CHAPTER

22

Resources

The Mt. Whaleback iron ore mine, located in western Australia, is over 5 km long and 1.5 km wide. *Photo © Peter Hendrie/Photographer's Choice/Getty Images*

LEARNING OBJECTIVES

- Explain the difference between a reserve and a resource and the factors that determine whether a resource is regarded as a reserve.
- Compare the geologic processes that lead to the formation of coal, oil, and natural gas deposits.
- Understand how a nuclear reactor works, and discuss the pros and cons of nuclear energy.
- Describe each of the renewable sources of energy, and compare their importance to fossil-based energy sources.
- Name the important metallic and nonmetallic resources, their primary uses, and the geologic processes through which they form.
- Describe the mining techniques used to extract metallic and nonmetallic resources.
- Consider the environmental impact of resource extraction and consumption.

Geologic resources sustain life, and the most fundamental of these resources are soil and water. Industrial civilization, however, draws a much greater variety of resources from the Earth. In many ways, our modern lives have come to depend upon dozens of different kinds of Earth materials, from the coal that powers our electricity to the neodymium used to make the tiny powerful batteries that allow us to have small portable electronics such as cell phones and laptop computers. In early times, people knew what resources they needed to support their lives, and where to find them. Today, few people fully appreciate the multitude of resources and the complex web of supply and demand that enables each of us to live. Consider your typical morning routine. Your digital alarm clock is made of plastic produced from petroleum, and its LED display is made of materials such as silica and aluminum. When you brush your teeth, you are using a plastic toothbrush, and you are using toothpaste containing silica as an abrasive and fluoride from the mineral fluorite. Your bathroom mirror is made of glass (which is made from beach sand) and coated with silver or aluminum to make it reflective. It hangs on a wall that is most likely made of gypsum wallboard. You travel to work in a car or on a bus or bicycle—all made of a mixture of metal, plastic, and rubber components. These resources, and the many others that you use within the first few hours of your day, have to be mined and processed by machinery made of iron in factories powered by electricity.

Excluding soil and water, which we discuss elsewhere in the book, we group geologic resources into three general categories: (1) energy resources, (2) metallic resources, and (3) nonmetallic resources. *Energy resources,* like petroleum and uranium, provide the power that drives the modern world. *Metallic resources,* such as iron ore, enable us to create the metals which provide strength for modern construction and help many technologies operate—for example, by conducting electricity or sparking motors. *Nonmetallic resources,* including building stones and road gravels, have a long history in the development of civilization and are still vital to the modern world. Consider a highway overpass. It consists of a nonmetallic resource exterior (the concrete) with a metallic core (the rebar and girders). The overpass supports a road of asphalt—fossil organic matter mixed with nonmetallic aggregates—that provides access to cars made of metals (body and engine) and biological matter (rubber), and powered by petroleum.

Each year, the average American uses approximately 3,430 liters (906 gallons) of oil; 2,388 m^3 (84,348 ft^3) of natural gas; 199 kg (438 lb) of iron ore, aluminum ore, and copper; and 6,919 kg (15,253 lb) of crushed stone, sand, and gravel. Try to imagine how much mining, blasting, drilling, and pumping all of this requires, and it is easy to believe the fact that human activity now moves more earth—perhaps as much as 3 trillion tons annually—than all of the rivers of the world combined (a *mere* 24 billion tons per year of transported sediment).

Some geologic resources are *renewable,* that is, they are replenished by natural processes fast enough that people can use them continuously. Water is the best example. Under sustainable conditions, the supply of water is never ending, provided that we extract water no faster than it is replenished naturally by precipitation, runoff, and infiltration. Most geologic resources, however, are **nonrenewable resources.** They form very slowly, often over millions of years under unusual conditions in restricted geographic settings. Humans extract nonrenewable resources much faster than nature replaces them. The annual rate of extraction of crude oil, for example, is on the order of a million times faster than natural rates of replenishment.

In this chapter, we will first discuss the difference between a reserve and a resource. We will then explore energy resources, both nonrenewable and renewable, in terms of their origin and how they are exploited. We will move on to metallic and nonmetallic resources and a discussion of mining practices. Finally, the balance between our need for resources and our responsibilities toward protecting the environment and conserving resources for future generations will be discussed.

RESERVES AND RESOURCES

Resource is the term used to describe the total amount of any given geologic material of *potential economic interest,* whether discovered or not. A resource can be measured directly through mining or drilling ("demonstrated," "measured," or "indicated" resources), or simply inferred based upon reasonable geologic guesswork and statistical modeling ("inferred," "hypothetical," or "speculative" resources). The size of a nonrenewable resource does not change in time; it is a value that is fixed and theoretically determinable. **Reserve** is the term used to describe the portion of a resource that has been discovered or inferred with some

IN GREATER DEPTH 22.1

Copper and Reserve Growth

As the prices of metals and the energy used to extract them fluctuate, so do the potential profits from minerals. For example, in 1900, copper could be mined at a profit only if its concentration in ore exceeded 5%. By the early 1980s, this profit level dropped to 0.5%, and the world's recoverable copper reserves rose to a half billion tons. Since then, the world has consumed about 400 million tons of copper, but the introduction of recycling (which now provides the United States with almost as much copper as direct mining), the introduction of substitutes for copper (such as fiber-optic cable), and the discovery of new reserves actually increased world copper reserves to 680 million tons by 2013. Mineral markets and reserves are volatile and erratic, with reserves generally shrinking as market process declines and swelling as prices rise, most often due to investor speculation and temporary supply shortages and gluts. Nevertheless, there are some persistent trends: The world almost always appears to have large reserves of iron and aluminum, moderate reserves of copper, lead, and zinc, and scanty reserves of gold and silver. These levels reflect the relative abundance of these resources in nature. There is no sign that we are about to "run out" of any of these metals.

Other challenges, however, loom on the horizon because the sizes of mineral reserves are tied critically to the price of energy. It takes very large amounts of energy to mine, refine, process, and transport minerals for use. Mineral extraction, in fact, is the most energy-intensive industry in the world. Over most of the past 120 years, overall unit energy costs (adjusted for inflation) have not grown appreciably and have held generally steady, providing a reliable platform for industrial growth. If the long-term cost of energy increases, however, we might expect the sizes of mineral reserves to drop in response, simply because it will become so much more expensive to mine at a profit.

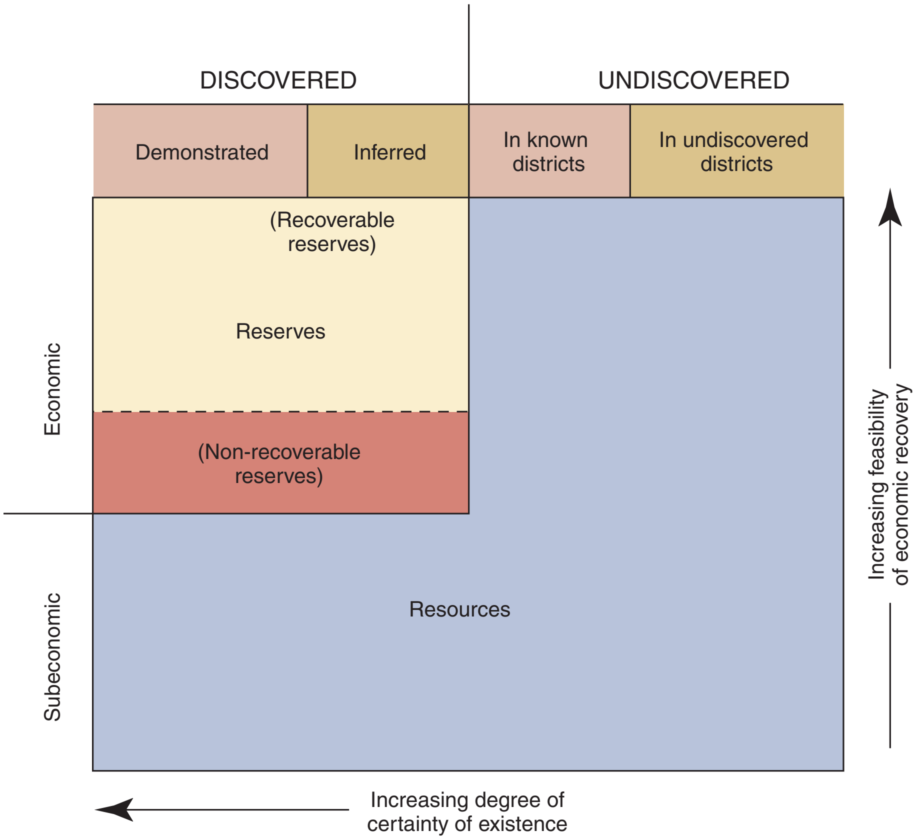


FIGURE 22.1

Important factors in the classification of reserves and resources. (Reserves are subsets of resources.)

degree of certainty and can be extracted for a profit. Figure 22.1 shows the relationship between resources and reserves. Unlike a resource, the size of a reserve can change over time, depending upon a variety of factors (box 22.1). For example, mining or drilling of a substance will cause the reserve to shrink, especially if no new discoveries are made. Wage increases and a drop in market price could make a deposit of a material too expensive to continue mining, which would also reduce the reserve size. On the other hand, new discoveries and new technologies making it easier to locate and mine a resource make a reserve larger. From 2000 to 2011, the price of gold rose precipitously from a little over $250 per ounce to almost $2,000 per ounce. This rise in the price of gold led to a revival of gold mining in California, with a number of old mines preparing to reopen. You can check the daily price of gold at http://www.kitco.com/charts/livegold.html. Since 2011, the price of gold has dropped, although at this writing it remains above $1,000 per ounce. What do you think will happen to plans for mining in California if the price of gold continues to fall? Changes in laws can also affect reserve sizes. Large areas of government-owned land are off-limits to mining and drilling, so any geologic materials under these areas are not legally extractable and cannot be included in reserves. Opening more land to extraction would therefore increase reserves.

Not all of a reserve may be recoverable. For example, in the United States, the total coal *resource* is on the order of 9 trillion tons. Only about 5% of this (440 billion metric tons) makes up the U.S. coal *reserve,* however. But not all of this reserve can actually be extracted. Some has to be left behind during mining for safety reasons—to support mine pillars, to prevent landslides, to avoid water pollution problems, and so on. In fact, only about 60% of the coal in any bed that is mined below ground can be removed. The value for strip and open-pit mines is somewhat greater—80 to 90%. The *recoverable reserve* for coal in the United States, hence, is only about 3% (233 billion metric tons) of the total known coal resource in the country. We will never be able to exhaust all the coal in the world, but this is only because we will never be able to mine it all safely *at a profit.*

ENERGY RESOURCES

Energy is simply "the ability to do work." Without energy, nothing could exist; in fact, it is basic to everything. There are many different forms of energy, and these are divided into two basic categories. **Kinetic energy** involves movement, while **potential energy** is stored energy. Kinetic energy forms include electrical energy (the movement of electrical charges), radiant energy (the movement of electromagnetic rays such as visible light or X rays), thermal energy (heat), motion energy (the movement of objects from one place to another), and sound. Potential energy forms include chemical energy (energy stored in atomic bonds), stored mechanical energy (such as the energy stored in a compressed spring), nuclear energy, and gravitational energy. We fuel our bodies with chemical energy stored in the food we eat. That energy ultimately comes from the radiant energy provided by the Sun. **Energy resources** are the materials we use to produce heat and electricity or as fuel for transport. Modern society is dependent upon energy resources, not only for heat and fuel but to produce all of the items we use daily in our homes and offices. Energy consumption in the United States makes up almost 19% of world energy consumption, although the U.S. population is only about 5% of world population. A single person in the United States uses approximately twice as much energy as a person in Europe, four times as much energy as a person in China, and just over fifteen times as much energy as a person in India.

Although interest in alternative, renewable energy resources is increasing, the majority of our energy needs are met by nonrenewable *fossil fuel resources* such as coal and oil. The state of our energy supplies is very much on the minds of many people today. How much oil do we have left? What will power the airplane of the future? Is a new "hydrogen economy" on the way? To answer some of these questions, we must examine how and where our energy resources are formed.

Nonrenewable Energy Resources

Nonrenewable energy resources are those that cannot be replenished naturally in a short period of time. Coal, petroleum, natural gas, and propane are all considered **fossil fuels** because they formed from the buried remains of plants and animals that lived millions of years ago. Uranium ore is an important energy resource that is *not* a fossil fuel. Geothermal power, although discussed in the Renewable Energy Resources section, can be regarded as nonrenewable because it can be exhausted readily, even though water and heat are both replenished rapidly over time.

