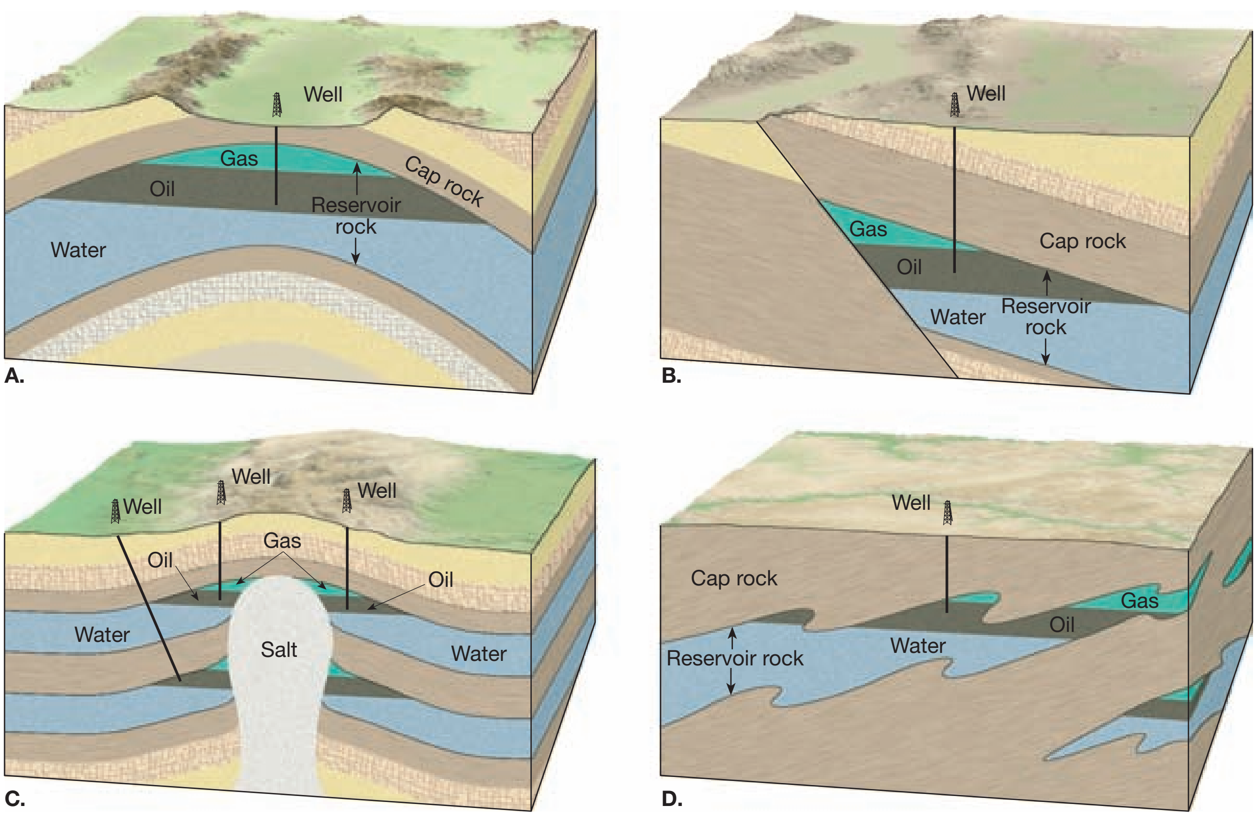


FIGURE 23.8 Common oil traps. **A.** Anticline. **B.** Fault trap. **C.** Salt dome. **D.** Stratigraphic (pinch-out) trap.

may force oil up the drill hole to the surface, causing a "gusher" or oil fountain at the surface. Usually, however, a pump is required to lift the oil out.

A drill hole is not the only means by which oil and gas can escape from a trap. Traps can be broken by natural forces. For example, Earth movements may create fractures that allow the hydrocarbon fluids to escape. Surface erosion may breach a trap with similar results. The older the rock strata, the greater the chance that deformation or erosion has affected a trap. Indeed, not all ages of rock yield oil and gas in the same proportions. The greatest production comes from the youngest rocks, those of Cenozoic age. Older Mesozoic rocks produce considerably less, followed by even smaller yields from the still older Paleozoic strata. There is virtually no oil produced from the most ancient rocks, those of Precambrian age.

Oil Sands and Oil Shale—Petroleum for the Future?

In years to come, world oil supplies will dwindle. When this occurs, a lower grade of hydrocarbon may have to be substituted. Are the fuels derived from oil sands and oil shales good candidates?

Oil Sands

Oil sands (also called *tar sands*) are usually mixtures of clay and sand combined with water and varying amounts of a black, highly viscous tar known as *bitumen.* The use of the term *sand* can be misleading, because not all deposits are associated with sands and sandstones. Some occur in other materials, including shales and limestones. The oil in these deposits is very similar to heavy crude oils pumped from wells. The major difference between conventional oil reservoirs and oil sand deposits is in the viscosity (resistance to flow) of the oil they contain. In oil sands, the oil is much more viscous and cannot simply be pumped out.

Substantial oil sand deposits occur in several locations around the world. The two largest are the Athabasca Oil Sands in the Canadian province of Alberta and the Orinoco River deposit in Venezuela (Figure 23.9).

Currently, oil sands are mined at the surface in a manner similar to the strip mining of coal. The excavated material is then heated with pressurized steam until the bitumen softens and rises. Once collected, the oily material is treated to remove impurities and then hydrogen is added. This last step upgrades the material to a synthetic crude, which can then be refined. Extracting and refining oil sands requires a great deal of energy—nearly half as much as the end product yields! Nevertheless, oil sands from Alberta's vast deposits are the source of about one-third of Canada's oil production.

Obtaining oil from oil sand has significant environmental drawbacks. Substantial land disturbance is associated with mining huge quantities of rock and sediment. Moreover, large quantities of water are required for processing, and when processing is completed, contaminated water and sediment accumulate in toxic disposal ponds.

A.


B.

FIGURE 23.9 A. In North America, the largest oil sand deposits occur in the Canadian province of Alberta. Known as the Athabasca Oil Sands, these deposits cover an area of more than 42,000 square kilometers (16,300 square miles). Albertas major oil sands deposits contain more than 1.7 trillion barrels of bitumen. However, much of the bitumen cannot be recovered at reasonable cost. With current technology, it is estimated that only about 300 billion barrels are recoverable. **B.** Mining of oil sands in Alberta. Notice the "tar" on the hands of the worker. (Photo by Burkard/Bilderberg/Peter Arnold, Inc.)

About 80 percent of the oil sands in Alberta are buried too deeply for surface mining. Oil from these deep deposits must be recovered by *in situ* techniques. Using drilling technology, steam is injected into the deposit to heat the oil sand, reducing the viscosity of the bitumen. The hot, mobile bitumen migrates towards producing wells, which pump it to the surface, while the sand is left in place (*"in situ"* is Latin for "in place"). *In situ* technology is expensive and requires certain conditions like a nearby water source. Production using *in situ* techniques already rivals open pit mining and in the future may well replace mining as the main source of bitumen production from the oil sands.

Challenges facing *in situ* processes include increasing the efficiency of oil recovery, management of water used to make steam, and reducing the costs of energy required for the process.

Oil Shale

Oil shale contains enormous amounts of untapped oil. Worldwide, the U.S. Geological Survey estimates that there are more than 3000 billion barrels of oil contained in shales that would yield more than 38 liters (10 gallons) of oil per ton of shale. But this figure is misleading because fewer than 200 billion barrels are known to be recoverable with present technology. Still, estimated U.S. resources are about 14 times as great as those of conventionally recoverable oil, and estimates will probably increase as more geological information is gathered.

Roughly half of the world supply is in the Green River Formation in Colorado, Utah, and Wyoming (Figure 23.10). Within this region the oil shales are part of sedimentary layers that accumulated at the bottoms of two vast, shallow lakes during the Eocene epoch (57 million to 36 million years ago).

Oil shale has been suggested as a partial solution to dwindling fuel supplies. However, the heat energy in oil shale is about one-eighth that in crude oil, owing to the large proportion of mineral matter in the shales.

This mineral matter adds cost to mining, processing, and waste disposal. Producing oil from oil shale has the same problems as producing oil from oil sands. Surface mining causes widespread land disturbance and presents significant waste-disposal problems. Moreover, processing requires large amounts of water, something that is in short supply in the semiarid region occupied by the Green River Formation.

At present, oil is plentiful and relatively inexpensive on world markets. Therefore, with current technologies, most oil shales are not worth mining. Oil shale research-and-development efforts have been nearly abandoned by industry. Nevertheless, the U.S. Geological Survey suggests that the large amount of oil that potentially can be extracted from oil shales in the United States probably ensures its eventual inclusion in the national energy mix.

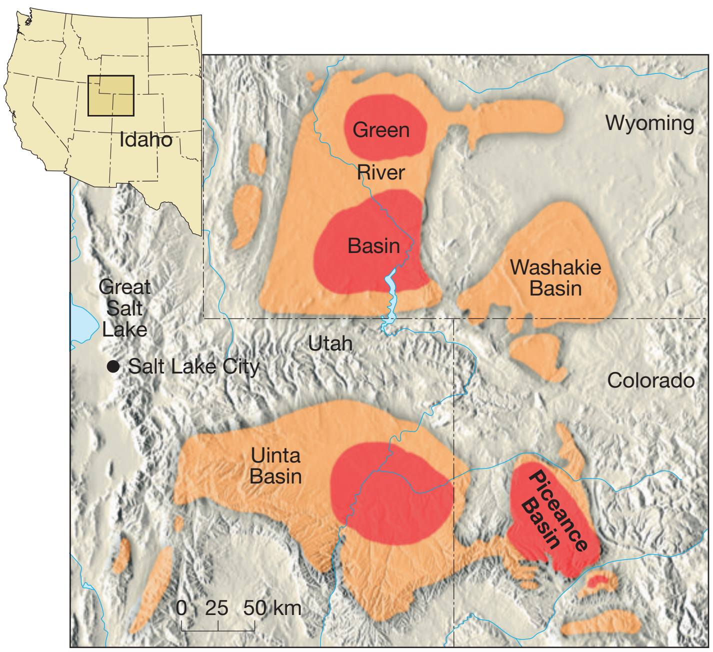


FIGURE 23.10 Distribution of oil shale in the Green River Formation of Colorado, Utah, and Wyoming. The areas shaded with the darker color represent the richest deposits. Government and industry have invested large sums to make these oil shales an economic resource, but costs have always been higher than the price of oil. However, as prices of competing fuels rise, these vast deposits may someday become economically more attractive. (After D. C. Duncan and V. E. Swanson, U.S. Geological Survey Circular 523, 1965)

Alternate Energy Sources

An examination of Figure 23.4 (see p. 630) clearly shows that we live in the era of fossil fuels. More than 85 percent of United States's energy needs comes from these nonrenewable resources. Present estimates indicate that the amount of recoverable fossil fuels may equal 10 trillion barrels of oil, which is enough to last 170 years at the present rate of consumption. Of course, as world population soars, the rate of consumption will climb. Thus, reserves will eventually be in short supply. In the meantime, the environmental impact of burning huge quantities of fossil fuels will undoubtedly have an adverse effect.

How can a growing demand for energy be met without radically affecting the planet we inhabit? Although no clear answer has yet been formulated, the need to rely more heavily on alternate energy sources must be considered. In this section, we will examine several possible sources, including nuclear, solar, wind, hydroelectric, geothermal, and tidal energy.

Nuclear Energy

Roughly 8 percent of the energy demand of the United States is being met by nuclear power plants. The fuel for these facilities comes from radioactive materials that release energy by the process of **nuclear fission.** Fission is accomplished by bombarding the nuclei of heavy atoms, commonly uranium-235, with neutrons. This causes the uranium nuclei to split into smaller nuclei and to emit neutrons and heat energy. The ejected neutrons, in turn, bombard the nuclei of adjacent uranium atoms, producing a *chain reaction.* If the supply of fissionable material is sufficient and if the reaction is allowed to proceed in an uncontrolled manner, an enormous amount of energy would be released in the form of an atomic explosion.

In a nuclear power plant, the fission reaction is controlled by moving neutron-absorbing rods into or out of the nuclear reactor. The result is a controlled nuclear chain reaction that releases great amounts of heat. The energy produced is transported from the reactor and used to drive steam turbines that turn electrical generators, which is similar to what occurs in most conventional power plants.

Uranium Uranium-235 is the only naturally occurring isotope that is readily fissionable and is therefore the primary fuel used in nuclear power plants.* Although large quantities of uranium ore have been discovered, most contain less than 0.05 percent uranium. Of this small amount, 99.3 percent is the nonfissionable isotope uranium-238 and just 0.7 percent consists of the fissionable isotope uranium-235. Because most nuclear reactors operate with fuels that are at least 3 percent uranium-235, the two isotopes must be separated in order to concentrate the fissionable uranium-235. The process of separating the uranium isotopes is difficult and substantially increases the cost of nuclear power.

Although uranium is a rare element in Earth's crust, it does occur in enriched deposits. Some of the most important occurrences are associated with what are believed to be ancient placer deposits in stream beds.** For example, in Witwatersrand, South Africa, grains of uranium ore (as well as rich gold deposits) were concentrated by virtue of their high density in rocks made largely of quartz pebbles. In the United States the richest uranium deposits are found in Jurassic and Triassic sandstones in the Colorado Plateau and in younger rocks in Wyoming. Most of these deposits have formed through the precipitation of uranium compounds from groundwater. Here precipitation of uranium occurs as a result of a chemical reaction with organic matter, as evidenced by the concentration of uranium in fossil logs and organic-rich black shales.

Obstacles to Development At one time nuclear power was heralded as the clean, cheap source of energy to replace fossil fuels. However, several obstacles have emerged to hinder the development of nuclear power as a major energy source. Not the least of these is the skyrocketing costs of building nuclear facilities that contain numerous safety features. More important, perhaps, is the concern over the possibility of a serious accident at one of the nearly 200 nuclear plants in existence worldwide (Figure 23.11). The 1979 accident at Three Mile Island near Harrisburg, Pennsylvania, helped bring this point home. Here, a malfunction led the plant operators to believe there was too much water in the primary system instead of too little. This confusion allowed the reactor core to lie uncovered for several hours. Although there was little danger to the public, substantial damage to the reactor resulted.

*Thorium, although not capable by itself of sustaining a chain reaction, can be used with uranium-235 as a nuclear fuel.

**Placer deposits are discussed later in the chapter.

FIGURE 23.11 Diablo Canyon nuclear power plant near San Luis Obispo, California. Reactors are in the dome-shaped buildings, and cooling water is being released to the ocean. The setting of this facility was controversial because of its close proximity to faults capable of producing potentially damaging earthquakes. (Photo by Comstock)

Unfortunately, the 1986 accident at Chernobyl in the former Soviet Union was far more serious. In this incident, the reactor ran out of control and two small explosions lifted the roof off the structure, allowing pieces of uranium to be thrown over the immediate area. During the 10 days that it took to quench the fire that ensued, high levels of radioactive material were carried by the atmosphere and detected as far away as Norway. In addition to the 18 people who died within six weeks of the accident, many thousands more face an increased risk of death from cancers associated with the fallout.

It should be emphasized that the concentrations of fissionable uranium-235 and the design of reactors are such that nuclear power plants cannot explode like an atomic bomb. The dangers arise from the possible escape of radioactive debris during a meltdown of the core or other malfunction. In addition, hazards such as the disposal of nuclear waste and the relationship that exists between nuclear energy programs and the proliferation of nuclear weapons must be considered as we evaluate the pros and cons of employing nuclear power.

Among the "pros" for nuclear energy is the fact that nuclear power plants do not emit carbon dioxide—the greenhouse gas that contributes significantly to global warming (see Chapter 21). By contrast, the generation of electricity from fossil fuels produces large quantities of carbon dioxide. Thus substituting nuclear power for power generated by fossil fuels represents one option for reducing carbon emissions.

Solar Energy

The term *solar energy* generally refers to the direct use of the Sun's rays to supply energy for the needs of people. The simplest and perhaps most widely used *passive solar collectors* are south-facing windows. As sunlight passes through the glass, its energy is absorbed by objects in the room. These objects in turn radiate heat that warms the air. In the

A.

B.

FIGURE 23.12 **A.** Solar One, a solar installation used to generate electricity in the Mojave Desert near Barstow, California. (Photo by Thomas Braise/Corbis/Stock Market) **B.** Solar cells, or photovoltaics, convert sunlight directly into electricity. Many photovoltaic systems in use today are in remote areas, but this array of solar panels is near Sacramento, California. (Photo by Martin Bond/Science Photo Library/Photo Researchers, Inc.)

United States we often use south-facing windows, along with better insulated and more airtight construction, to reduce heating costs substantially.

More elaborate systems used for home heating involve an *active solar collector.* These roof-mounted devices are usually large, blackened boxes that are covered with glass. The heat they collect can be transferred to where it is needed by circulating air or fluids through piping. Solar collectors are also used successfully to heat water for domestic and commercial needs. For example, solar collectors provide hot water for more than 80 percent of Israel's homes.

Although solar energy is free, the necessary equipment and its installation are not. The initial costs of setting up a system, including a supplemental heating unit for times when solar energy is diminished (cloudy days and winter) or unavailable (nighttime), can be substantial. Nevertheless, over the long term, solar energy is economical in many parts of the United States and will become even more cost effective as the price of other fuels increases.

Research is currently under way to improve the technologies for concentrating sunlight. One method being examined uses mirrors that track the Sun and keep its rays focused on a receiving tower. A solar collection facility with 2000 mirrors has been constructed near Barstow, California (Figure 23.12A). Solar energy focused on a central tower heats water in pressurized panels to more than 500°C. The superheated water is then transferred to turbines, which turn electrical generators.

Another type of collector uses photovoltaic (solar) cells that convert the Sun's energy directly into electricity. An experimental facility that uses photovoltaic cells is located near Sacramento, California (Figure 23.12B).

Recently small rooftop photovoltaic systems have begun being used in rural households of some Third World countries, including the Dominican Republic, Sri Lanka, and Zimbabwe. These units are about the size of an open briefcase and use a battery to store electricity that is generated during the daylight hours. In the tropics these small photovoltaic systems are capable of running a television or radio, plus a few lightbulbs, for three to four hours. Although much cheaper than building conventional electric generators, these units are still too expensive for poor families. Consequently, an estimated 2 billion people in developing countries still lack electricity.

Students Sometimes Ask . . .

Are electric vehicles better for the environment?

Yes, but probably not as much as you might think. This is because much of the electricity that electric-powered vehicles use comes from power plants that use nonrenewable fossil fuels. Thus, the pollutants are not coming directly from the car; rather, they are coming from the power plant that generated electricity for the car. Nonetheless, modern electric-powered vehicles are engineered to be more fuel efficient than traditional gasoline-powered vehicles, so they generate fewer pollutants per mile.

Wind Energy

Air has mass, and when it moves (that is, when the wind blows), it contains the energy of that motion—kinetic energy. A portion of that energy can be converted into other forms—mechanical force or electricity—that we can use to perform work (Figure 23.13).