Coal

Coal, as described in chapter 6, is a sedimentary rock that forms from the compaction of plant material that has not completely decayed. The most abundant fossil fuel in the Earth's crust, coal became a major substitute for wood as a source of energy in Europe beginning in the fifteenth century. Efforts to mine coal from greater depths led Englishman Thomas Newcomen to invent a pump in 1712 to drain deep coal mines that were below the water table. This pump was the ancestor of the steam engine that started the Industrial Revolution four decades later. Coal was the main fuel of industrial civilization until people discovered that large amounts of petroleum could be pumped from the Earth, and that petroleum provided a less dirty, more transportable fuel with all sorts of new and exciting uses. The Coal Age gave way to the Petroleum Interval almost a century ago. In 1900, more than 90% of American energy needs were satisfied by burning coal. Today, the United States uses coal to provide only about 20% of its energy demand and, in recent years, as coal-fired power plants were converted to natural gas, the reliance on coal for electricity has declined. About 27% of the world's total coal reserves lie in the United States (Figure 22.2). Russia has the second-most-abundant reserve base (15–20%), with China and India making up another 20%. At current rates of consumption, U.S. recoverable reserves will be exhausted in about 250 years. A similar level of depletion is occurring worldwide. Of course, the many factors just mentioned may alter the sizes of the world's coal reserves, and continued rapid economic growth will significantly impact the

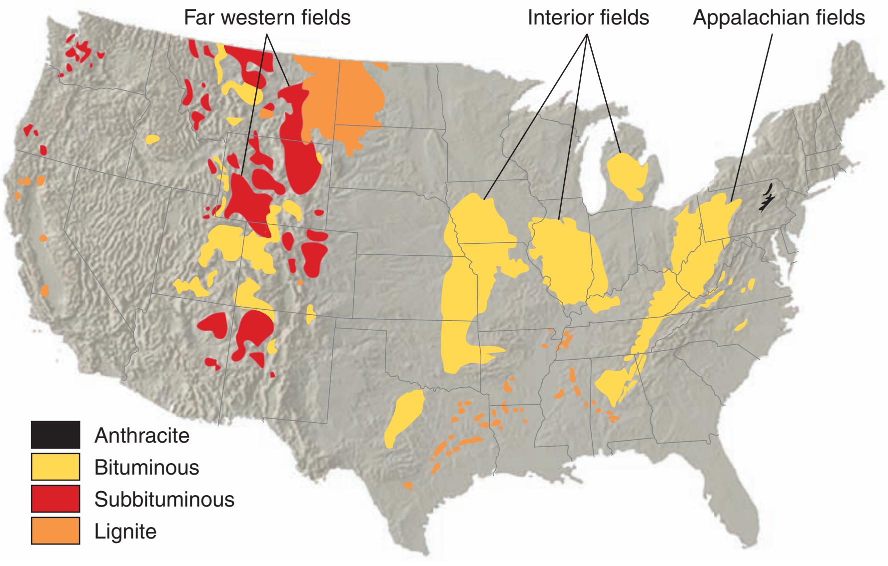


FIGURE 22.2

Coal fields of the United States. Alaska also has coal. *From U.S. Geological Survey*

TABLE 22.1 Varieties (Ranks) of Coal

	Color	Water Content (%)	Other Volatiles (%)	Fixed Carbon[2] (%)	Approximate Heat Value (BTUs of heat per pound of dry coal)
Peat[1]	Brown	75	10	15	Varies
Lignite	Brown to brownish-black	45	25	30	7,000
Subbituminous coal	Black	25	35	40	10,000
Bituminous coal (soft coal)	Black	5 to 15	20 to 30	45 to 86	10,500 to 15,000
Anthracite (hard coal)	Black	5 to 10	5	86 to 98	14,000 to 15,000

1. Peat is not truly a coal, but may be thought of as "pre-coal."
2. "Fixed carbon" means solid combustible material left after water, volatiles, and ash (noncombustible solids) are removed.

longevity of any resource supply. The 250-year estimate for the United States is based on current consumption rates. However, a report released in 2011 predicted that U.S. coal consumption would increase by about 1% per year during the next 25 years. If that growth rate were to continue, the U.S. reserves would be exhausted in about 120 years.

How does coal form? Imagine a swampy, coastal environment in a tropical setting. Sunlight filters through the still trees onto dark, stagnant water below, providing the energy for photosynthesis to take place even in the shadows. Photosynthesis converts the Sun's radiant energy into chemical energy stored in molecular bonds, holding together hydrocarbon (hydrogen + carbon) molecules, the building blocks of cellulose and other plant tissues. This is the photosynthetic reaction:

$$CO_2 + H_2O \rightarrow CH_2O + O_2$$

(Atmospheric carbon dioxide + water from the soil combine in sunlight to make cellulose and other plant tissues, releasing oxygen by plant respiration.)

When a plant dies, it will decay readily in the atmosphere, and its stored energy will return to the atmosphere. The reaction taking place during decay is essentially the reverse of the photosynthetic reaction, with oxygen reacting with dead tissues to release pungent gases and water. But if the dead plant matter settles into stagnant, oxygen-depleted water and becomes buried by sediment, it takes that stored energy with it. In time, the inherited energy may become even more concentrated as the molecules in the dead plant break down into less-complex forms. Under pressure and heat, the fossil plant remains transform into coal.

There is a succession of stages in coal development, from relatively low-energy forms with a small amount of concentrated carbon inside, to higher-energy forms with high relative carbon contents (table 22.1). The more carbon that is present, the more combustible—and economically desirable—the coal. The initial stage of coal development begins as a mat of densely packed, spongy, moist, unconsolidated plant material called *peat* (Figure 22.3). When dried out, peat can be burned as a fuel, as in Britain and ancient Rome. With compaction, peat transforms into solid *lignite (brown coal),* which may still contain visible pieces of wood. Lignite is soft and often crumbles as it dries in air. It is subject to spontaneous combustion as it oxidizes in air, and this somewhat limits its use as a fuel. *Subbituminous coal* and *bituminous coal (soft coal)* are black and often banded with layers of different plant material. They are dusty to handle, ignite easily, and burn with a smoky flame. *Anthracite (hard coal),* the highest "grade" or "rank" of coal, has the most concentrated stored solar energy and is hard to ignite, but it is dust-free and smokeless. If the coal is squeezed and heated any further, its hydrocarbon molecules break down altogether under essentially metamorphic conditions, and all that remains is pure carbon—graphite, the stuff we put in pencil leads.

FIGURE 22.3

A layer of peat being cut and dried for fuel on the island of Mull, Scotland. Coal often forms from peat. *Photo by David McGeary*

The scientific unit of energy is the *joule.* One joule is roughly equivalent to the amount of energy needed to heat one gram of dry, cool air by 1°C. In the United States, energy is measured in terms of BTUs, or *British Thermal Units.* One BTU is equivalent to 1,055 joules. A kilogram of ordinary bituminous coal, the most common type of coal in the United States, typically contains 45–86% carbon and releases 25–35 million joules, or megajoules of heat energy (10,500–15,000 BTU per pound). This is sufficient to produce electricity and is equivalent to two to three times the food energy consumed by the average person every day. Anthracite, the highest-grade coal (86–98% carbon) will produce 26–35 megajoules per kilogram

FIGURE 22.4

Coal embedded with sandstone. *Photo © Parvinder Sethi*

(14,000–15,000 BTU/lb). In comparison, average-grade gasoline produces 47 megajoules per kilogram (20,200 BTU/lb).

Coal beds are typically interlayered with ordinary sedimentary rocks, including sandstones and shales (Figure 22.4). Beds typically range in thickness from a few centimeters to 30 meters or more. Miners dig up beds that lie close to the surface—within a few tens of meters—by **strip mining,** the complete removal of overlying rock and vegetation (Figure 22.5). Strip mining is an environmentally harmful activity that destroys topsoil and leaves behind open pits that must be filled back in and replanted to curb further erosion and water pollution. But strip mining is the only way much of the world's coal supply can be safely mined. Shaft and tunnel mining provide access to deeper coal deposits (Figure 22.6). This form of "deep-rock" mining is especially dangerous because of the weakness of coal beds and high concentrations of flammable gas and coal dust. In the decade before Congress established the U.S. Bureau of Mines in 1910, 2,000 persons died each year in coal-mining accidents in the United States alone. From 2006 to 2013, the average number of U.S. coal-mining fatalities was 30 per year. In comparison, during the same time period the average number of coal-mining fatalities in China was 2,653 per year. The most recent coal-mining accident in the United States that generated a lot of attention was the Upper Big Branch accident in 2010, which resulted in 29 deaths.

Once the coal is mined, it is shipped as raw rubble by train, barge, or freighter to power plants, foundries, smelters, and other distributors; little additional processing is needed to make it usable. When lightly burned, the most volatile ingredients in coal—particularly noxious sulfur fumes—escape to leave a new form of coal called *coke.* Coke releases more intense heat in a furnace than does ordinary coal, and it is hardly smoky at all. Because of these fortunate properties, it has become one of the most important substances in our industrial civilization, serving as the main fuel for producing steel in foundries. Without coke, our metals would be too brittle to use in building skyscrapers, bridges, and other infrastructure.

FIGURE 22.5

Mountaintop strip mined for coal in West Virginia. *Photo © Edmond Van Hoorick/Getty Images RF*

FIGURE 22.6

Coal miner working in a mine in West Yorkshire, England. *Photo by Monty Rakusen/Getty Images*

Coal has also been converted into liquid fuels. The South Africans and Chinese, in fact, are looking at their immense coal reserves as a potential source of future automobile fuels. Less-refined, liquefied coal—*slurry*—can be flushed through pipelines stretching up to several hundred miles from mine to factory or power plant.

Petroleum and Natural Gas

In recent years, an argument has raged between economists, who believe that abundant supplies of new petroleum can yet be discovered, and many resource geologists, who caution that most of the regions that contain "new" oil have already been explored and, in fact, are being rapidly depleted. Who is right? We won't know for sure until we complete global exploration and experience a peak in global petroleum production, but odds are that the geologists know something that many more optimistic business people don't: The geologic factors responsible for creating a rich petroleum reservoir are special indeed, and greatly limit the chances for petroleum to form under natural conditions.

Petroleum, and **natural gas,** like coal, are formed from the partially decayed remains of organic matter. The origin of petroleum and natural gas, however, differs significantly from that of coal. Instead of a coastal swamp, imagine well-lit coastal seawater, or a sparkling, tropical lagoon, light-green, with suspended microscopic life-forms including plankton, foraminifera, diatoms, and other organisms. These life-forms thrive continuously in waters well supplied with nutrients from upwelling marine currents and rivers entering the sea nearby. This type of marine environment is typically rich in oxygen, and dead organic matter is readily decayed before it can settle on the sea floor. Oil forms when rapid accumulation of mud and sand bury dead organic matter and separate it from the oxidized seawater. In this anoxic (oxygen-deprived) environment, the organic remains break down slowly. With continued accumulation of sediment, the organic remains are buried more and more deeply (Figure 22.7).

The buried hydrocarbons break down or "crack" into simpler molecules with increasing pressure and temperature as the organic-rich sediments are buried more and more deeply by continued sediment accumulation. Initially, chemical reactions with the clay minerals in the sediment produce a gooey, hydrocarbon-rich sediment known as *sapropel.* As it is buried deeper, the sapropel heats up, at a rate of 25°C for every thousand meters (44°F for every 1,000 feet). In order to form oil, the sapropel must be buried deeply enough for temperatures to reach 50° to 100°C—approximately 2,000–4,500 meters (6,500–13,000 feet). This is known as the oil window (Figure 22.7). At temperatures between 100°C and 200°C (200–400°F), the liquid petroleum will break down to natural gas. Beyond 200°C, the hydrocarbons will break down completely.

The result of this process is a petroleum-bearing **source rock,** such as oil shale. Once petroleum has formed, it must next accumulate in concentrations that can be drilled and pumped. Under deep-burial conditions, pressure easily squeezes the oil and gas up into overlying, permeable **reservoir rocks.** The upwelling petroleum may continue to migrate all the way to the surface to issue from the Earth as tar and oil seeps (*breas*) (Figure 22.8). The first uses of oil, in providing mortar for mud bricks in ancient Sumeria, exploited such sites.

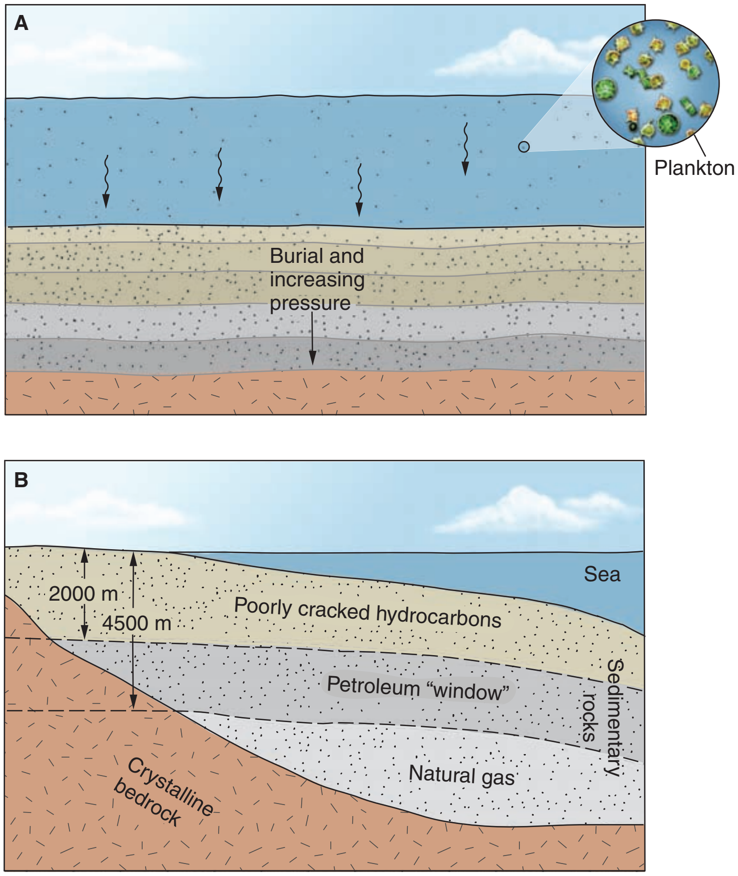


FIGURE 22.7

Formation of oil and typical depths of hydrocarbon cracking. (*A*) Remains of organisms collect on the sea floor and are buried by sediment. (*B*) The "oil window" lies between 2,000 and 4,500 meters (6,500–13,000 feet). Depth will vary somewhat, depending on the geothermal gradient.