Mechanical energy from wind is commonly used for pumping water in rural or remote places. The "farm windmill," still a familiar sight in many rural areas, is an example. Mechanical energy converted from wind can also be used for other purposes, such as sawing logs, grinding grain, and propelling sailboats. By contrast, wind-powered electric turbines generate electricity for homes, businesses, and for sale to utilities.

Approximately 0.25 percent (one quarter of 1 percent) of the solar energy that reaches the lower atmosphere is transformed into wind. Although it is just a minuscule percentage, the absolute amount of energy is enormous. According to one estimate, North Dakota alone is theoretically capable of producing enough wind-generated power to meet more than one-third of U.S. electricity demand. Wind speed is a crucial element in determining whether a place is a suitable site for installing a wind-energy facility. Generally a minimum, annual average wind speed of 21 kilometers (13 miles) per hour is necessary for a utility-scale wind-power plant.

> The power available in the wind is proportional to the cube of its speed. Thus, a turbine operating at a site with an average wind speed of 12 mph could in theory generate about 30 percent more electricity than one at an 11-mph site, because the cube of 12 (1728) is 30 percent larger than the cube of 11 (1331). (In the real world, the turbine will not produce quite that much more electricity, but it will still generate much more than the 9 percent difference in wind speed.) The important thing to understand is that what seems like a small difference in wind speed can mean a large difference in available energy and in electricity produced, and therefore a large difference in the cost of the electricity generated. Also, there is little energy to be harvested at very low wind speeds (6-mph winds contain less than one-eighth the energy of 12-mph winds).*

As technology has improved, efficiency has increased and the costs of wind-generated electricity have become more competitive. Between 1983 and 2005 technological advances cut the cost of wind power by more than 85 percent. As a result, the growth of installed capacity has grown dramatically. Worldwide the total amount of installed wind power grew from 7636 megawatts in 1997 to about 59,000 in 2005 (Table 23.1). 59,000 megawatts is enough to supply more than 13 million average American households, or as much as could be generated by 17 large nuclear power plants. By mid-2006, U.S. capacity reached nearly 10,000 megawatts (Figure 23.14).

The U.S. Department of Energy has announced a goal of obtaining 5 percent of U.S. electricity from wind by the year 2020—a goal that seems consistent with the current growth

*American Wind Energy Association, "Wind Energy Basics," http://www.awea.org.

FIGURE 23.13 **A.** Farm windmills are still familiar sights in some areas. Mechanical energy from wind is commonly used to pump water. (Photo by Darren Bennett) **B.** The use of wind turbines for generating electricity is growing rapidly. These turbines are at Crowley Ridge, Alberta, Canada. (Photo by Alan Sirulnikoff/Photo Researchers, Inc.)

A.

B.

TABLE 23.1 World leaders in wind energy capacity (2005)

Country	Capacity (megawatts*)
Germany	18,428
Spain	10,027
United States	9149
India	4430
Denmark	3122
Italy	1717
United Kingdom	1353
China	1260
Netherlands	1219
Japan	1078
Rest of the world	7301
Total	59,084

*1 megawatt is enough electricity to supply about 250–300 average American households.

Source: Global Wind Energy Council.

rate of wind energy nationwide. Thus, wind-generated electricity seems to be shifting from being an "alternative" to being a "mainstream" energy source.

Hydroelectric Power

Falling water has been an energy source for centuries. Through much of human history, the mechanical energy produced by waterwheels was used to power mills and other machinery. Today the power generated by falling water is used to drive turbines that produce electricity, hence the term **hydroelectric power.** In the United States, hydroelectric power plants contribute about 3 percent of the country's demand. Most of this energy is produced at large dams,

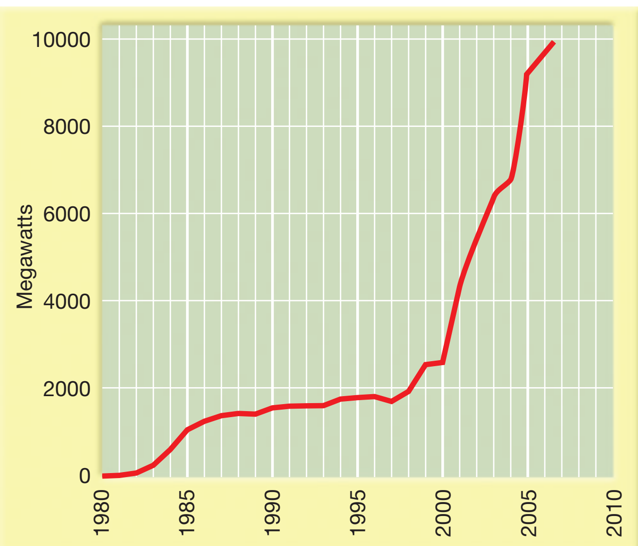


FIGURE 23.14 U.S.-installed wind-power capacity (in megawatts in mid-2006). Growth in recent years has been dramatic. (Data from U.S. Department of Energy and American Wind Energy Association)

which allow for a controlled flow of water (Figure 23.15). The water impounded in a reservoir is a form of stored energy that can be released at any time to produce electricity.

Although water power is considered a renewable resource, the dams built to provide hydroelectricity have finite lifetimes. All rivers carry suspended sediment that is deposited behind the dam as soon as it is built. Eventually the sediment will completely fill the reservoir. This takes 50 to 300 years, depending on the quantity of suspended material transported by the river. An example is Egypt's huge Aswan High Dam, which was completed in the 1960s. It is estimated that half of the reservoir will be filled with sediment from the Nile River by the year 2025.

The availability of appropriate sites is an important limiting factor in the development of large-scale hydroelectric power plants. A good site provides a significant height for the water to fall and a high rate of flow. Hydroelectric dams exist in many parts of the United States, with the greatest concentrations occurring in the Southeast and the Pacific Northwest. Most of the best U.S. sites have already been developed, limiting the future expansion of hydroelectric power. The total power produced by hydroelectric sources might still increase, but the relative share provided by this source will likely decline because other alternate energy sources will increase at a faster rate.

In recent years a different type of hydroelectric power production has come into use. Called a *pumped water-storage system*, it is actually a type of energy management. During times when demand for electricity is low, unneeded power produced by nonhydroelectric sources is used to pump water from a lower reservoir to a storage area at a higher elevation. Then, when demand for electricity is great, the water stored in the higher reservoir is available to drive turbines and produce electricity to supplement the power supply.

Students Sometimes Ask . . .

What is the world's largest hydropower project?

That distinction goes to the Three Gorges Project on China's Yangtze River. Construction began in 1993. When fully operational in 2009, it is expected to generate 85 billion kilowatt-hours of electricity each year, equal to about 6.5 percent of China's electrical needs in 2001. Flood control was presumably the primary motivation for building the controversial dam. Its reservoir will inundate 632 square kilometers (244 square miles) of land stretched over about 660 kilometers (412 miles) of the river.

Geothermal Energy

Geothermal energy is harnessed by tapping natural underground reservoirs of steam and hot water. These occur where subsurface temperatures are high, owing to relatively recent volcanic activity. Geothermal energy is put to use in

FIGURE 23.15 Lake Powell is the reservoir that was created when Glen Canyon Dam was built across the Colorado River. As water in the reservoir is released, it drives turbines and produces electricity. Eventually the reservoir will be filled with sediment deposited by the Colorado River. (Photo by Michael Collier)

two ways: The steam and hot water are used for heating and to generate electricity.

Iceland is a large volcanic island with current volcanic activity (Figure 23.16). In Iceland's capital, Reykjavik, steam and hot water are pumped into buildings throughout the city for space heating. They also warm greenhouses, where fruits and vegetables are grown all year. In the United States, localities in several western states use hot water from geothermal sources for space heating.

As for generating electricity geothermally, the Italians were first to do so in 1904, so the idea is not new. By the turn of the 21st century, more than 250 geothermal power plants in 22 countries were producing more than 8000 megawatts (million watts). These plants provide power to more than 60 million people. The leading producers of geothermal power are listed in Table 23.2.

The first commercial geothermal power plant in the United States was built in 1960 at The Geysers, north of San Francisco (Figure 23.17). The Geysers remains the world's largest geothermal power plant, generating nearly 1000 megawatts of U.S. geothermal power (see Box 23.2). In addition to The Geysers, geothermal development is occurring elsewhere in the western United States, including Nevada, Utah, and the Imperial Valley in southern California. The U.S. geothermal generating capacity of more than 2500 megawatts is enough to power more than 3 million homes. This is an amount of electricity comparable to burning about 60 million barrels of oil each year.

What geologic factors favor a geothermal reservoir of commercial value?

1. *A potent source of heat,* such as a large magma chamber deep enough to ensure adequate pressure and slow cooling, yet not so deep that the natural water circulation is inhibited. Such magma chambers are most likely in regions of recent volcanic activity.
2. *Large and porous reservoirs with channels connected to the heat source,* near which water can circulate and then be stored in the reservoir.
3. *A cap of low-permeability rocks* that inhibits the flow of water and heat to the surface. A deep, well-insulated reservoir contains much more stored energy than a similar but uninsulated reservoir.

As with other alternative methods of power production, geothermal sources are not expected to provide a high percentage of the world's growing energy needs. Nevertheless, in regions where its potential can be developed, its use will no doubt continue to grow.

Tidal Power

Several methods of generating electrical energy from the oceans have been proposed, but the ocean's energy potential remains largely untapped. The development of tidal power is the principal example of energy production from the ocean.

Tides have been used as a source of power for centuries. Beginning in the 12th century, waterwheels driven by the tides were used to power gristmills and sawmills. During the 17th and 18th centuries, much of Boston's flour was produced at a tidal mill. Today far greater energy demands must be satisfied, and more sophisticated ways of using the force created by the perpetual rise and fall of the ocean must be employed.

Tidal power is harnessed by constructing a dam across the mouth of a bay or an estuary in a coastal area having a large tidal range (Figure 23.18A). The narrow opening between the bay and the open ocean magnifies the variations in water level that occur as the tides rise and fall. The strong in-and-out flow that results at such a site is then used to drive turbines and electrical generators.

Tidal energy utilization is exemplified by the tidal power plant at the mouth of the Rance River in France. By far the largest yet constructed, this plant went into operation in 1966 and produces enough power to satisfy the needs of Brittany and also contribute to the demands of other regions. Much smaller experimental facilities have been built near Murmansk in Russia and near Taliang in China, and on the Annapolis River estuary, an arm of the Bay of Fundy in the Canadian province of Nova Scotia (Figure 23.18B).

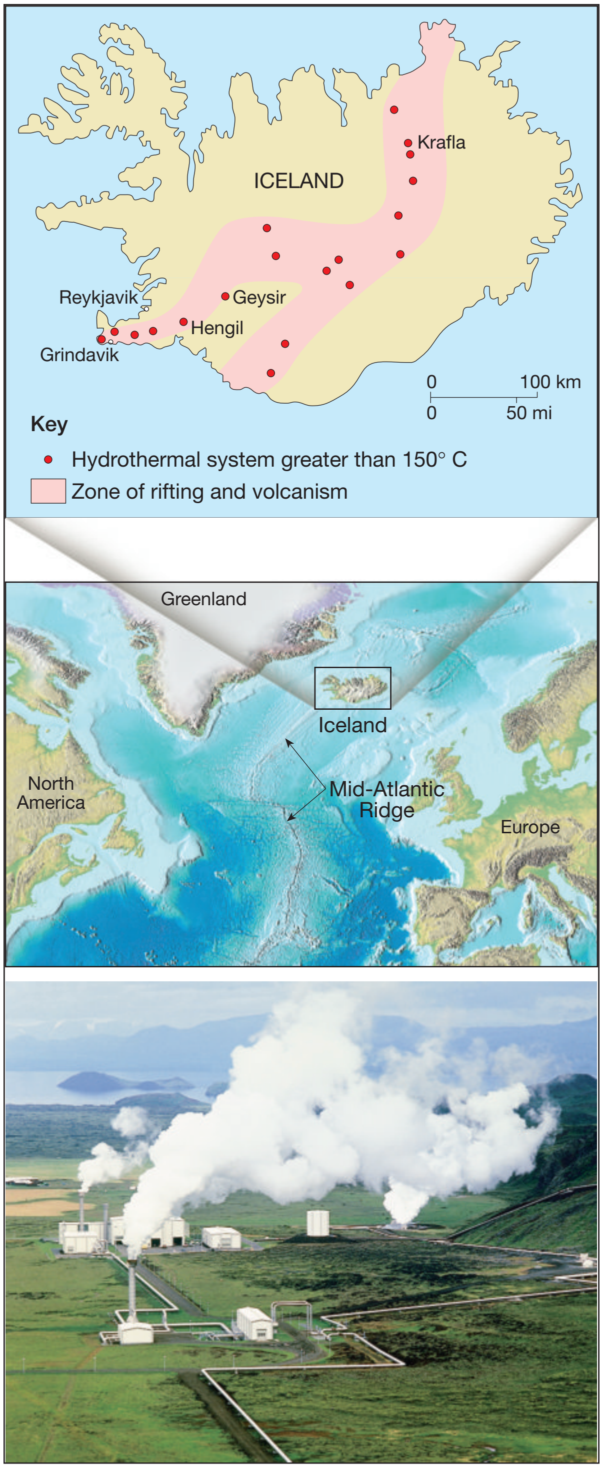


FIGURE 23.16 Iceland straddles the Mid-Atlantic Ridge. This divergent plate boundary is the site of numerous active volcanoes and geothermal systems. Because the entire country consists of geologically young volcanic rocks, warm water can be encountered in holes drilled almost anywhere. More than 45 percent of Iceland's energy comes from geothermal sources. The photo shows a power station in southwestern Iceland. The steam is used to generate electricity. Hot (83°C) water from the plant is sent via an insulated pipeline to Reykjavik for space heating. (Photo by Simon Fraser/Science Photo Library/Rhoto Researchers, Inc.)

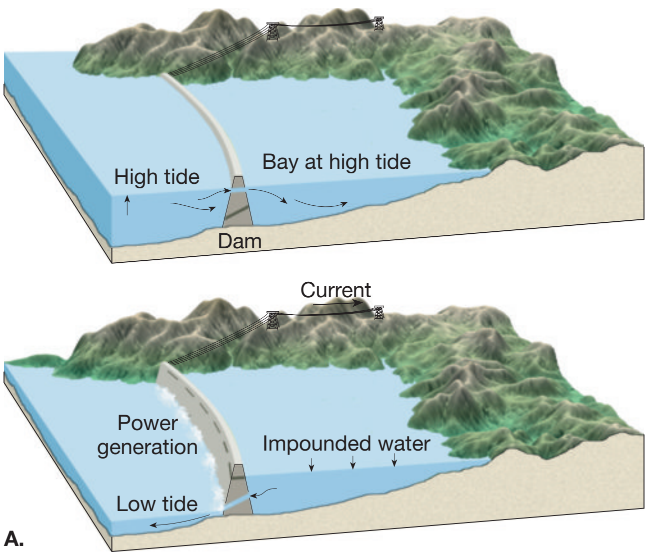
TABLE 23.2 Worldwide Geothermal Power Production, 2005

Producing Country	Megawatts
United States	2564
Philippines	1931
Mexico	953
Indonesia	797
Italy	791
Japan	535
New Zealand	435
Iceland	202
Costa Rica	163
El Salvador	151
All others	411
Total	8933

Source: Geothermal Resources Council.

Along most of the world's coasts it is not possible to harness tidal energy. If the tidal range is less than 8 meters (25 feet), or if narrow, enclosed bays are absent, tidal power development is uneconomical. For this reason the tides will never provide a very high portion of our ever increasing electrical energy requirements. Nevertheless, the development of tidal power may be worth pursuing at feasible sites because electricity produced by the tides consumes no exhaustible fuels and creates no noxious wastes.

FIGURE 23.17 The Geysers, near the city of Santa Rosa in northern California, is the world's largest electricity-generating geothermal development. Most of the steam wells are about 3000 meters deep. (AP Photo/Calpine)



A.

B.

FIGURE 23.18 **A.** Simplified diagram showing the principle of the tidal dam. Electricity is generated only when a sufficient water-height difference exists between the bay and the ocean. **B.** Tidal power plant at Annapolis Royal, Nova Scotia, on the Bay of Fundy. (Photo by James P. Blair)

Students Sometimes Ask . . .

Is power from ocean waves a practical alternative energy source?

Wave energy technology is very young compared to generating electricity from hydro or wind turbines, but methods for harnessing wave energy are being developed. In November 2000 the world's first commercial wave power station began operating on the Scottish island of Islay, providing power to the United Kingdom power grid. The 500-kilowatt power station uses a technology called the oscillating water column, in which the incoming waves push air up and down inside a concrete tube that is partially submerged in the ocean. The air rushing into and out of the top of the tube is used to drive a turbine to produce electricity. If this technology proves successful, it may open the door for wave power to be a significant contributor of renewable energy in appropriate coastal settings.

Mineral Resources

Earth's crust is the source of a wide variety of useful and essential substances. In fact, practically every manufactured product contains substances derived from minerals. Table 23.3 lists some important examples.

Mineral resources are the endowment of useful minerals ultimately available commercially. Resources include already identified deposits from which minerals can be

BOX 23.2 ▸ PEOPLE AND THE ENVIRONMENT

Maintaining the Flow of Geothermal Energy at The Geysers*

As a result of the rapid development at The Geysers during the 1980s and some subsequent development, there was a decline in the rate of steam production (and electrical generation) due to loss of pressure in production wells. Steam production peaked in 1988 and declined for the next decade.

Most of the geothermal energy of this system remains intact, stored in hot rocks that constitute the hydrothermal reservoir. To mitigate the decline of steam pressure in production wells and thereby extend the useful life of the resource, a team of private industry and governmental agencies devised a clever and effective solution. The solution also provided an effective method for disposing of large volumes of wastewater from nearby communities. Simply put, the wastewater of treated sewage is injected underground through appropriately positioned wells. As it flows toward the intake zones of production wells, the wastewater is heated by contact with hot rocks. Production wells then tap the natural steam augmented by vaporized wastewater.

In 1997, a 50-kilometer-long pipeline began delivering about 30 million liters of wastewater a day for injection into the southern part of The Geysers geothermal field. This slowed the pressure decline and resulted in the recovery of 75 megawatts of generating output that had been lost to the preinjection pressure decline.

The initial experiment was so successful that a second pipeline was completed in 2003 that delivers another 40 million liters per day to the central part of the field. Together, these two sources of recharge water replace nearly all of the geothermal fluid being lost to electricity production. The injection program is expected to maintain total electrical output from The Geysers at about 1000 megawatts for at least two more decades and possibly much longer.

*Based on material appearing in Wendell A. Duffield and John H. Sass, *Geothermal Energy—Clean Power From the Earth's Heat*, U.S. Geological Survey Circular 1249, p. 14.

TABLE 23.3 Occurrence of Metallic Minerals

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

extracted profitably, called **reserves,** as well as known deposits that are not yet economically or technologically recoverable. Deposits inferred to exist but not yet discovered are also considered as mineral resources. In addition, the term **ore** is used to denote those useful metallic minerals that can be mined at a profit. In common usage the term *ore* is also applied to some nonmetallic minerals such as fluorite and sulfur. However, materials used for such purposes as building stone, road aggregate, abrasives, ceramics, and fertilizers are not usually called ores; rather, they are classified as industrial rocks and minerals.