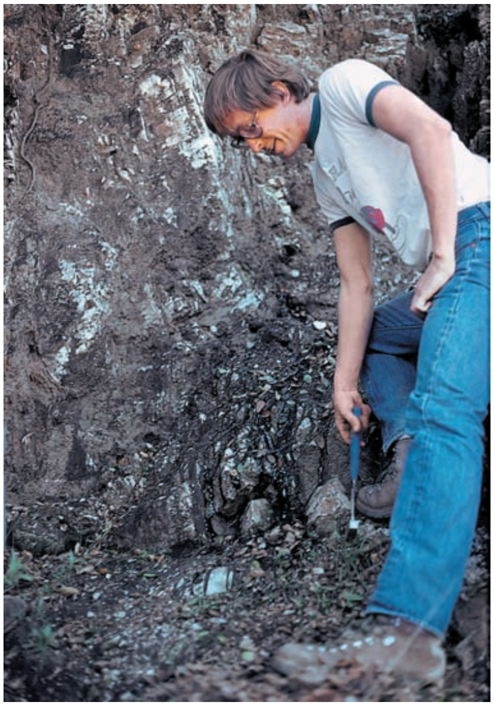
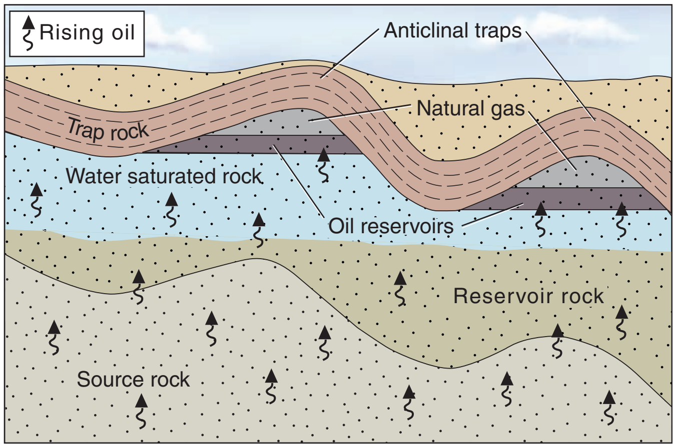


FIGURE 22.8

A brea, or natural oil seep, in a hill slope near Santa Paula, California. *Photo by Richard Hazlett*

Natural oil seeps do not concentrate enough oil, however, to be of interest in the modern economy. Instead, petroleum geologists look for places where upward-infiltrating oil has encountered a **structural (or oil) trap,** a place where impermeable rock (called "trap rock") prevents any further upward percolation of petroleum (Figure 22.9). Natural gas requires the same conditions as oil for accumulation, and drillers can never be quite certain how much natural gas they may encounter when they first begin exploiting a potential petroleum deposit. In fact, as you might suppose, some prospects yield up nothing but natural gas.



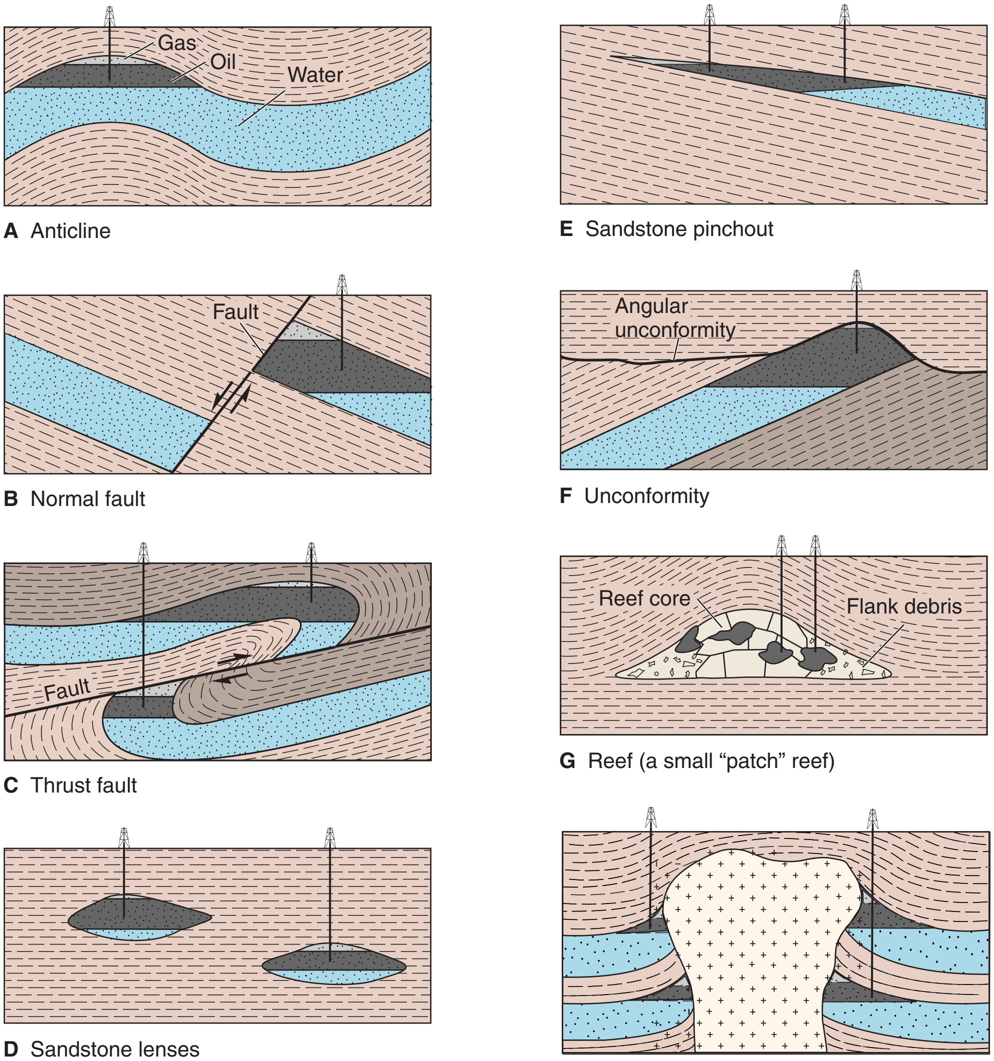
Accumulation of petroleum into reservoirs

FIGURE 22.9

Features related to petroleum reservoirs.

Figure 22.10 depicts several types of structural traps for oil and gas. Some types of traps are more abundant in particular regions than in others. For example, anticlines and domes (described in chapter 15) create the most common oil traps in the Persian Gulf; anticlines and faults are important trap-formers in southern California's oil field; and salt domes account for most of the petroleum reserve in the Gulf of Mexico. Where oil and water occur together in folded sandstone beds, the oil droplets, being less dense than water, rise within the permeable sandstones toward the top of the fold. There, the oil may be trapped by impermeable shale overlying the sandstone reservoir rocks. Because natural gas is less dense than oil, the gas collects in a pocket under fairly high pressure, on top of the oil. It is important to bear in mind that, as with aquifers, this layered pool of fluids does not fill a hollow underground chamber, like a flooded cave, but is merely *filling all of the pore spaces* in a highly permeable sedimentary rock (Figure 22.10).

As you can see, petroleum requires a set of very special circumstances in order for it to be found in large enough accumulations to be economically useful. The accumulation of organic matter requires a warm, tropical sea that can support large numbers of organisms. Rapid sediment accumulation is required in order for the organic matter to be buried and protected from decay in the highly oxygenated ocean waters. The hydrocarbon-bearing sediment must then be buried to just the right depth to turn the organic matter into oil or natural gas contained in a source rock. The upwelling petroleum must then encounter a porous and permeable layer in which it can become concentrated—the reservoir rock. An impermeable oil trap must exist in order to stop the petroleum from reaching the surface. This may involve tectonic



A Anticline

E Sandstone pinchout

B Normal fault

F Unconformity

C Thrust fault

G Reef (a small "patch" reef)

D Sandstone lenses

H Salt dome

FIGURE 22.10

Major types of petroleum traps. In all cases, impermeable rock encloses or caps the petroleum.

activity to fold or fault the rocks and produce trapping structures. The entire process requires millions of years. When you consider all of this, it is easy to understand why the world's petroleum is a finite resource and why geologists are unsure whether we will be able to continue to make new oil discoveries to meet the world's demand for petroleum products.

Oil is exploited by drilling down into an oil reservoir. **Oil fields** are regions underlain by one or more oil reservoirs. When a drill hole first penetrates an oil reservoir, pressurized natural gas within may drive the petroleum all the way to the surface so that no pumping has to be done. This "fluid-pressure effect" saves oil companies a tremendous amount of money and, in fact, may make all the difference between a successful drilling operation and one that needs to be abandoned. The celebrated gushers of many oil photos showing the discovery of new oil reservoirs illustrate the very high fluid pressures that gas may help generate in some deposits. With continued extraction, fluid pressure in the reservoir will diminish and an oil field becomes less economical to operate. Remaining oil may be flushed out of the ground by "flooding" the reservoir with injected groundwater. The groundwater drives the petroleum ahead of it from the area of injection wells toward oil wells for removal (Figure 22.11). Developers have also used steam to drive out the oil. As much as one-third of the original reserve in an oil field may be extracted using these *secondary recovery* methods.

One important consideration in operating an oil field is a factor called *energy return on energy invested (EROEI).* This is the ratio of the amount of energy extracted versus the amount of energy put into the extraction process. If it takes more energy to get petroleum out of the ground than is derived from the sale and consumption of that petroleum, then it is no longer worth operating the oil field. During the heyday of petroleum exploration in the 1940s, EROEI for newly discovered oil fields was typically around 100:1. Since then, less and less oil has been discovered, and the EROEI for a newly discovered oil field now is only 8:1 on average. The peak in global new discoveries occurred in the mid-1960s. Because of the surface tension effect in petroleum-bearing pores, and because oil drilling is increasingly taking place at greater depths or in more remote places (thanks to the exhaustion of older fields and rising global demand), mean global EROEI has declined. When it reaches 1:1, the industrial world will have to find a new energy source. Long before this happens, one would hope we will have turned to new energy technologies and a much different kind of civilization. One of the implications of EROEI is that we will never really run out of oil. However, it will become too expensive for us to continue exploiting oil in large quantities, perhaps within your lifetime.

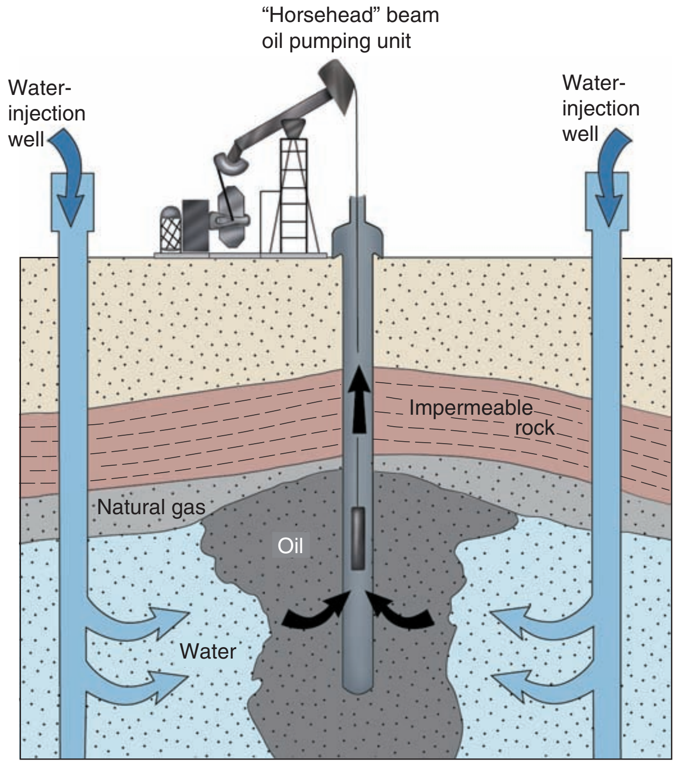


FIGURE 22.11

Water is often injected to drive additional, hard-to-get oil out of the ground.

Society demands a wide range of oil and gas products. Table 22.2 lists the various types of hydrocarbons that we artificially crack from oil delivered to refineries. In the early days of oil, from the late 1850s until around 1900, the sole product of interest was kerosene for lighting lamps. No more than about 40% of any barrel of oil pumped would go to market as this product. Since there was no use for the heavier compounds of oil, such as asphalt and diesel fuel, this material was often simply burned near the well, creating awful palls of smog. The lighter stuff, including gasoline, was often dumped in rivers and streams. Gases simply vented to the air, worsening the already severe environmental impact. Subsequent demand for oil products arose with the invention of the automobile and the conversion of the military forces to petroleum-based transport. Asphalt—essentially the dead bodies of countless, tiny marine organisms—ended up paving roads to minimize dust and facilitate high-speed driving. Kerosene became aviation fuel. Of the gasolines, octane (C_8H_{18}) proved best for performance (speed, power) in car engines and produced the least exhaust upon combustion. But because refineries have never been able to produce enough pure octane to meet demand, we have introduced substitutes ("reformulated fuels") to provide the same fuel services. Some of these substitutes (e.g., leaded fuels and MTBE—methyl tributyl alcohol) have proven to be costly environmental hazards. Highly complex hydrocarbons, such as polyethylene, end up in supermarket "plastic" bags. Indeed, from nylon and computer components to food production and pharmaceuticals, it is hard to see where petroleum products *aren't* used in the modern world.

Over 30% of the world's oil comes from exploitation of oil fields in the Middle East, much less than in the recent past. Although the two largest oil fields in the United States, in East Texas and Alaska (Figure 22.12) are in decline, the United States is currently experiencing an oil boom, which has decreased its dependency on foreign oil sources. This boom is the result of increased production of oil from oil-bearing shales (also referred

TABLE 22.2 Types of Cracked Petroleum-Related Hydrocarbons and Their Uses (Listed in Order of Increasing Complexity)

Name	Chemical Formula	Type of Hydrocarbon	Use
Methane	CH_4	Natural gas	Fertilizer manufacture; source of hydrogen for fuel cells
Ethane	C_2H_6	Natural gas	Fertilizer manufacture; source of hydrogen for fuel cells
Propane	C_3H_8	Gas condensates*	Cooking stoves, home heating, lanterns
Butane	C_4H_{10}	Gas condensates*	Cooking stoves, lanterns, lighters, home heating, soldering irons
Hexane	C_6H_{14}	Gasoline	
Heptane	C_7H_{16}	Gasoline	
Octane	C_8H_{18}	Gasoline	Isooctane, a form of octane, is the best kind of gasoline for internal combustion engines
Nonane	C_9H_{20}		
Decane	$C_{10}H_{22}$		

Successively Heavier Hydrocarbon Molecules:
1 Kerosenes and heating oils—aviation fuel, home heating
2 Diesel fuels—transportation fuel for trucks, trains, ships
3 Heavy crude oils ($C_{17}H_{36}$–$C_{22}H_{46}$)—lubricating and engine oils
4 Asphalts, waxes, greases, paraffins—paving, machinery lubricating
5 Plastics, polyethylene—computer frames, shopping bags, toys, CDs, etc.
*Also called “natural gas liquids,” “drip gases,” or “white gold”

FIGURE 22.12

Major oil fields in North America. The amount of oil in a field is not necessarily related to its areal extent on a map. It is also governed by the vertical “thickness” of the oil pools in the field. The fields with the most oil are in Alaska and east Texas. *From U.S. Geological Survey and other sources*

FIGURE 22.13

Drilling rig on Alaska's North Slope. *Photo by B. P. America, Inc.*

to as tight oil) in North Dakota and Montana through the use of horizontal drilling and hydraulic fracturing techniques. In addition, exploitation of unconventional oil sources such as oil sands and oil shale has increased. However, unless demand for oil decreases, the vision of a world scrambling to meet demand for a shrinking resource is an ominous portent of conflict. The peace and organization of human society are basically dictated by the choice of the resources we exploit.