Recall that more than 98 percent of the crust is composed of only eight elements. Except for oxygen and silicon, all other elements make up a relatively small fraction of common crustal rocks (see Figure 3.26, p. 89). Indeed, the natural concentrations of many elements are exceedingly small. A deposit containing the average percentage of a valuable element is worthless if the cost of extracting it exceeds the value of the material recovered. To be considered valuable, an element must be concentrated above the level of its average crustal abundance. Generally, the lower the crustal abundance, the greater the concentration.

For example, copper makes up about 0.0135 percent of the crust. However, for a material to be considered a copper ore, it must contain a concentration that is about 50 times this amount. Aluminum, in contrast, represents 8.13 percent of the crust and must be concentrated to only about four times its average crustal percentage before it can be extracted profitably.

It is important to realize that a deposit may become profitable to extract or lose its profitability because of economic changes. If demand for a metal increases and prices rise, the status of a previously unprofitable deposit changes, and it becomes an ore. The status of unprofitable deposits may also change if a technological advance allows the useful element to be extracted at a lower cost than before. This occurred at the copper-mining operation located at Bingham Canyon, Utah, one of the largest open-pit mines on Earth (Box 23.3). Mining was halted here in 1985 because outmoded equipment had driven the cost of extracting the copper beyond the selling price. The owners responded by replacing an antiquated 1000-car railroad with conveyor belts and pipelines for transporting the ore and waste. These devices achieved a cost reduction of nearly 30 percent and returned this mining operation to profitability.

Over the years, geologists have been keenly interested in learning how natural processes produce localized concentrations of essential metallic minerals. One well-established fact is that occurrences of valuable mineral resources are closely related to the rock cycle. That is, the mechanisms that generate igneous, sedimentary, and metamorphic rocks, including the processes of weathering and erosion, play a major role in producing concentrated accumulations of useful elements. Moreover, with the development of the plate tectonics theory, geologists added yet another tool for understanding the processes by which one rock is transformed into another.

Mineral Resources and Igneous Processes

Some of the most important accumulations of metals, such as gold, silver, copper, mercury, lead, platinum, and nickel, are produced by igneous processes (see Table 23.3). These mineral resources, like most others, result from processes that concentrate desirable materials to the extent that extraction is economically feasible.

Magmatic Segregation

The igneous processes that generate some of these metal deposits are quite straightforward. For example, as a large magma body cools, the heavy minerals that crystallize early tend to settle to the lower portion of the magma chamber. This type of magmatic segregation is particularly active in large basaltic magmas where chromite (ore of chromium), magnetite, and platinum are occasionally generated. Layers of chromite, interbedded with other heavy minerals, are mined from such deposits in the Stillwater Complex of Montana. Another example is the Bushveld Complex in South Africa, which contains over 70 percent of the world's known reserves of platinum.

Magmatic segregation is also important in the late stages of the magmatic process. This is particularly true of granitic

BOX 23.3 ▶ PEOPLE AND THE ENVIRONMENT

Utah's Bingham Canyon Mine

In the photo, a mountain once stood where there is now a huge pit (Figure 23.C). This is the world's largest open-pit mine, Bingham Canyon copper mine, about 40 kilometers (25 miles) southwest of Salt Lake City, Utah. The rim is nearly 4 kilometers (2.5 miles) across and covers almost 8 square kilometers (3 square miles). Its depth is 900 meters (3000 feet). If a steel tower were erected at the bottom, it would have to be five times taller than the Eiffel Tower to reach the top of the pit!

It began in the late 1800s as an underground mine for veins of silver and lead. Later copper was discovered. Similar deposits occur at several sites in the American Southwest and in a belt from southern Alaska to northern Chile.

As in other places in this belt, the ore at Bingham Canyon is disseminated throughout *porphyritic* igneous rocks; hence, the name *porphyry copper deposits.* The deposit formed after magma was intruded to shallow depths. Following this, shattering created extensive fractures that were penetrated by hydrothermal solutions from which the ore minerals precipitated.

FIGURE 23.C Aerial view of Bingham Canyon copper mine near Salt Lake City, Utah. This huge open-pit mine is about 4 kilometers across and 900 meters deep. Although the amount of copper in the rock is less than 1 percent, the huge volumes of material removed and processed each day (about 200,000 tons) yield significant quantities of metal. (Photo by Michael Collier)

Although the percentage of copper in the rock is small, the total volume of copper is huge. Ever since open-pit operations started in 1906, some 5 billion tons of material have been removed, yielding more than 12 million tons of copper. Significant amounts of gold, silver, and molybdenum have also been recovered.

The ore body is far from exhausted today. Over the next 25 years, plans call for an additional 3 billion tons of material to be removed and processed. This largest of artificial excavations has generated most of Utah's mineral production for more than 80 years and has been called the "richest hole on Earth."

Like many older mines, the Bingham pit was unregulated during most of its history. Development occurred prior to the present-day awareness of the environmental impacts of mining and prior to effective environmental legislation. Today problems of groundwater and surface water contamination, air pollution, solid and hazardous wastes, and land reclamation are receiving long overdue attention at Bingham Canyon.

magmas in which the residual melt can become enriched in rare elements and heavy metals. Further, because water and other volatile substances do not crystallize along with the bulk of the magma body, these fluids make up a high percentage of the melt during the final phase of solidification. Crystallization in a fluid-rich environment, where ion migration is enhanced, results in the formation of crystals several centimeters, or even a few meters, in length. The resulting rocks, called **pegmatites,** are composed of these unusually large crystals (Figure 4.9, p. 107).

Most pegmatites are granitic in composition and consist of unusually large crystals of quartz, feldspar, and muscovite. Feldspar is used in the production of ceramics, and muscovite is used for electrical insulation and glitter. Further, pegmatites often contain some of the least abundant elements. Thus, in addition to the common silicates, some pegmatites include semiprecious gems such as beryl, topaz, and tourmaline. Moreover, minerals containing the elements lithium, cesium, uranium, and the rare earths* are occasionally found (Figure 23.19). Most pegmatites are located within large igneous masses or as dikes or veins that cut into the host rock surrounding the magma chamber (Figure 23.20).

Not all late-stage magmas produce pegmatites, nor do all have a granitic composition. Rather, some magmas become enriched in iron or occasionally copper. For example, at Kiruna, Sweden, magma composed of over 60 percent magnetite solidified to produce one of the largest iron deposits in the world.

*The rare earths are a group of 15 elements (atomic numbers 57 through 71) that possess similar properties. They are useful catalysts in petroleum refining and are used to improve color retention in television picture tubes.

FIGURE 23.19 This pegmatite in the Black Hills of South Dakota was mined for its large crystals of spodumene, an important source of lithium. Arrows are pointing to impressions left by crystals. Note person in upper center of photo for scale. (Photo by James G. Kirchner)

Diamonds

Another economically important mineral with an igneous origin is diamond. Although best known as gems, diamonds are used extensively as abrasives. Diamonds originate at depths of nearly 200 kilometers, where the confining pressure is great enough to generate this high-pressure form of carbon. Once crystallized, the diamonds are carried upward through pipe-shaped conduits that increase in diameter toward the surface. In diamond-bearing pipes, nearly the entire pipe contains diamond crystals that are disseminated throughout an ultramafic rock called *kimberlite*. The most productive kimberlite pipes are those found in South Africa. The only equivalent source of diamonds in the United States is located near Murfreesboro, Arkansas, but this deposit is exhausted and today serves merely as a tourist attraction.

Hydrothermal Solutions

Among the best-known and most important ore deposits are those generated from **hydrothermal** (hot-water) **solutions.** Included in this group are the gold deposits of the Homestake mine in South Dakota; the lead, zinc, and silver ores near Coeur d'Alene, Idaho; the silver deposits of the Comstock Lode in Nevada; and the copper ores of the Keweenaw Peninsula in Michigan (Figure 23.21).

The majority of hydrothermal deposits originate from hot, metal-rich fluids that are remnants of late-stage magmatic processes. During solidification, liquids plus various metallic ions accumulate near the top of the magma chamber. Because of their mobility, these ion-rich solutions can migrate great distances through the surrounding rock before they are eventually deposited, usually as sulfides of various metals (Figure 23.20). Some of this fluid moves along openings such as fractures or bedding planes, where it cools and precipitates the metallic ions to produce **vein deposits** (Figure 23.22). Many of the most productive deposits of gold, silver, and mercury occur as hydrothermal vein deposits.

Another important type of accumulation generated by hydrothermal activity is called a **disseminated deposit.** Rather than being concentrated in narrow veins and dikes, these ores are distributed as minute masses throughout the entire rock mass. Much of the world's copper is extracted from disseminated deposits, including those at Chuquicamata, Chile, and the huge Bingham Canyon copper mine in Utah (see Box 23.3). Because these accumulations contain only 0.4 to

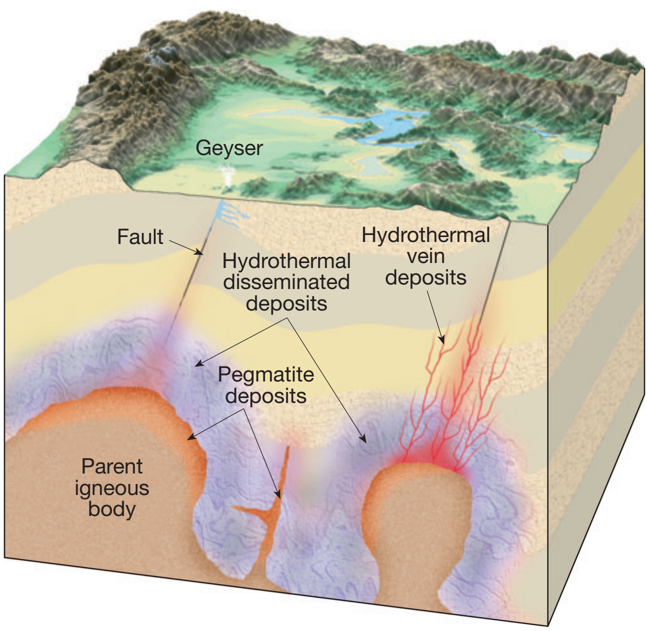


FIGURE 23.20 Illustration of the relationship between a parent igneous body and the associated pegmatite and hydrothermal deposits.

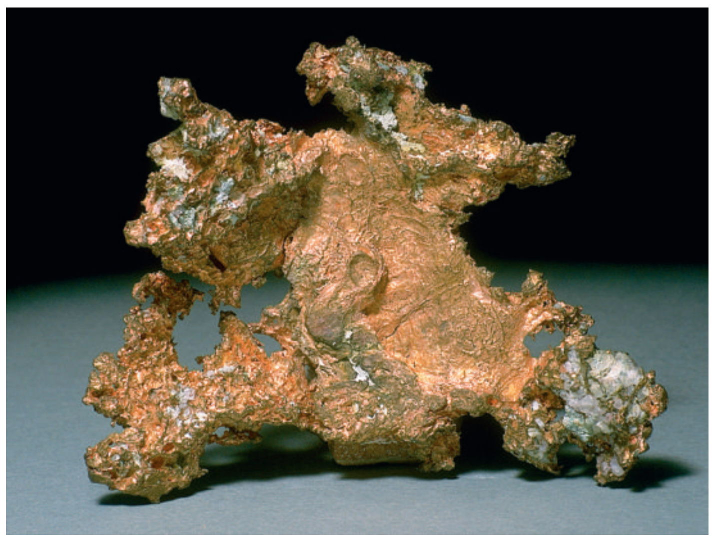


FIGURE 23.21 Native copper from northern Michigan's Keweenaw Peninsula is an excellent example of a hydrothermal deposit. At one time this area was an important source of copper, but it is now largely depleted. (Photo by E. J. Tarbuck)

FIGURE 23.22 Gneiss laced with quartz veins at Diablo Lake Overlook, North Cascades National Park, Washington. (Photo by James E. Patterson)

0.8 percent copper, between 125 and 250 kilograms of ore must be mined for every kilogram of metal recovered. The environmental impact of these large excavations, including the problem of waste disposal, is significant.

Some hydrothermal deposits have been generated by the circulation of ordinary groundwater in regions where magma was emplaced near the surface. The Yellowstone National Park area is a modern example of such a situation (Figure 23.23). When groundwater invades a zone of recent igneous activity, its temperature rises, greatly enhancing its ability to dissolve minerals. These migrating hot waters remove metallic ions from intrusive igneous rocks and carry them upward, where they may be deposited as an ore body. Depending on the conditions, the resulting accumulations may occur as vein deposits, as disseminated deposits, or, where hydrothermal solutions reach the surface in the form of hot springs or geysers, as surface deposits.

FIGURE 23.23 Some hydrothermal deposits are formed by the circulation of heated groundwater in regions where magma is near the surface, as in the Yellowstone National Park area. (Photo by Craig J. Brown/Liaison Agency, Inc.)

With the development of the plate tectonics theory it became clear that some hydrothermal deposits originated along ancient oceanic ridges. A well-known example is found on the island of Cyprus, where copper has been mined for more than 4000 years. Apparently, these deposits represent ores that formed on the seafloor at an ancient oceanic spreading center.

Since the mid-1970s, active hot springs and metal-rich sulfide deposits have been detected at several sites, including study areas along the East Pacific Rise and the Juan de Fuca Ridge. The deposits are forming where heated seawater, rich in dissolved metals and sulfur, gushes from the seafloor as particle-filled clouds called *black smokers.* As shown in Figure 23.24, seawater infiltrates the hot oceanic crust along the flanks of the ridge. As the water moves through the newly formed material, it is heated and chemically interacts with the basalt, extracting and transporting sulfur, iron, copper, and other metals. Near the ridge axis, the hot, metal-rich fluid rises along faults. Upon reaching the seafloor, the spewing liquid mixes with the cold seawater, and the sulfides precipitate to form massive sulfide deposits.

Mineral Resources and Metamorphic Processes

The role of metamorphism in producing mineral deposits is frequently tied to igneous processes. For example, many of the most important metamorphic ore deposits are produced by contact metamorphism. Here the host rock is recrystallized and chemically altered by heat, pressure, and hydrothermal solutions emanating from an intruding igneous body. The extent to which the host rock is altered depends on the nature of the intruding igneous mass as well as the nature of the host rock.

Some resistant materials, such as quartz sandstone, may show very little alteration, whereas others, including limestone, might exhibit the effects of metamorphism for several kilometers from the igneous pluton. As hot, ion-rich fluids move through limestone, chemical reactions take place, which produce useful minerals such as garnet and corundum. Further, these reactions release carbon dioxide, which greatly facilitates the outward migration of metallic ions. Thus, extensive aureoles of metal-rich deposits commonly surround igneous plutons that have invaded limestone strata.

The most common metallic minerals associated with contact metamorphism are sphalerite (zinc), galena (lead), chalcopyrite (copper), magnetite (iron), and bornite (copper). The hydrothermal ore deposits may be disseminated throughout the altered zone or exist as concentrated masses that are located either next to the intrusive body or along the margins of the metamorphic zone.

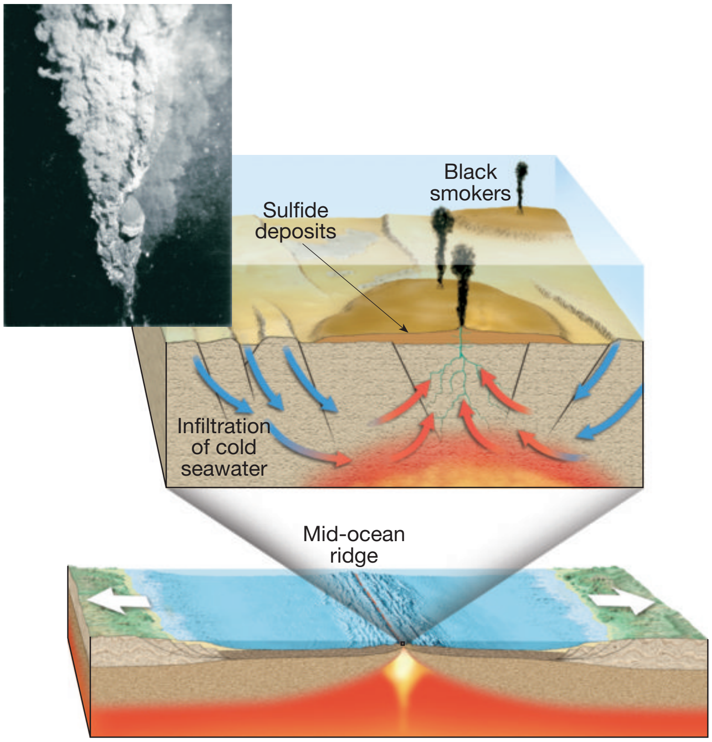


FIGURE 23.24 Massive sulfide deposits can result from the circulation of seawater through the oceanic crust along active spreading centers. As seawater infiltrates the hot basaltic crust, it leaches sulfur, iron, copper, and other metals. The hot, enriched fluid returns to the seafloor near the ridge axis along faults and fractures. Some metal sulfides may be precipitated in these channels as the rising fluid begins to cool. When the hot liquid emerges from the seafloor and mixes with cold seawater, the sulfides precipitate to form massive deposits. Photo shows a close-up view of a black smoker spewing hot, mineral-rich seawater along the East Pacific Rise. (Photo © Robert Ballard, Woods Hole Oceanographic Institution)

Regional metamorphism can also generate useful mineral deposits. Recall that at convergent plate boundaries the oceanic crust, along with sediments that have accumulated at the continental margins, are carried to great depths. In these high-temperature, high-pressure environments the mineralogy and texture of the subducted materials are altered, producing deposits of nonmetallic minerals such as talc and graphite.

Weathering and Ore Deposits

Weathering creates many important mineral deposits by concentrating minor amounts of metals that are scattered through unweathered rock into economically valuable concentrations. Such a transformation is often termed **secondary enrichment** and takes place in one of two ways. In one situation chemical weathering coupled with downward-percolating water removes undesirable materials from decomposing rock, leaving the desirable elements enriched in the upper zones of the soil. The second way is basically the reverse of the first. That is, the desirable elements that are found in low concentrations near the surface are removed and carried to lower zones, where they are redeposited and become more concentrated.

Bauxite

The formation of *bauxite,* the principal ore of aluminum, is one important example of an ore created as a result of enrichment by weathering processes (Figure 23.25). Although aluminum is the third most abundant element in Earth's crust, economically valuable concentrations of this important metal are not common, because most aluminum is tied up in silicate minerals from which it is extremely difficult to extract.

Bauxite forms in rainy tropical climates in association with laterites. (In fact, bauxite is sometimes referred to as aluminum laterite.) When aluminum-rich source rocks are subjected to the intense and prolonged chemical weathering of the tropics, most of the common elements, including calcium, sodium, and silicon, are removed by leaching. Because aluminum is extremely insoluble, it becomes concentrated in the soil as bauxite, a hydrated aluminum oxide. Thus, the formation of bauxite depends both on climatic conditions in which chemical weathering and leaching are pronounced and on the presence of an aluminum-rich source rock. Important deposits of nickel and cobalt are also found in laterite soils that develop from igneous rocks rich in ferromagnesian silicate minerals.