While coal resources and reserves may be estimated or ascertained with reasonable confidence, geologists are less confident about the amount of petroleum in the world because it is more widely dispersed through the crust and difficult to locate. Current estimates of the world's recoverable oil reserves average approximately 1,650 billion barrels (a barrel contains 159 liters, or 42 gallons, of oil). At present, the world consumes 90 million barrels of oil every day, giving us approximately 50 years before the current reserve disappears. These numbers, however, do not take into account discoveries of new reserves or the increased size of reserves due to new technology. In addition, as you will read in the following sections, there are alternative sources of petroleum that, although less economical to exploit, are becoming more important as the reserves of light, easily recoverable oil are depleted.

The total resource, of course, is much larger than the reserve. Much of the resource however, is in difficult-to-reach localities under the sea floor or in subarctic settings (Figure 22.13). Exploration in these areas can lead to the degradation of sensitive ecosystems such as the subarctic or major environmental disasters such as the 2010 oil spill in the Gulf of Mexico (see box 22.2).

Natural gas *resources* are even more difficult to estimate. The Energy Information Agency estimates that there are approximately 70 trillion cubic meters (2,472 trillion cubic feet or tcf) of technically recoverable natural gas in the United States. Current U.S. levels of consumption amount to around 0.7 trillion cubic meters (25 tcf) per year, around 20% of the world's total—giving approximately 100 years of natural gas from domestic sources alone. Most natural gas comes from just five states: Texas, Louisiana, Wyoming, Oklahoma, and Colorado. Current U.S. *reserves* are estimated to be about 300 tcf, giving only 12 years of natural gas from domestic sources alone. Reserve estimates for natural gas in the western United States would certainly increase—though it's not known by how much—by opening certain public lands to gas extraction, including some national forests and monuments. This has made the further development of gas reserves a controversial issue.

It is much harder to transport natural gas than petroleum, requiring pipelines and LNG (liquid-natural gas) tankers for widespread distribution. Nevertheless, natural gas has become vital in the modern world. It is used to heat homes, cook food, make synthetic NPK (nitrogen-phosphorus-potassium) fertilizers for agriculture, produce electricity, and power fuel cells. In fact, the much-discussed "Hydrogen Revolution" may be launched thanks to cheap supplies of natural gas. Another bonus is that it is a less-polluting fuel than coal or petroleum, and has a high EROEI—from 10.2 to 6.3, depending on whether extraction is done from onshore wells or offshore.

Fracking

Recently, the United States has experienced a boom in oil and natural gas production, greatly reducing its reliance on foreign oil sources. This boom is the result of advances in horizontal drilling and hydraulic fracturing (commonly referred as *fracking*), which have increased our ability to exploit oil and gas trapped in low-permeability shale deposits. Hydraulic fracturing works by injecting a high-pressure mixture of water mixed with sand and chemicals into a well. The high pressure causes the rock to fracture, greatly increasing its permeability. Once the pressure is decreased, the sand grains injected with the water hold open the fractures, and any oil or gas present is able to migrate through these fracture pathways to the well. Due to its heavy use of water, and concerns about groundwater pollution, fracking is a controversial technique (see box 11.3).

Coal Bed Methane

Coal beds themselves may prove to be a major source of natural gas in the future. When coal forms, water and natural gas in the form of methane are trapped in the fine pores, pockets, and fractures that speckle and lace the interior of the coal. Pumping the water out lowers pressure and releases gas in huge quantities. Coal can store six to seven times more gas than an

ENVIRONMENTAL GEOLOGY 22.2

The Gulf of Mexico Spill—The Cost of Oil Exploration in Ever More Difficult-to-Reach Areas

On April 20, 2010, at approximately 9:45 P.M., a massive explosion caused by methane gas rising up from great depths engulfed the Deepwater Horizon drilling rig, killing eleven workers (box figure 1). The platform eventually sank after 36 hours. Almost a mile of drill pipe collapsed onto the sea floor. Oil rose from depths of almost 3.5 miles below the sea floor and began gushing from the broken pipe. Over the next three months, as engineers struggled to find a way to stop the leak, an estimated 4.9 billion barrels of crude oil gushed from the broken drill pipes on the sea floor—the largest marine oil spill in history (box figure 2). The spill impacted the ecology of the Gulf of Mexico, affecting marine creatures, birds, and the delicate ecosystems of the wetlands along the Gulf Coast. The economic impact on the fishing industry was enormous.

Although it has now been attributed to shortcuts taken by the drilling company and human error, this disaster highlights the enormous risks involved as we search for new sources of petroleum. One of the frontiers in oil exploration is deep-sea drilling—exploiting oil reservoirs that are not only buried deep in the Earth, but are also under great depths of ocean water. In the Gulf of Mexico, it is estimated that there are 60 billion barrels of oil beneath the sea floor, enough to supply U.S. demand for a decade. The Deepwater Horizon platform was drilling an exploratory well into the Macondo Prospect about 41 miles off the coast of Louisiana under 1,500 meters (5,000 feet—almost a mile) of water and about 5,500 meters (18,000 feet—almost 3.5 miles) of sediment. These conditions made containment of the spill very difficult for engineers who had to use deep-water submersibles to work due to the high pressures at such great depths. After a number of failed attempts, the spill was eventually halted on July 15, 2010, using a large containment cap lowered over the well head. It took until September 2010 to drill a relief well that intersected the original well and then to plug it by pumping in cement.

Four years after the Deepwater Horizon disaster, the environmental impacts of the spill are still being evaluated. A recent study of dolphins off the coast of Louisiana shows that as many as half of the dolphins exhibit signs of sickness and disease. Immediately following the disaster, the U.S. Department of the Interior ordered a six-month moratorium on offshore drilling, and the safety practices and emergency plans of oil companies were questioned. The number of new permits being issued drastically declined. However, offshore drilling accounts for over 20% of U.S. oil production, and with concerns about dependence on foreign oil, deep water drilling will most likely remain the next big frontier in oil production.

What do you think? Is exploration in ever deeper water worth the risk to the environment? How much risk is acceptable? Can deep-sea drilling ever truly be safe?

Additional Resources

- http://news.nationalgeographic.com/news/energy/2011/04/110420-gulf-oil-spill-anniversary/

This *National Geographic* site includes a number of interesting features on the oil spill and its effects.

- www.nature.com/news/2010/100901/full/467022a.html

This *Nature* article examines the ecological effects of the spill.

- www.bp.com

BP, the owners of the drill rig, have a series of items regarding the accident, their efforts to contain the spill, and the restoration effort. Click on the Gulf of Mexico Restoration link.

BOX 22.2 ■ FIGURE 1

Fire boat response crews battle the blazing remnants of the offshore oil rig Deepwater Horizon on April 21, 2010. *Photo: U.S. Coast Guard*

BOX 22.2 ■ FIGURE 2

NASA satellite image captures sunlight illuminating the oil slick off the Mississippi Delta on May 24, 2010. *Photo: NASA image by Jeff Schmaltz, MODIS Rapid Response Team* equivalent amount of rock in an ordinary natural gas field. A problem arises with respect to the water removed during pumping. Coal-water gets saltier the deeper the deposit, and disposal of salty water into surface watersheds seriously degrades water quality. Groundwater supplies may also be contaminated during gas extraction. In any event, there is a considerable amount of **coal bed methane** in the United States and, according to the Energy Information Administration, it accounted for 7.3% of U.S. natural gas production in 2011. The overall resource may exceed 20 trillion cubic meters (700 tcf), but only about 2.8 trillion cubic meters (100 tcf) is likely to be economically recoverable. The U.S. Geological Survey estimates that the total coalbed methane resource worldwide might be as high as 200 trillion cubic meters (7,500 tcf).

Heavy Crude and Oil Sands

Heavy crude is dense, viscous petroleum. It may flow into a well, but its rate of flow is too slow to be economical. As a result, heavy crude is left out of reserve and resource estimates of less viscous "light oil" or regular oil. Heavy crude can be made to flow faster by injecting steam or solvents down wells, and if it can be recovered, it can be refined into gasoline and many other products just as light oil is. Most California oil is heavy crude.

Oil sands (or **tar sands**) are bitumen-cemented sand or sandstone deposits. The bitumen is solid, so oil sands are often mined rather than drilled into, although the techniques for reducing the viscosity of heavy crude often work on oil sands as well.

The origin of heavy crude and oil sands is uncertain. They may form from regular oil if the lighter components are lost by evaporation or other processes. Oil sands and asphalt seeps at Earth's surface (such as the Rancho La Brea Tar Pits in Los Angeles) probably formed from evaporating oil. But some heavy crude and oil sands are found as far as 4,000 meters underground. Most have much higher concentrations of sulfur and metals, such as nickel and vanadium, than does regular oil. Some geologists believe that oil sands represent oil that arose from source rocks but never became trapped and concentrated by structural traps.

The best-known oil sand deposit in the world is the Athabasca Tar Sand in northern Alberta, Canada. Approximately 50% of Canada's present oil production comes from these oil sands. Counting this unconventional resource, this gives Canada the third-largest total oil reserves in the world, after Saudi Arabia and Venezuela. Oil-hungry countries such as the United States view these deposits with keen interest. Unfortunately, the EROEI of extracting petroleum from oil sands is substantially lower than that of conventional oil—close to 1:1 by some estimates. This is mostly due to the need to dilute the viscous heavy oil ("bitumen") to get it out of the sand. Natural gas, gas condensates, hot water, steam, and naptha (an aromatic solvent) are all used—and each of these flushing compounds is, in and of itself, an energy material or requires energy to produce.

The time-tested method of extracting the bitumen requires mining the ground directly. For every 2 tons of earth processed, only one barrel of oil can be made. Disposing of this material, not to mention dealing with environmental concerns such as natural habitat destruction and water pollution, has raised serious questions about the future of the industry. New technology more recently has allowed miners to extract the oil from deep underground without disturbing the surface. This process involves mixing the oil sands in place with hot water and then pumping the slurry through a pipeline to the processing plant. Questions of pollution and low EROEI remain, but this is a definite improvement, and it appears that the oil sand industry has established a firm future for itself in the world economy.

Oil Shale

Oil shale is a black or brown sedimentary rock with a high content of solid organic matter or *kerogen.* Oil shale, not to be confused with oil-bearing shale deposits, is both a source of oil and a fuel as it can be burned with little or no processing. Oil shale is formed in much the same way as conventional oil deposits, but the sapropel is not buried as deeply and doesn't reach the temperatures required for cracking the hydrocarbons into lighter fractions. The kerogen in oil shale is solid and, as a result, will not separate from the sedimentary rock. Thus, oil shales must be processed by distillation to convert the solid oil to an extractable substance.

Oil shale formations are found in many locations around the world. The largest are found in the United States. The best-known oil shale in the United States is the Green River Formation, which covers more than 40,000 square kilometers in Colorado, Wyoming, and Utah, with deposits up to 650 meters (2,100 feet) thick (Figure 22.14). The oil shale, which includes numerous fossils of fish skeletons, formed from mud deposited on the bottom of large, shallow Eocene lakes. The organic matter came from algae and other organisms that lived in the lake. The Green River Formation is estimated to contain up to 3 trillion barrels of oil, up to half of which may be recoverable, although this estimate has been disputed. Relatively low-grade oil shales in Montana contain another 180 billion barrels of recoverable oil in shale that should be economical to mine because of its high content of vanadium, nickel, and zinc.

FIGURE 22.14

Cliffs of oil shale that have been mined near Rifle, Colorado. *Photo by William W. Atkinson, Jr.*

Therefore, oil shale can supply potentially vast amounts of oil in the future as our liquid petroleum runs out.

A few distillation plants extract shale oil, but the current price for oil makes shale oil uneconomical. With oil prices increasing at such a high rate since 2000, the level of interest in oil shales has been increasing. Large-scale production of shale oil may be feasible in the future.

The mining of oil shale can create environmental problems. Mined oil shale is crushed prior to processing, which increases the volume of the rock. During distillation, the shale expands. This increase in volume creates a space problem—the solid by-products will take up more space than the hole from which they were mined. Spent shale could be piled in valleys and compacted, but land reclamation would be troublesome. A great amount of water is required, for both distillation and reclamation, and water supply is always a problem in the arid western United States. New processing techniques that extract the oil in place without bringing the shale to the surface may eventually help solve some of the problems and lower the water requirements. One method involves using heaters placed in deep holes to heat the oil in place. After one to two years, the surrounding rock has reached high enough temperatures for the oil to be fluid enough for extraction. All of the methods for underground extraction are currently viewed as experimental.

Uranium

The metal *uranium,* which powers nuclear reactors, occurs as uraninite (more commonly referred to as *pitchblende*), a black uranium oxide mineral found in hydrothermal veins, or, much more commonly in the United States, as yellow *carnotite,* a complex, hydrated oxide mineral found as incrustations in sedimentary rocks. Oxidized uranium is relatively soluble and easily transported by water. It precipitates in association with organic matter where bacterial activity reduced the oxygen.

Most of the easily recoverable uranium in the United States is found in sandstone in New Mexico, Utah, Colorado, and Wyoming, some of it in and near petrified wood. During the 1950s uranium boom, western prospectors looked for petrified logs and checked them with Geiger counters. Some individual logs contained tens of thousands of dollars worth of uranium. Some petrified logs have so much uranium that it would be dangerous to keep them as souvenirs. Most of the uranium, however, is in sandstone channels that contain plant fragments.

Organic phosphorite deposits of marine origin in Idaho and Florida also contain uranium. The uranium is not very concentrated, but the deposits are so large that, overall, they contain a substantial amount of uranium. The black Devonian shales of the eastern United States also contain uranium. These shales are really low-grade oil shales (Figure 22.14). Uranium may be recovered from phosphorites or shales as a by-product of another mining operation.