Other Deposits

Many copper and silver deposits result when weathering processes concentrate metals that are deposited through a low-grade primary ore. Usually such enrichment occurs in deposits containing pyrite (FeS_2), the most common and

FIGURE 23.25 Bauxite is the ore of aluminum and forms as a result of weathering processes under tropical conditions. Its color varies from red or brown to nearly white. (Photo by E. J. Tarbuck)

widespread sulfide mineral. Pyrite is important because when it chemically weathers, sulfuric acid forms, which enables percolating waters to dissolve the ore metals. Once dissolved, the metals gradually migrate downward through the primary ore body until they are precipitated. Deposition takes place because of changes that occur in the chemistry of the solution when it reaches the groundwater zone (the zone beneath the surface where all pore spaces are filled with water). In this manner the small percentage of dispersed metal can be removed from a large volume of rock and redeposited as a higher-grade ore in a smaller volume of rock.

This enrichment process is responsible for the economic success of many copper deposits, including one located in Miami, Arizona. Here the ore was upgraded from less than 1 percent copper in the primary deposit to as much as 5 percent copper in some localized zones of enrichment. When pyrite weathers (oxidizes) near the surface, residues of iron oxide remain. The presence of these rusty-colored caps at the surface indicates the possibility of an enriched ore below, and this represents a visible sign for prospectors.

Placer Deposits

Sorting typically results in like-sized grains being deposited together. However, sorting according to the specific gravity of particles also occurs. This latter type of sorting is responsible for the creation of **placers,** which are deposits formed when heavy minerals are mechanically concentrated by currents. Placers associated with streams are among the most common and best known, but the sorting action of waves can also create placers along the shore. Placer deposits usually involve minerals that are not only heavy but also durable (to withstand physical destruction during transportation) and chemically resistant (to endure weathering processes). Placers form because heavy minerals settle quickly from a current, whereas less dense particles remain suspended and are carried onward. Common sites of accumulation include point bars on the insides of meanders as well as cracks, depressions, and other irregularities on stream beds.

Many economically important placer deposits exist, with accumulations of gold the best known. Indeed, it was the placer deposits discovered in 1848 that led to the famous California gold rush. Years later similar deposits created a gold rush to Alaska as well (Figure 23.26). Panning for gold by washing sand and gravel from a flat pan to concentrate the fine "dust" at the bottom was a common method used by early prospectors to recover the precious metal, and it is a process similar to that which created the placer in the first place.

In addition to gold, other heavy and durable minerals form placers. These include platinum, diamonds, and tin. The Ural Mountains contain placers rich in platinum, and placers are important sources of diamonds in southern Africa. Significant portions of the world's supply of cassiterite, the principal ore of tin, have come from placer deposits in Malaysia and Indonesia. Cassiterite is often widely disseminated through granitic igneous rocks. In this state the mineral is not sufficiently concentrated to be extracted profitably. However, as the enclosing rock dissolves and disintegrates, the heavy and durable cassiterite grains are set free. Eventually the freed particles are washed to a stream, where they are deposited in placers that are significantly more concentrated than the original deposit. Similar circumstances and events are common to many minerals mined from placers.

FIGURE 23.26 **A.** It was placer deposits that led to the 1848 California gold rush. Here, a prospector in 1850 swirls his gold pan, separating sand and mud from flecks of gold. (Photo courtesy of Seaver Center for Western History Research, Los Angeles County Museum of Natural History) **B.** Modern gold mining of a placer deposit near Nome, Alaska. The dredge scoops up thawed gravel. (Photo by Fred Bruemmer/DRK Photo)

A. B.

Students Sometimes Ask . . .

How big was the largest gold nugget ever discovered?

The largest gold nugget ever discovered was the Welcome Stranger Nugget found in 1869 three centimeters below the surface within the roots of a Stringybark tree in the gold-mining region of Victoria, Australia. It weighed a massive 2316 troy ounces (about 72 kilograms). The largest gold nugget known to remain in existence today is the Hand of Faith Nugget, which was found in 1980 near Kingower, Victoria, Australia. It was found with a metal detector and weighs 876 troy ounces (27.2 kilograms). Sold in 1982, it is now on display in the Golden Nugget Casino in Las Vegas, Nevada.

In some cases, if the source rock for a placer deposit can be located, it too may become an important ore body. By following placer deposits upstream, one can sometimes locate the original deposit. This is how the gold-bearing veins of the Mother Lode in California's Sierra Nevada batholith were found, as well as the famous Kimberly diamond mines of South Africa. The placers were discovered first, their source at a later time.

Nonmetallic Mineral Resources

Earth materials that are not used as fuels or processed for the metals they contain are referred to as **nonmetallic mineral resources.** Realize that use of the word "mineral" is very broad in this economic context and is quite different from the geologist's strict definition of mineral found in Chapter 3. Nonmetallic mineral resources are extracted and processed either for the nonmetallic elements they contain or for the physical and chemical properties they possess.

People often do not realize the importance of nonmetallic minerals because they see only the products that resulted from their use and not the minerals themselves. That is, many nonmetallics are used up in the process of creating other products. Examples include the fluorite and limestone that are part of the steelmaking process, the abrasives required to make a piece of machinery, and the fertilizers needed to grow a food crop (see Table 23.4).

The quantities of nonmetallic minerals used each year are enormous. A glance at Figure 23.2 (p. 629) reminds us that the per capita consumption of nonfuel resources in the United States totals more than 11 metric tons, of which about 94 percent are nonmetallics. Nonmetallic mineral resources are commonly divided into two broad groups—*building materials* and *industrial minerals.* Because some substances have many different uses, they are found in both categories. Limestone, perhaps the most versatile and widely used rock of all, is the best example. As a building material, it is used not only as crushed rock and building stone but also in the making of cement. Moreover, as an industrial mineral, limestone is an ingredient in the manufacture of steel and is used in agriculture to neutralize soils.

Building Materials

Natural aggregate consists of crushed stone, sand, and gravel. From the standpoint of quantity and value, aggregate is a very important building material. The United States produces nearly 2 billion tons of aggregate per year, which represents about one half of the entire nonenergy mining volume in the country. It is produced commercially in every state and is used in nearly all building construction and in most public works projects (Figure 23.27).

TABLE 23.4 Occurrences and Uses of Nonmetallic Minerals

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

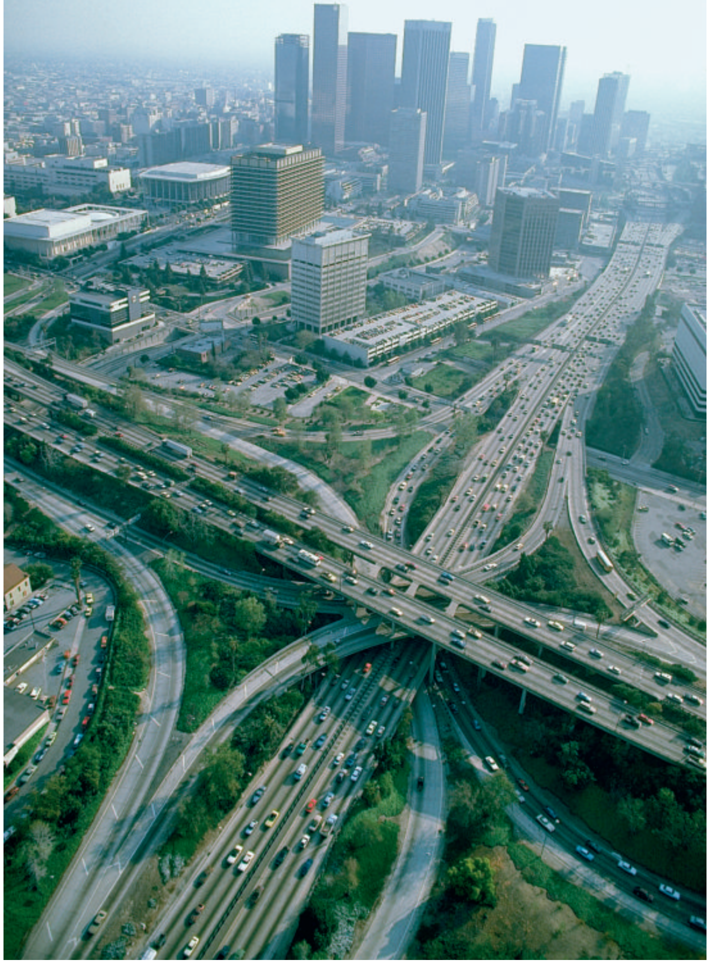


FIGURE 23.27 Crushed stone and sand and gravel are primarily used for aggregate in the construction industry, especially in cement concrete for residential and commercial buildings, bridges, and airports, and as cement concrete or bituminous concrete (asphalt) for highway construction. A large percentage is used without a binder as road base, for road surfacing, and as railroad ballast. (Photo by Robert Ginn/PhotoEdit)

Besides aggregate, other important building materials include gypsum for plaster and wallboard, clay for tile and bricks, and cement, which is made from limestone and shale. Cement and aggregate go into the making of concrete, a material that is essential to practically all construction. Aggregate gives concrete its strength and volume, and cement binds the mixture into a rock-hard substance. Just 2 kilometers of four-lane highway require more than 85 metric tons of aggregate. On a smaller scale, 90 tons of aggregate are needed just to build an average six-room house.

Because most building materials are widely distributed and present in almost unlimited quantities, they have little intrinsic value. Their economic worth comes only after the materials are removed from the ground and processed. Since their per-ton value compared with metals and industrial minerals is low, mining and quarrying operations are usually undertaken to satisfy local needs. Except for special types of cut stone used for buildings and monuments, transportation costs greatly limit the distance most building materials can be moved.

Industrial Minerals

Many nonmetallic resources are classified as industrial minerals. In some instances these materials are important because they are sources of specific chemical elements or compounds. Such minerals are used in the manufacture of chemicals and the production of fertilizers. In other cases their importance is related to the physical properties they exhibit. Examples include minerals such as corundum and garnet, which are used as abrasives. Although supplies are generally plentiful, most industrial minerals are not nearly as abundant as building materials. Moreover, deposits are far more restricted in distribution and extent. As a result, many of these nonmetallic resources must be transported considerable distances, which of course adds to their cost. Unlike most building materials, which need a minimum of processing before they are ready to use, many industrial minerals require considerable processing to extract the desired substance at the proper degree of purity for its ultimate use.

Fertilizers The growth in world population toward 7 billion requires that the production of basic food crops continues to expand. Therefore, fertilizers—primarily nitrate, phosphate, and potassium compounds—are extremely important to agriculture. The synthetic nitrate industry, which derives nitrogen from the atmosphere, is the source of practically all the world's nitrogen fertilizers. The primary source of phosphorus and potassium, however, remains Earth's crust. The mineral apatite is the primary source of phosphate. In the United States most production comes from marine sedimentary deposits in Florida and North Carolina (Figure 23.28). Although potassium is an abundant element in many minerals, the primary commercial sources are evaporite deposits containing the mineral sylvite. In the United States, deposits near Carlsbad, New Mexico, have been especially important.

Sulfur Because it has many uses, sulfur is an important nonmetallic resource. In fact, the quantity of sulfur used is considered one index of a country's level of industrialization. More than 80 percent is used to produce sulfuric acid. Although its principal use is in the manufacture of phosphate fertilizer, sulfuric acid has a large number of other applications as well. Sources include deposits of native sulfur associated with salt domes and volcanic areas, as well as common iron sulfides such as pyrite. In recent years an increasingly important source has been the sulfur removed from coal, oil, and natural gas in order to make these fuels less polluting.

Salt Common salt, known by the mineral name *halite,* is another important and versatile resource. It is among the more prominent nonmetallic minerals used as a raw material in the chemical industry. In addition, large quantities are used to "soften" water and to keep streets and highways free of ice. Of course, most people are aware that it is also a basic nutrient and a part of many food products.

FIGURE 23.28 Large open-pit phosphate mine in Florida. The phosphorus-bearing mineral apatite is a calcium phosphate associated with bones and teeth. Fish and other marine organisms extract phosphate from seawater to form apatite. These sedimentary deposits are associated with the floor of a shallow sea. (Photo by C. Davidson/ Comstock)

Salt is a common evaporite, and thick deposits are exploited using conventional underground mining techniques. Subsurface deposits are also tapped, using brine wells in which a pipe is introduced into a salt deposit and water is pumped down the pipe. The salt dissolved by the water is brought to the surface through a second pipe. In addition, seawater continues to serve as a source of salt as it has for centuries. The salt is harvested after the Sun evaporates the water.

Summary

- *Renewable resources* can be replenished over relatively short time spans. Examples include natural fibers for clothing and trees for lumber. *Nonrenewable resources* form so slowly that, from a human standpoint, Earth contains fixed supplies. Examples include fuels such as oil and coal, and metals such as copper and gold. A rapidly growing world population and the desire for an improved living standard cause nonrenewable resources to become depleted at an increasing rate.
- *Coal, petroleum,* and *natural gas,* the *fossil fuels* of our modern economy, are all associated with sedimentary rocks. Coal originates from large quantities of plant remains that accumulate in an oxygen-deficient environment, such as a swamp. More than 70 percent of present-day coal usage is for the generation of electricity. Air pollution produced by the sulfur oxide gases that form from burning most types of coal is a significant environmental problem.
- Oil and natural gas, which commonly occur together in the pore spaces of some sedimentary rocks, consist of various *hydrocarbon compounds* (compounds made of hydrogen and carbon) mixed together. Petroleum formation is associated with the accumulation of sediment in ocean areas that are rich in plant and animal remains that become buried and isolated in an oxygen-deficient environment. As the mobile petroleum and natural gas form, they migrate and accumulate in adjacent permeable beds such as sandstone. If the upward migration is halted by an impermeable rock layer, referred to as a *cap rock,* a geologic environment that allows for economically significant amounts of oil and gas to accumulate underground, called an *oil trap,* develops. The two basic conditions common to all oil traps are (1) a porous, permeable *reservoir rock* that will yield petroleum and/or natural gas in sufficient quantities, and (2) a cap rock.
- When conventional petroleum resources are no longer adequate, fuels derived from *oil sands* and *oil shale* may become substitutes. Presently, oil sands from the province of Alberta are the source of about 15 percent of Canada's oil production. Oil from oil shale is presently uneconomical to produce. Oil production from both oil sands and oil shale has significant environmental drawbacks.
- More than 85 percent of our energy is derived from fossil fuels. In the United States the most important alternative energy sources are *nuclear energy* and *hydroelectric power.* Other alternative energy sources are locally important but collectively provide about 1 percent of the U.S. energy demand. These include *solar power, geothermal energy, wind energy,* and *tidal power.*
- *Mineral resources* are the endowment of useful minerals ultimately available commercially. Resources include already identified deposits from which minerals can be extracted profitably, called *reserves,* as well as known deposits that are not yet economically or technologically recoverable. Deposits inferred to exist but not yet discovered are also considered mineral resources. The term *ore* is used to denote those useful metallic minerals that can be mined for a profit, as well as some nonmetallic minerals, such as fluorite and sulfur, that contain useful substances.
- Some of the most important accumulations of metals, such as gold, silver, lead, and copper, are produced by

igneous processes. The best-known and most important ore deposits are generated from *hydrothermal* (hot-water) *solutions.* Hydrothermal deposits originate from hot, metal-rich fluids that are remnants of late-stage magmatic processes. These ion-rich solutions move along fractures or bedding planes, cool, and precipitate the metallic ions to produce *vein deposits.* In a *disseminated deposit* (e.g., much of the world's copper deposits) the ores from hydrothermal solutions are distributed as minute masses throughout the entire rock mass.

- Many of the most important metamorphic ore deposits are produced by contact metamorphism. Extensive aureoles of metal-rich deposits commonly surround igneous bodies where ions have invaded limestone strata. The most common metallic minerals associated with contact metamorphism are sphalerite (zinc), galena (lead), chalcopyrite (copper), magnetite (iron), and bornite (copper). Of equal economic importance are the metamorphic rocks themselves. In many regions, slate, marble, and quartzite are quarried for a variety of construction purposes.
- Weathering creates ore deposits by concentrating minor amounts of metals into economically valuable deposits. The process, often called *secondary enrichment*, is accomplished by either (1) removing undesirable materials and leaving the desired elements enriched in the upper zones of the soil, or (2) removing and carrying the desirable elements to lower zones where they are redeposited and become more concentrated. *Bauxite,* the principal ore of aluminum, is one important ore created as a result of enrichment by weathering processes. In addition, many copper and silver deposits result when weathering processes concentrate metals that were formerly dispersed through low-grade primary ore.
- Earth materials that are not used as fuels or processed for the metals they contain are referred to as *nonmetallic resources.* Many are sediments or sedimentary rocks. The two broad groups of nonmetallic resources are *building materials* and *industrial minerals.* Limestone, perhaps the most versatile and widely used rock of all, is found in both groups.

Review Questions

1. Contrast renewable and nonrenewable resources. Give one or more examples of each.
2. What is the estimated world population for the year 2015? How does this compare to the figures for 1930 and 1975? Is demand for resources growing as rapidly as world population?
3. More than 70 percent of present-day coal usage is for what purpose?
4. What is an oil trap? List two conditions common to all oil traps.
5. List two drawbacks associated with the processing of oil sands recovered by surface mining.
6. The United States has huge oil shale deposits but does not produce oil shale commercially. Explain.
7. What is the main fuel for nuclear fission reactors?
8. List two obstacles that have hindered the development of nuclear power as a major energy source. What environmental advantage does nuclear power have compared to fossil fuels?
9. Briefly describe two methods by which solar energy might be used to produce electricity.
10. Explain why dams built to provide hydroelectricity do not last indefinitely.
11. What advantages does tidal power production offer? Is it likely that tides will ever provide a significant proportion of the world's electrical energy requirements?
12. Contrast *resource* and *reserve.*
13. What might cause a mineral deposit that had not been considered an ore to be reclassified as an ore?
14. List two general types of hydrothermal deposits.
15. Metamorphic ore deposits are often related to igneous processes. Provide an example.
16. Name the primary ore of aluminum and describe its formation.
17. A rusty-colored zone of iron oxide at the surface may indicate the presence of a copper deposit at depth. Briefly explain.
18. Briefly describe the way in which minerals accumulate in placers. List four minerals that are mined from such deposits.
19. Which is greater, the per capita consumption of metallic resources or that of nonmetallic mineral resources?
20. Nonmetallic resources are commonly divided into two broad groups. List the two groups and some examples of materials that belong to each. Which group is most widely distributed?

Key Terms

cap rock (p. 632)
disseminated deposit (p. 645)
fossil fuel (p. 630)
geothermal energy (p. 639)
hydroelectric power (p. 639)
hydrothermal solution (p. 645)
mineral resource (p. 642)
nonmetallic mineral resource (p. 649)
nonrenewable resource (p. 620)
nuclear fission (p. 625)
oil trap (p. 632)
ore (p. 643)
pegmatite (p. 644)
placer (p. 648)
renewable resource (p. 628)
reserve (p. 643)
reservoir rock (p. 632)
secondary enrichment (p. 647)
vein deposit (p. 645)

Web Resources

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

- Online review quizzes.
- Critical thinking exercises.
- Links to chapter-specific Web resources.
- Internet-wide key-term searches.

http://www.prenhall.com/tarbuck