The principal use of uranium at present is to provide power for electricity-generating nuclear reactors, although uranium was also used to make tens of thousands of nuclear warheads during the Cold War. Some naval craft use uranium to power ship-borne nuclear engines, but concerns about accidents and radioactive pollution greatly limit expansion of this form of transportation. At present, 100 nuclear reactors produce approximately 20% of the energy needs of the United States. France is the industrialized nation most dependent upon nuclear power, which generates over 75% of its electricity. However, the problems at Fukushima in Japan following the 2011 earthquake (see box 22.3) have led many countries to reduce their nuclear power production, and France is now planning on reducing its nuclear power production by a third over the next 20 years.

Electricity is generated in nuclear power plants in much the same way as in coal-fired plants. The fuel (in this case, uranium) is used to boil water which generates steam which, in turn, powers turbines which generate electricity. Unlike coal, the heat generation in a nuclear power plant does not come from burning the fuel but from a process called **fission.** Fission is the splitting apart of the nucleus of an atom into lighter components such as the nuclei of lighter atoms and neutrons. When a heavy element is split apart (or fissioned), this process also generates heat.

In chapter 8, we discussed isotopes and radioactivity. Uranium has three natural isotopes, all of which are unstable. Uranium-238 (^{238}U) is the most stable and the most abundant, making up 99.8% of all uranium isotopes. Uranium-235 (^{235}U) and uranium 234 (^{234}U) are less abundant (0.7% and 0.005%, respectively). ^{235}U is the most important isotope of uranium as it is the only one known to be fissile—that is, it can be split apart when bombarded by neutrons. To be useful in a nuclear reactor, the uranium minerals must be processed to concentrate the unstable isotope uranium-235 (^{235}U), the main reactor fuel. Only 0.7% of the mass of natural uranium consists of ^{235}U. The refining of uranium ore to concentrate ^{235}U requires considerable amounts of energy, metals, and other resources.

Once processed, the ^{235}U goes into *fuel rods,* which are inserted into the cores of nuclear reactors (Figure 22.15). A reactor core consists of a *containment vessel,* or reservoir, lined

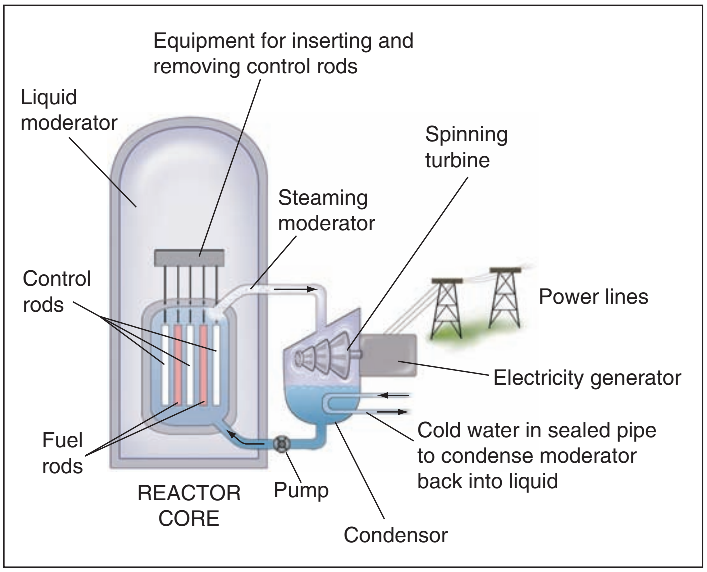


FIGURE 22.15

Basic design of a nuclear reactor. This shows operation of a BWR- (boiling water) type reactor, the simplest design.

ENVIRONMENTAL GEOLOGY 22.3

The Nuclear Crisis in Japan—The Future of Nuclear Power Put to the Test

The magnitude 9.0 earthquake and tsunami that hit eastern Japan on March 11, 2011, was devastating. Entire coastal towns and villages were destroyed, leaving hundreds of thousands of people homeless. As of 2012, the official death toll was 15,854 with another 3,203 missing. The disaster also caused a nuclear crisis that has global implications for the future of nuclear power.

Nuclear power has been viewed as a way to reduce reliance on foreign sources of fossil fuels, but there are many risks associated with nuclear reactors that have been highlighted by the events in Japan. Prior to the earthquake and tsunami, Japan relied on nuclear power for 30% of its electricity and had plans to expand its nuclear capacity to 50% by 2030. Located in a region known for powerful earthquakes and tsunami, the Fukushima Daiichi plant was designed with many safety features. When the earthquake hit, the plant's electricity was cut off, but backup generators quickly kicked in and began an emergency shutdown of the active reactors. Cooling systems pumping water around the fuel rods kept the reactors from overheating. One hour later, a 14-meter (46-foot) tsunami reached the plant, which was protected by a seawall. Unfortunately, while planners had assumed a 10-meter seawall would provide adequate protection against tsunami, they did not anticipate an event of this magnitude or the 1-meter drop in elevation of the coast caused by the massive earthquake. The seawall was easily overtopped by the massive wave. Water flooded the facility and disabled the backup generators, which were all located at or below ground level. All power was lost, and without cooling water circulating through them, the reactors began to overheat and partially melt down. In the following weeks, efforts to get the reactors under control were hampered by explosions and fires as well as flooding with radioactive water (box figure 1). Spent fuel rods stored in pools in each reactor building also began to overheat as water levels in the pools dropped. It took months to fully stabilize the plant, and it could take decades to remove the melted core material and complete a cleanup of the area.

BOX 22.3 ■ FIGURE 1

Smoke from the damaged Fukushima Daiichi nuclear plant in Okuma, Japan. *Photo © DigitalGlobe via Getty Images*

Radiation leaked from the plant as a result of explosions, planned steam releases to relieve pressure in the reactors, and discharge of coolant water into the sea. The Japanese government evacuated people living within 30 km (18 miles) of the plant (box figure 2). Radiation was detected in milk and food produced in the area as well as in water in Tokyo. Trace amounts of radiation were observed around the world, although the levels were extremely low and were not considered to pose any threat. Cleanup efforts continue as of this writing at Fukushima and will likely take decades to complete. Of grave concern is the continued leak of radioactive waters into the ocean and the groundwater.

The crisis at Fukushima caused many countries to reconsider the benefits of nuclear power. Japan is moving to reduce its dependence on nuclear energy. Germany made a decision to close the last of its seventeen nuclear reactors. The Swiss government also recommended phasing out its nuclear power plants. Italy put an indefinite hold on plans to build new power plants. France, which currently relies on nuclear power for 75% of its electricity, recently announced plans to cut nuclear output by a third in 20 years. In the United States, plans to expand nuclear power capacity may be slowed or even halted.

What will be the implications of a worldwide decrease in nuclear power production? Without a decrease in demand for energy, it will most likely lead to increased reliance on fossil fuels like coal and oil. What will be the impact on the climate of increased use of carbon-based fuel? How do we weigh the risk of a nuclear disaster against long-term climate change?

Additional Resources

- www.iaea.org/newscenter/focus/fukushima/

The International Atomic Energy Agency has set up a special site focused on the Fukushima nuclear accident.

- http://news.nationalgeographic.com/news/energy/2011/03/ 1103165-japan-nuclear-chernobyl-three-mile-island/

This article by *National Geographic* compares the disaster in Japan to the accidents at Chernobyl and Three Mile Island.

- http://news.nationalgeographic.com/news/energy/2011/03/ 110314-japan-nuclear-power-plant-disaster/

Another article by National Geographic

BOX 22.3 ■ FIGURE 2

A man being screened for radiation exposure. *Photo © AP Photo/Gregory Bull* with steel and concrete to protect outsiders from harmful radiation. The vessel is filled with a fluid called a *moderator,* usually water. Each fuel rod is about the size of an automobile, but because of the high atomic weight of its constituent materials, weighs around 30,000 kilograms (65,000 pounds). It contains only about 2–3% ^{235}U (most of the uranium is harmless ^{238}U).

As the nucleus of a ^{235}U atom disintegrates, heat and neutrons escape and the uranium atom transforms into daughter nuclei. These, in turn, produce more neutrons through radioactive decay. The escaping neutrons may be slow-moving or fast. The slower neutrons penetrate the nuclei of neighboring ^{235}U atoms, triggering their decay as well and, in short order, a full, heat-generating chain reaction is underway. The moderator fluid helps to slow the neutrons, thus stimulating the chain reaction even further. The fluid also gets very hot, reaching the boiling point and generating steam to drive turbines for electricity. (In some nuclear reactors, the moderator is passed through a heat exchanger to boil a secondary supply of water for the turbines. This keeps radioactivity out of the turbines.)

To control the nuclear reaction, *control rods* made of carbon, or cadmium (which is quite poisonous) must be inserted into the moderator. These soak up neutrons and can stop a chain reaction altogether. Careful manipulation of control and fuel rods brings a reactor to just the right level of heat production for energy-generation purposes. Nuclear accidents may take place if this balance in control is lost (box 22.3).

There are tremendous environmental problems associated with the disposal of fuel rods once their ^{235}U has depleted. A typical fuel rod has a service lifetime of only about three years. Even though most of its ^{235}U may be gone, neutrons released during a chain reaction will transform ^{238}U into deadly plutonium-239 (^{239}Pu). Spent fuel rods, hence, are quite dangerous. Temporary storage of used fuel rods takes place in a pool near the reactor core at a plant site. Later, the spent rods may be transported and reprocessed to extract the ^{239}Pu for nuclear weapons development. This is a special concern for persons who monitor nuclear proliferation—"rogue states" that have built nuclear reactors, ostensibly for "peaceful purposes," can easily create the fuel to build nuclear weapons. The ^{239}Pu may also be used as a fuel in a different kind of reactor, a *breeder reactor,* which greatly enhances the ability of uranium to produce energy. Full conversion of nuclear reactors to breeder designs could extend the effective uranium reserve lifetime sixty-fold at current consumption rates, providing the world with electricity for several millennia to come. Breeder reactors, unfortunately, have notably higher potential for disastrous accidents. The moderator in conventional breeder reactors, liquid sodium, is very sensitive and explosive, and reactor core blasts into the kiloton range are possible.

Spent fuel rods and other nuclear waste, particularly ^{239}Pu, must be stored someplace out of contact from people for a long period of time—as long as 250,000 years. Many proposals have arisen to do this, including "science-fiction" scenarios that require shooting this deadly waste into the sun or placing it in subduction zones. In the United States, the proposed "permanent" waste repository was Yucca Mountain, located in southern Nevada. The nation's reactor waste was to be housed in welded pyroclastic rocks nearly 300 meters (1,000 feet) underground. The rocks contain zeolite minerals, which are natural sponges that absorb escaping radioactivity. The proposed Yucca Mountain site was controversial however, and in 2010 the plan was scrapped. In Scandinavia, a similar repository stores nuclear wastes in a granite bedrock vault underneath the Baltic Sea. The advantage of this site is that any escaping waste will remain confined in saline groundwater beneath the ocean floor, rather than infiltrate water supplies tapped by people on surrounding lands. Many other waste facilities have been established, but it is beyond the scope of this book to consider them all. In all cases, they involve the shallow, underground storage of nuclear materials.

Expensive refining of uranium ore and high costs of building and shutting down power plants contribute to the rather moderate EROEI level of nuclear power—around 5. In all, about 65,000 tons of uranium ore must be produced every year to satisfy the needs of the world's 436 nuclear reactors, which supply about 12% of the world's total energy needs. Present world reserves of uranium (at about $115 per kilogram of uranium) are around 5.5 million tons. Canada is currently the largest producer of uranium in the world. Some of the world's largest reserves are located in Australia and Kazakhstan. Reserves at current consumption rates would last about eighty years. The size of the total uranium resource is unknown given incomplete exploration and the wide dispersion of uranium-bearing minerals, even in ordinary rocks such as granite. In any case, it is likely that the largest, most accessible uranium deposits have already been identified and are undergoing exploitation.

Renewable Energy Sources

Some energy resources are unquestionably renewable and easily tapped. These include solar, wind, wave, tidal, and hydroelectric power. Geothermal energy is also regarded as a renewable energy source. Together they provide the world with as much as 20% of its electricity. At present, the growth in renewable electricity supply is about 5% per year.

Unlike fossil fuels, which require huge industries to mine, transport, and distribute to users, solar and wind power can be generated locally—even in a backyard or atop the roof of one's own home. The development of solar and wind power is stimulating a transformation from highly centralized power production to much more distributed, smaller-scale, "neighborhood-scale" sources of power.

Geothermal Energy

Geothermal energy is heat energy from beneath the Earth's surface. The word *geothermal* comes from the Greek words *geo* (earth) and *therme* (heat). There is an enormous amount of heat escaping from the Earth's interior every day. In the upper 10 kilometers of Earth's surface within the United States alone, there is the heat equivalent of 1,000 trillion tons of coal—enough energy to satisfy the country's needs for 100,000 years! But in most locations it would take an area about the size of a football field to provide the escaping heat energy needed to power a single 60-watt, high-efficiency (20%) light bulb.

In some parts of the world, however, there are areas of unusually high heat flow around young, cooling plutons and volcanic areas that can be exploited for energy development. The temperature of the crust in these areas rises to as high as 350°C or more at depths of 1 to 3 kilometers—enough to turn groundwater into steam if it is pumped all the way to the surface. (Water under great pressures will not boil.) The escaping steam, in turn, can be channeled into turbines to generate electricity. If the hot groundwater occurs in a confined aquifer, so much the better; the groundwater will require little, if any, effort to extract as high fluid pressure drives it surfaceward through boreholes.

Geothermal energy is used to generate electricity in over twenty nations worldwide. In Iceland (Figure 22.16), geothermal energy accounts for 25% of all electricity needs (the remaining 75% is produced using hydroelectric power) and 90% of all heating needs. The world's largest geothermal power plant is at the Geysers in the Coast Ranges of northern California. This 750-megawatt facility provides the energy needs for 750,000 people, though its level of production has been declining steadily since 1980. The most important reason for this is that groundwater supplies are withdrawn faster than nature can replenish—and reheat—them. Water is an excellent natural carrier of heat energy. Dry rock acts as an insulator, or a slow conductor of heat. In areas where the groundwater supply has been depleted, or where there is not much groundwater due to arid climate conditions, water can be injected into hot, dry rocks, and artificial fracturing of these rocks can create reservoir space for a considerable volume of water. At the Geysers, 34 million liters (9 million gallons) of treated wastewater, carried through a 66-kilometer (41-mile) underground pipeline from the town of Santa Rosa, is injected into the ground every day. This water maintains the pressure in the aquifer, stabilizing the energy production level from the field.

Even where water is recycled by pumping it directly back into the Earth after passing through turbines, costs of operating a geothermal power plant can be quite high. Hot groundwater often carries with it dissolved minerals and acids that corrode metal pipes and turbines or clog them with precipitated minerals. Maintenance costs to keep a plant in operation may be prohibitive for this reason alone. Furthermore, there is a cost involved in scrubbing and purifying vapors that may contain natural contaminants. Despite all of these limitations, energy production from geothermal power is on the whole quite competitive with that of fossil fuels. EROEI levels as high as 13 exist, and for lightly populated regions such as Iceland and New Zealand, there is great incentive to develop geothermal energy rather than import oil or build nuclear reactors. The world production of geothermal power provides over 11,000 megawatts of electricity—equivalent to that of around twenty-four conventional nuclear reactors. In some nations, including parts of the United States, geothermal waters provide heat as well as electricity. The hot water passes through pipes and walls to warm home interiors, and can even be used directly in showers and taps. In Iceland, instead of turning on the hot water tap and waiting for it to run hot, you can find yourself turning on the cold water tap and waiting for it to run cold!

Because groundwater and geothermal heat are considered to be renewable resources, geothermal energy is technically a renewable energy resource. However, it is important to point out that if heated groundwater is drawn from the ground at a faster rate than it can be replenished and heated, then this energy resource can be regarded as nonrenewable.

FIGURE 22.16

A geothermal station about 50 kilometers to the east of Reykjavik, Iceland, extracts hot groundwater heated by shallow magma intrusions and pumps it to Reykjavik for commercial and residential use. *Photo by Richard Hazlett*

Solar Energy

The Sun's energy drives many of Earth's systems, including the hydrologic cycle, the winds, and the ocean currents. The amount of energy provided by the Sun is vast, amounting to as much energy in an hour as humans use in a year. However, the Sun's energy is diffuse, and harnessing it efficiently is a major challenge to widespread use of solar power.

Solar energy must be concentrated to produce heat or electricity. Three strategies for using solar energy are *passive, active,* and the use of *photovoltaic cells* to generate electricity. **Passive solar heating** can be achieved by including large Sun-facing windows and efficient insulation in a building's design. **Active solar heating** uses solar panels to heat water which can be used to provide hot water and space heating. The solar panels consist of a black surface beneath a glass panel. The Sun's energy is absorbed by the black surface, which heats up. Water passed through the panel will be heated and can then be stored in a central hot water tank. **Photovoltaic cells** (Figure 22.17) convert sunlight directly into electricity. The cells are made of thin wafers of silicon that has been doped with other elements to form an electric field. One side is treated with an element that will produce electrons, the other is treated with an element that will capture electrons. When sunlight hits the wafer, electrons are able to travel from one side to the other, producing an electrical current. Photovoltaic cells are still relatively inefficient, converting only 10–15% of the Sun's energy into electricity, and the cells are expensive to produce. New technologies may increase this efficiency in the future, with estimated EROEIs around 30.

FIGURE 22.17

Photovoltaic cells convert sunlight directly into electricity. *Photo © Corbis RF*

Wind Power

Winds are generated by the Sun. The energy of the wind has been harnessed by humankind for many years in the form of windmills. Today, modern wind turbines are used to generate electricity. The wind turns the blades on a turbine that is connected to a generator that produces electricity. Wind turbines must be placed in an area with constant strong winds—and, to generate large amounts of electricity, hundreds of turbines are needed. These fields of turbines, such as the one at Altamont Pass in California, are called wind farms (Figure 22.18).

The Danish government, which has invested heavily in developing wind power for its national energy supply, estimates that EROEI may climb as high as 50 in harvesting the strong sea breezes of that country. Currently, wind power produces only about 2.5% of the world's energy use; in Denmark, wind power accounts for 21% of energy production.

Hydroelectric Power

Hydroelectric power facilities transform gravitational energy in the form of falling water into electrical energy. Most hydroelectric power stations lie at the foot of dams, where water spilling from reservoirs into rivers downstream spins turbines. These stations produce electricity somewhat more cheaply than fossil fuels (EROEI is around 100), especially in regions where oil, coal, or gas has to be imported from afar. Downstream bank erosion, disruption of fish migrations, the flooding of land, and displacement of populations by filling reservoirs are major environmental concerns.

Hydroelectric power is by far the largest of the developed renewable energy resources at present, accounting for 84% of all renewable electricity production. Hydropower provides 2.8% of the energy and 7% of the electricity consumed in the United States today. It can be generated locally; a small station placed on a creek or stream can provide the power needs of a home, farm, or ranch. Hydropower does not directly produce any air pollution, and can even be tapped during times of low energy demand to recycle water back upriver by pumping into reservoirs.

Tidal Power

Tidal power is a variation of hydropower. A barrier, called a *barrage,* must be constructed across the mouth of an estuary or bay (Figure 22.19). Gates in the barrage allow water to pass through as the tide rides, spinning turbines to produce electricity. The gates close when the tide is in, capturing the water inshore from the barrage. The gates reopen after the tide falls on the seaward side, and the water pouring out spins the turbines again in reverse.

The world's largest tidal-generating station, at Rance in France, generates 320 megawatts, enough to supply several hundred thousand users. High costs; concerns about impacts on fish, bird life, and ecosystem health; and irregular power supply have greatly impeded development of tidal mills elsewhere

FIGURE 22.18

Altamont Pass Wind Farm, California. *Photo by Doug Sherman*

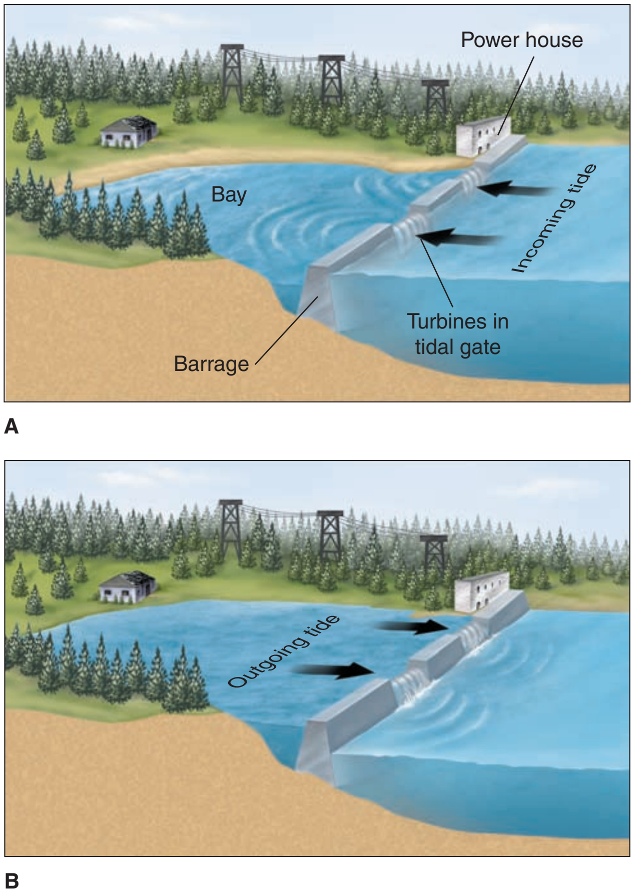


FIGURE 22.19

Generation of tidal power.

in the world. In fact, only six countries at present—France, China, Russia, South Korea, Northern Ireland, and Canada—have tidal power facilities.

Wave Power

Wave power is often confused with tidal power. Instead of capturing the energy of the tides, wave power captures the energy held in waves. This energy is a combination of kinetic energy and potential energy. The energy is transferred from the wind to the surface of the ocean. The technology to harness wave energy is still mostly experimental, and there are a number of different devices that work in different ways. One device consists of a segmented tube floating on the surface. As the wave passes along the length of the tube, the different segments move up and down relative to each other. The resistance between them is used to pump oil though hydraulic motors, which in turn drive electrical generators. Electricity is then fed to a cable that is connected to land.

Wave power does not contribute much to the world's energy needs and, to date, there are only a couple of wave farms in production or in development. The world's first commercial wave farm opened in 2008 off the coast of Portugal. It consists of three 140-meter-long segmented tubes that can generate 2.25 megawatts of energy, enough to supply the annual needs of 1,500 homes. Another wave farm is currently being developed off the coast of southwest England. In the United States, small wave-energy projects, using different technologies, are being tested off New Jersey and Hawaii, with another project being planned for Oregon.

Biofuels

Biofuel is defined as fuel derived from biologic matter. It differs from fossil fuels in that the biologic matter is recently dead. In recent years, interest has increased in the use of plant matter to produce fuel. The two most commonly used types of biofuel are ethanol and vegetable oil. Ethanol is generated by yeast fermentation from plants that contain a lot of sugar (sugar cane) or starch (corn). Vegetable oil comes from plants such as soybeans that produce a lot of oil. The oil can be used to fuel a diesel engine, or can be processed to form biodiesel. Although the production of biofuels does produce the greenhouse gas carbon dioxide, this is offset by the uptake of carbon dioxide by the plants grown to produce the fuel.

One of the problems associated with the increased use of biofuels is the competing demands for food and fuel. A World Bank report released in 2008 suggested that biofuels may have contributed to world food price increases. As demand for alternative fuel sources continues to rise, the "fuel vs. food" debate is likely to intensify.

METALLIC RESOURCES

Modern industrial society stands upon two feet—one of fossil fuels and the other of metal. While civilizations have always had access to basic construction materials—and always will—the production of high-quality, high-strength metals and the exploitation of fossil fuels make our times stand out in all of human history. Table 22.3 shows common metallic resources and some of their uses.

The successful search for metals depends on finding **ores,** which are naturally occurring materials that can be profitably mined (table 22.3). It is important to recognize that the local concentration of a metal must be greater (usually much greater) than its average crustal abundance to be a potential ore body. Metals must be concentrated in a particular place in a large enough amount to be viable ore bodies. Take gold in seawater. You could become fabulously wealthy if you could extract a fraction of the gold in seawater. There are over 10^{11} troy ounces of gold—around $52 trillion worth in the world's oceans. But the concentration is 4 grams per 1 million tons of water. It would cost you far more to remove that gold than you could sell it for.

Whether or not a mineral (or rock) is considered a metal ore depends on its chemical composition, the percentage of extractable metal, and the market value of the metal. The mineral hematite (Fe_2O_3), for example, is usually a good *iron ore* because it contains 70% iron by weight; this high percentage is profitable to extract at current prices for iron. Limonite ($FeO(OH) \cdot nH_2O$) contains less iron than hematite and, hence, is not as extensively mined. Even a mineral containing a high

TABLE 22.3 Common Metallic Resources

Ore Minerals and Their Uses

Metal	Ore Mineral	Composition	Uses
Aluminum	Bauxite	$AlO(OH)$ and $Al(OH)_3$	Manufacture of beer and soft drink cans, airplanes, electrical cables
Chromium	Chromite	$FeCr_2O_4$	Essential ingredient in stainless steel, coating on automobile parts
Copper	Native copper	Cu	Electrical wire and equipment, production of brass
	Chalcocite	Cu_2S	
	Chalcopyrite	$CuFeS_2$	
Gold	Native gold	Au	Coins, jewelry, dentistry, electronics
Iron	Hematite	Fe_2O_3	Essential ingredient of steel
	Magnetite	Fe_3O_4	
Lead	Galena	PbS	Batteries
Manganese	Pyrolusite	MnO_2	Alloy in steel
Mercury	Cinnabar	HgS	Thermometers, silent electrical switches, batteries
Nickel	Pentlandite	$(Fe,Ni)S$	Important alloy in steel
Silver	Native silver	Ag	Coins, tableware, jewelry, photographic film
	Argentite	Ag_2S	
Tin	Cassiterite	SnO_2	Solder, anti-corrosion plating, bronze
Zinc	Sphalerite	ZnS	Galvanized steel, brass

TABLE 22.4 Some Ways Ore Deposits Form

Type of Ore Deposit	Some Metals Found in This Type of Ore Deposit
Crystal settling within cooling magma	Chromium, iron
Hydrothermal deposits (contact metamorphism, hydrothermal veins, disseminated deposits, hot-spring deposits)	Copper, lead, zinc, gold, silver, iron, molybdenum, tungsten, tin, mercury, cobalt
Pegmatites	Lithium, rare metals
Chemical precipitation as sediment	Iron, manganese, copper
Placer deposits	Gold, tin, platinum, titanium
Concentration by weathering and groundwater	Aluminum, nickel, copper, silver, uranium, iron, manganese, lead, tin, mercury

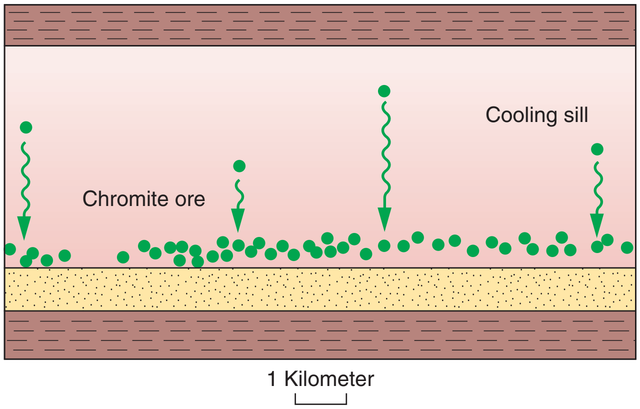


FIGURE 22.20

Early-forming minerals such as chromite may settle through magma to collect in layers near the bottom of a cooling sill.

percentage of metal is not described as an *ore* if the metal is too difficult to extract or the site is too far from a market; profit is part of what defines an ore.

Many different kinds of geologic processes can accumulate ores, from weathering and sedimentation to the settling of crystals deep within magma chambers (table 22.4). We'll survey the possibilities, moving from the Earth's interior to the surface, in the pages that follow. In all cases, note that people mined ore minerals long before we understood how they form. The field of *economic geology* developed, in large part, to study the origin of ore deposits and to expand our ability to locate and develop new reserves more easily.

Ores Formed by Igneous Processes

Crystal Settling

Crystal settling occurs as early-forming minerals crystallize and settle to the bottom of a cooling body of magma (Figure 22.20). This process was described under differentiation in chapter 3. The metal chromium comes from chromite bodies near the base of sills and other intrusions. Most of the world's chromium comes from a single intrusion, the huge Bushveldt Complex in South Africa. In Montana, another huge Precambrian sill called the Stillwater Complex contains similar, but lower-grade deposits.

Hydrothermal Fluids

Hydrothermal fluids, also discussed in chapter 7, are the most important source of metallic ore deposits other than for iron and aluminum. The hot water and other fluids are part of the magma itself, injected into the surrounding country rock during the last stages of magma crystallization (Figure 22.21). Atoms of metals such as copper and gold, which do not fit into the growing crystals of feldspar and other minerals in the cooling pluton, are concentrated residually in the remaining water-rich magma. Eventually, a hot solution, rich in metals and silica (quartz is the lowest-temperature mineral on Bowen's reaction series), moves into the country rock to create ore deposits. Most hydrothermal ores are metallic sulfides, often mixed with quartz. The origin of the sulfur is widely debated.

A magma body or hot rock may heat groundwater and cause convection circulation. This water may mix with water given off from solidifying magma, or it may leach metals from solid rock and deposit metallic minerals elsewhere as the water cools. However the hydrothermal solutions form, they tend to create four general types of hydrothermal ore deposits: (1) contact metamorphic deposits, (2) hydrothermal veins, (3) disseminated deposits, and (4) hot-springs deposits.

Contact metamorphism can create ores of iron, tungsten, copper, lead, zinc, silver, and other metals in country rock. The country rock may be completely or partially removed and replaced by ore (Figure 22.22*A*). This is particularly true of limestone beds, which react readily with hydrothermal solutions. (The metasomatic addition of ions to country rock is described in chapter 7.) The ore bodies can be quite large and very rich.

Hydrothermal veins are narrow ore bodies formed along joints and faults (Figure 22.22*B*). They can extend great distances from their apparent plutonic sources. Some extend so far that it is questionable whether they are even associated with plutons. The fluids can precipitate ore (and quartz) within cavities along the fractures and may replace the wall rock of the fractures with ore. Hydrothermal veins (Figure 22.23) form

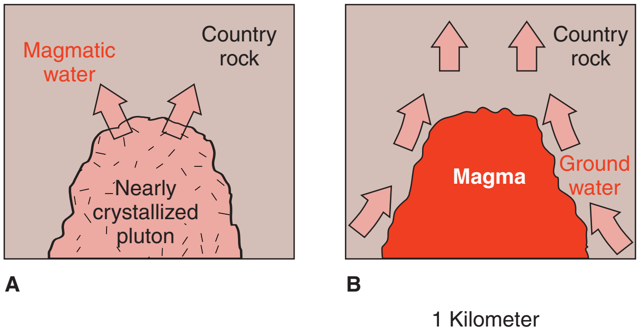


FIGURE 22.21

Two possible origins of hydrothermal fluids. (*A*) Residually concentrated magmatic water moves into country rock when magma is nearly all crystallized. (*B*) Groundwater becomes heated by magma (or by a cooling solid pluton), and a convective circulation is set up.

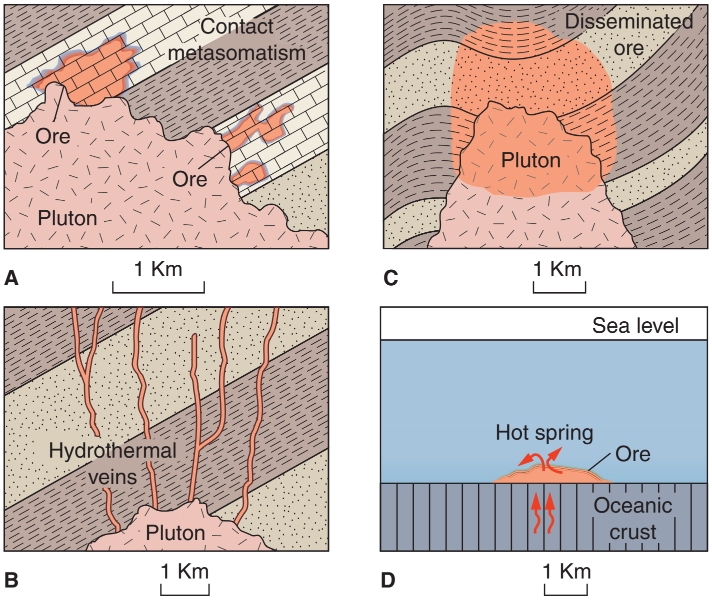


FIGURE 22.22

Hydrothermal ore deposits. (*A*) Contact metamorphism in which ore replaces limestone. (*B*) Ore emplaced in hydrothermal veins. (*C*) Disseminated ore within and above a pluton (porphyry copper deposits, for example). (*D*) Ore precipitated around a submarine hot spring (size of ore deposit is exaggerated).

FIGURE 22.23

Hydrothermal quartz veins in granite. *Photo by David McGeary* most of the world's great deposits of lead, zinc, silver, gold, tungsten, tin, mercury, and, to some extent, copper.

Hot solutions can also form *disseminated deposits* in which metallic sulfide ore minerals are distributed in very low concentration through large volumes of rock, both above and within a pluton (Figure 22.22*C* and box 22.4). Most of the world's copper comes from disseminated deposits (also called *porphyry copper deposits* because the associated pluton is usually porphyritic). Along with the copper are deposited many other metals, such as lead, zinc, molybdenum, silver, and gold (and iron, though not in commercial quantities).

Where hot solutions rise to Earth's surface, *hot springs* form (see chapters 11 and 18). Hot springs on land may contain large amounts of dissolved metals. More impressive are hot springs on the sea floor (Figure 22.22*D*), which can precipitate large mounds of metallic sulfides, sometimes in commercial quantities (chapters 7 and 19).

Pegmatites (see box 3.1), very coarse-grained plutonic rocks, are another type of ore deposit associated with igneous activity. They may contain important concentrations of minerals containing lithium, beryllium, and other rare metals, as well as gemstones such as emeralds and sapphires.

Ores Formed by Surface Processes

Chemical precipitation in layers is the most common origin for ores of iron and manganese. A few copper ores form in this way, too. Banded iron ores, usually composed of alternating layers of iron minerals and chert, formed as sedimentary rocks in many parts of the world during the Precambrian, apparently in shallow, water-filled basins (Figure 22.24). Later folding, faulting, metamorphism, and solution have destroyed many of the original features of the ore, so the origin of the ore is difficult to interpret. The water may have been fresh or marine, and the iron may have come from volcanic activity or deep weathering of the surrounding continents. The alternating bands may have been created by some rhythmic variation in volcanic activity, river runoff, basic water circulation, growth of organisms, or some other factor. Since banded iron formations are all Precambrian, their origin might be connected to an ancient atmosphere or ocean chemically different from today's.

Placer deposits in which streams have concentrated heavy sediment grains in a river bar are described in chapter 10. Wave action can also form placers at beaches. Placers include gold nuggets and dust, native platinum, diamonds, and other gemstones, and worn pebbles or sand grains composed of the heavy oxides of titanium and tin.

Ore deposits due to *concentration by weathering* were described in chapter 5. Aluminum (in bauxite) forms through weathering in tropical climates.

Another type of concentration by weathering is the *supergene enrichment* of disseminated ore deposits. Through supergene enrichment, low-grade ores of 0.3% copper in rock can be enriched to a minable 1% copper. The major ore mineral in a disseminated copper deposit is chalcopyrite, a copper-iron sulfide containing about 35% copper. Near Earth's surface, downward-moving groundwater can leach copper and sulfur from the ore, leaving the iron behind (Figure 22.25). At or below the water table, the dissolved copper can react with

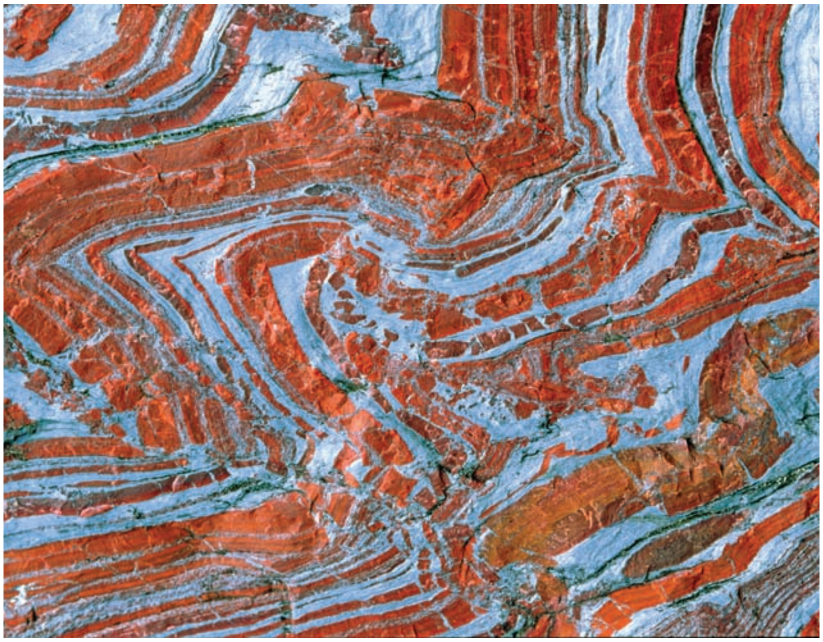


FIGURE 22.24

A 2.1 billion-year-old banded iron formation from Michigan. *Photo © Doug Sherman/Geofile*

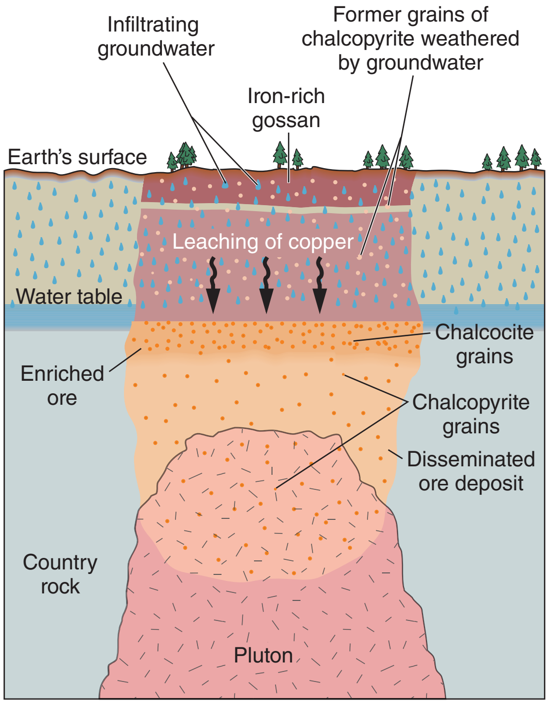


FIGURE 22.25

Supergene enrichment. Groundwater leaches copper from upper part of disseminated deposit and precipitates it at or below the water table, forming rich ore.

ENVIRONMENTAL GEOLOGY 22.4

The World's Largest Human-made Hole— The Bingham Canyon Copper Mine

The Bingham Canyon mine near Salt Lake City, Utah, is thought to be the biggest single human-made hole in the world (box figure 1). (The Morenci mine in Arizona is volumetrically larger, but is not a single pit.) The 800-meter (½-mile) deep open pit mine is 4 kilometers (2½miles) wide at the top and continues to be enlarged. The reason for this hole is copper.

About 40,000 kilograms of explosives are used per day to blast apart over 60,000 tons of ore (copper-bearing rock) and an equal amount of waste rock. An 8-kilometer-long conveyor belt system moves up to 10,000 tons of crushed rock per hour through a tunnel out of the pit for processing.

Mining began here as a typical underground operation in 1863. The shafts and tunnels of the mine followed a series of veins. Originally, ores of silver and lead were mined. Later, it was discovered that fine-grained, copper-bearing minerals (chalcopyrite and other copper sulfide minerals) were disseminated in tiny veinlets throughout a granite stock. Although the percentage of copper in the rock was small, the total volume of copper was recognized as huge. With efficient earth-moving techniques, large volumes of ore-bearing rock can be moved and processed. Today, mining is still going on, and the company is able to make a profit even though only 0.6% of the rock being mined is copper. Since 1904, over 12 million tons of copper have been mined, processed, and sold. The mine has also produced impressive amounts of gold, silver, and molybdenum.

Such an operation is not without environmental problems. Some people regard the huge hole in the mountains as an eyesore (but it is a popular tourist attraction). Disposing of the waste—over 99% of the rock material mined—creates problems. Wind stirs up dust storms from the piles of finely crushed waste rock unless it is kept wet. The nearby smelter that extracts the pure copper from the sulfide minerals has created a toxic smoke containing sulfuric acid fumes. During most of the twentieth century, the toxic smoke was released into the atmosphere; occasionally, wind blew polluted air to Salt Lake City. Now, over 99% of the sulfur fumes are removed at the smelter.

Additional Resource

Bingham Canyon Mine Site

- www.infomine.com/minesite/minesite.asp?site=bingham

BOX 22.4 ■ FIGURE 1

Bingham Canyon copper mine in Utah. *Photo © Royce Bair/Hemera 360/Getty Images* chalcopyrite in the lower part of the disseminated deposit, forming a richer ore mineral such as chalcocite, which is about 80% copper:

$$\underset{\substack{\text{Copper}\\ \text{dissolved}\\ \text{in groundwater}}}{3\text{Cu}^{++}} + \underset{\text{Chalcopyrite}}{\text{CuFeS}_2} \rightarrow \underset{\text{Chalcocite}}{2\text{Cu}_2\text{S}} + \underset{\substack{\text{Iron in}\\ \text{solution}}}{\text{Fe}^{++}}$$

In this way, copper is removed from the top of the deposit, and added to the lower part (Figure 22.25). The ore below the water table may be several times richer than the ore in the rest of the deposit, with silver concentrating as readily as copper. The iron remains behind, staining the surface as it oxidizes to form a gossan (defined in the next section).

MINING

As in the case of coal, miners use both surface and underground techniques to extract ore minerals (Figure 22.26). Strip mining—the wholesale removal of large areas of soil and shallow rock cover—has already been mentioned in connection with coal beds. Aluminum ore (bauxite), which forms in weathered soil beds under tropical conditions, is often most easily extracted this way. *Open-pit mining* is related to strip mining, but concentrates on the removal of valuable deposits from a specific, relatively small area (Figure 22.27). Open-pit mines often dig much deeper than strip mines.

Placer mines are localized to ancient or modern river bar or beach deposits. In some parts of the world, gold is found concentrated in placer deposits (California's Gold Rush of 1849 was triggered by discoveries of placer gold). Gold nuggets, flakes, and dust can be separated from the other sediments by (1) panning; (2) *sluice boxes* (Figure 22.28), which catch the heavy gold on the bottom of a box as gravel is washed through it; (3) *hydraulic mining* (Figure 22.29), which washes gold-bearing gravel from a hillside into a sluice box; or (4) floating *dredges* (Figure 22.30), which separate gold from gravel aboard a large barge, piling the spent gravel behind.

Underground, or *bedrock mining,* must be done to excavate many valuable mineral deposits. Bedrock mining of ores typically extends to much greater depths than ordinary coal mines, and this presents its own set of technical challenges. The world's deepest mines, in South Africa, extend to depths of 1,500–2,500 meters. The walls grow hot to the touch so deep underground, and pumping of fresh, cool air and water must be done to make working conditions tolerable. Mines have notoriously poor air circulation, and the use of dynamite to blast openings releases toxic gases that must be removed. Ammonium nitrate (NH_4NO_3) mixed with fuel oil (CH_2) is a typical blasting agent. The explosive reaction generates poisonous carbon monoxide whenever there is a slight excess of oil in the mixture. Carbon monoxide (CO) is a heavier-than-air gas that sinks deep into the mine. This is one of the reasons why abandoned mines should never be explored.

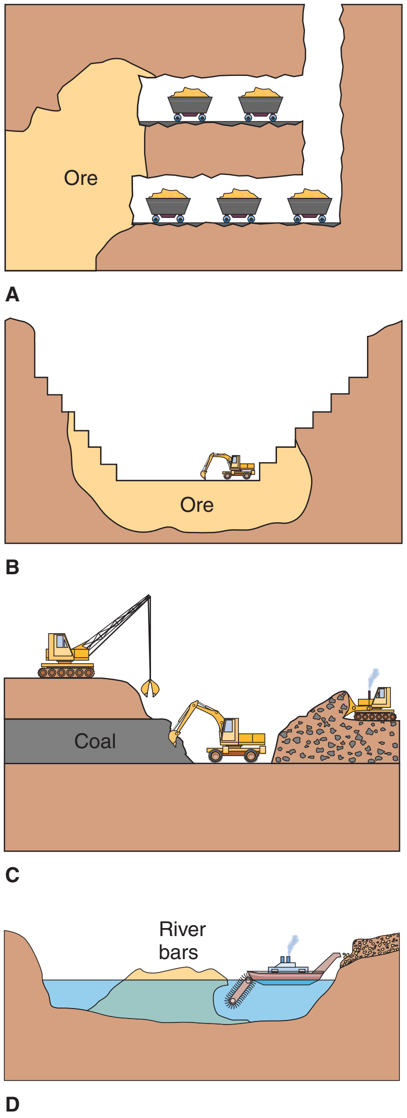


FIGURE 22.26

Types of mines: (*A*) Underground. (*B*) Open pit. (*C*) Strip. (*D*) Placer (being mined by a floating dredge).

FIGURE 22.27

Open-pit copper mine in Morenci, Arizona. Heavy equipment in the bottom of the pit gives a sense of scale. *Photo by David McGeary*

FIGURE 22.28

Sluice box used to separate gold from gravel in Alaska. *Photo by D. J. Miller, U.S. Geological Survey*

FIGURE 22.29

Hydraulic mining for gold in Alaska. *Photo by T. L. Péwé, U.S. Geological Survey*

FIGURE 22.30

A gold dredge separates gold from gravel. *Photo by David McGeary*

Where the mines extend beneath the water table, the water that seeps in must be pumped out to avoid flooding. An active mine consumes large amounts of energy as well as material resources.

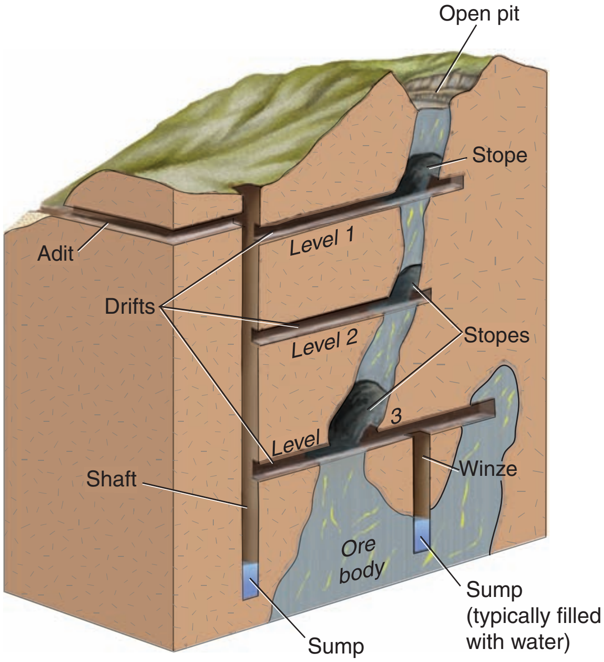


FIGURE 22.31

Design of a typical bedrock mine.

The design of a mine takes into consideration three vital factors: (1) the geometry of the underground ore body; (2) the need for safety; and (3) the need to maximize profit. It is typically easiest for miners to construct a set of vertical and horizontal passages to access and remove the ore (Figure 22.31). The vertical openings, called *shafts* (or *winzes,* if they do not open all the way to the surface), allow elevators to take miners underground and bring ore up to the surface. Shafts are also conduits for electrical cables, water hoses, and air lines. Miners can blast and dig open a shaft at a rate of 30 feet every day. The horizontal tunnels, termed *adits* (or *drifts,* if they do not open to the surface), are the pathways through which ore is directly excavated. In larger mines, multiple drifts radiate off of shafts. *Ramps* are slanted tunnels, many of which have tracks for winching ore carts. In some places, the ore may be so rich that miners excavate a giant underground chamber called a *stope.* To avoid collapse, the walls of the stope may have to be shored up with timbers or other construction materials.

In earlier times, prospectors located potential ore bodies by looking at the eroded rock fragments ("float") in streams and on hillsides, hoping to find telltale minerals such as white quartz with gold or oxidized sulfide minerals, red jasper, or bright blue crysocholla. Following this debris upslope, the treasure seekers might discover what they were looking for—a *gossan,* an area of yellow or ruddy orange, oxidized ground marking the intersection of an ore body or vein with the surface. The Spanish termed such areas "colorados," and the name of the state, in fact, derives from this origin. "Gossan" is itself a Cornish mining term, meaning "iron hat," in reference to the fact that gossans cap deeper ore bodies.

Today, more sophisticated—and expensive—prospecting techniques are applied to locating and determining the shape of an underground ore body. Exploration geologists must study the structural geology (stratigraphy and deformation of the surrounding rocks), examine the evidence brought up in preliminary boreholes, and conduct geophysical surveys, including the use of gravimeters, magnetometers, and electrical-resistivity equipment. Some ore bodies are excellent electrical conductors and may be highly magnetic. Exploration geologists have the ultimate say on whether or not a company should proceed with mining.

Given the dangers and economic factors involved, whole technical schools have been established to train mining engineers (e.g., the Colorado School of Mines). Today, these schools must also consider environmental factors because, in the past, mines have been terrible sources of watershed pollution, among other problems. Groundwater running or being pumped out of a mine causes *acid mine drainage.*

Sulfide ore minerals (table 22.3) and pyrite (FeS_2) are most often the source of the trouble. Groundwater transports oxygen to the sulfides, which are then oxidized to iron oxide and sulfuric acid. In some mines, expensive programs of holding and neutralizing drainage water in ponds or artificial wetlands prevent pollution of surface streams and harm to forests and wildlife. The worst problem is with long-abandoned mines that are still draining acid waters. Many of these may never be neutralized.

NONMETALLIC RESOURCES

Nonmetallic resources are Earth resources that are not mined to extract a metal or as a source of energy. Most rocks and minerals contain metals, but when nonmetallic resources are mined, it is usually to use the rock (or mineral) as is (for example, gravel and sand for construction projects), whereas metallic ores are processed to extract metal. With the exception of the gemstones such as diamonds and rubies, nonmetallic resources do not have the glamour of many metals or energy resources. Nonmetallic resources are generally inexpensive and are needed in large quantities (again, except for gemstones); however, their value exceeds that of all mined metals. The large demand and low unit prices mean that these resources are best taken from local sources. Transportation over long distances would add significantly to the cost.

Construction Materials

Sand and *gravel* are both needed for the manufacture of concrete for building and highway construction. Sand is also used in mortar, which holds bricks and cement blocks together. The demand for sand and gravel in the United States has more than doubled in the last twenty-five years. Sand dunes, river channel and bar deposits, glacial outwash, and beach deposits are common sources for sand and gravel. Cinder cones are mined for "gravel" in some areas. Sand and gravel are ordinarily mined in open pits (Figure 22.32).

FIGURE 22.32

Sand and gravel pit in a glacial esker near Saranac Lake, New York. *Photo © Randy Schaetzl, Michigan State University*

Stone refers to rock used in blocks to construct buildings or crushed to form roadbed. Most stone in buildings is limestone or granite, and most crushed stone is limestone. Huge quantities of stone are used each year in the United States. Stone is removed from open pits called *quarries* (Figure 22.33).

Limestone has many uses other than building stone or crushed roadbed. Cement, used in concrete and mortar, is made from limestone and is vital to an industrial economy. Pulverized limestone is in demand as a soil conditioner and is the principal ingredient of many chemical products.

Fertilizers and Evaporites

Fertilizers (phosphate, nitrate, and potassium compounds) are extremely important to agriculture today, so much so that they are one of the few nonmetallic resources transported across the sea. *Phosphate* is produced from phosphorite, a sedimentary rock formed by the accumulation and alteration of the remains of marine organisms. Major phosphate deposits in the United States are in Idaho, Wyoming, and Florida. *Nitrate* can form directly as an evaporite deposit but today is usually made from atmospheric nitrogen. *Potassium compounds* are often found as evaporites.

Rock salt is coarsely crystalline halite formed as an evaporite. Salt beds are mined underground in Ohio and Michigan; underground salt domes are mined in Texas and Louisiana. (Some salt is also extracted from seawater by evaporation.) Rock salt is used in many ways—deicing roads in winter, preserving food, as table salt, and in manufacturing hydrochloric acid and sodium compounds for baking soda, soap, and other products. Rock salt is heavily used by industry.

Gypsum forms as an evaporite. Beds of gypsum are mined in many states, notably California, Michigan, Iowa, and Texas. Gypsum, the essential ingredient of plaster and wallboard (Sheetrock$^{®}$), is used mainly by the construction industry, although there are other uses.

Sulfur occurs as bright yellow deposits of elemental sulfur. Most of its commercial production comes from the cap rock

FIGURE 22.33

A limestone quarry in northern Illinois. The horizon marks the original land surface before the rock was removed. *Photo by David McGeary*

of salt domes. Sulfur is widely used in agriculture as a fungicide and fertilizer and by industry to manufacture sulfuric acid, matches, and many other products.

Other Nonmetallics

Gemstones (called *gems* when cut and polished) include precious stones such as diamonds, rubies, emeralds, and sapphires and semiprecious stones such as beryl, garnet, jade, spinel, topaz, turquoise, and zircon. Gems (see box 2.5) are used for jewelry, bearings, and abrasives (most are above 7 on Mohs' scale of hardness). Diamond drills and diamond saws are used to drill and cut rock. Old watches and other instruments often have hard gems at bearing points of friction ("17-jewel watches"). Gemstones are often found in pegmatites or in close association with other igneous intrusives. Some are recovered from placer deposits.

Asbestos is a fibrous variety of serpentine or chain silicate minerals. The fibers can be separated and woven into fireproof fabric used for firefighters' clothes and theater curtains. Asbestos is also used in manufacturing ceiling and sound insulation, shingles, and brake linings, although the use of asbestos is being rapidly curtailed because of concern about its connection with lung cancer (see box 2.3). The United States no longer produces asbestos. Large amounts are mined in Canada, chiefly in Quebec. *Talc,* used in talcum powder and other products, is often found associated with asbestos (see box 20.2).

Other nonmetallic resources are important. *Mica* is used in electrical insulators. *Barite* ($BaSO_4$), because of its high specific gravity, is used to make heavy drilling mud to prevent oil gushers. *Borates* are boron-containing evaporites used in fiberglass, cleaning compounds, and ceramics. *Fluorite* (CaF_2) is used in toothpaste, Teflon finishes, and steel smelting. *Clays* are used in ceramics, manufacturing paper, and as filters and absorbents. *Diatomite* is used in swimming pool filters and to filter out yeast in beer and wine. *Glass sand,* which is over 95% quartz, is the main component of glass. *Graphite* is used in foundries, lubricants, steelmaking, batteries, and pencil "lead."

RESOURCES, THE ENVIRONMENT, AND SUSTAINABILITY

There is a saying, "If it can't be grown, it must be mined." As we described at the beginning of this chapter, every day you interact with materials that are either directly mined or produced from materials that are mined. The demand for fossil fuels, metallic ores, and nonmetallic materials is only likely to increase as world population grows and developing nations continue to industrialize and become more wealthy. The extraction and transportation of resources can have an enormous impact on the environment, leaving enormous holes in the ground (Figure 22.27), removing entire mountaintops (Figure 22.5), or resulting in massive oil spills (box 22.2). Release of greenhouse gases through the burning of fossil fuels and during extraction, processing, and transportation of resources may be causing global climate change (chapter 21). Additionally, many of these resources take many millions of years to form, and unchecked exploitation of them now may deprive future generations of the resources that they need.

It is a complicated issue. It is not feasible to ban all mining and drilling because we need those materials to sustain our lifestyles. Nor is it acceptable to exploit with no regard for the effect on the environment or for the needs of future generations. Almost everyone agrees that we need to find a middle ground that includes both mining practices that minimize environmental impact and reducing consumption and increasing recycling to ensure a supply of resources for future generations. The challenge is in finding the right balance and one that all nations—developed and developing—can agree upon. Your understanding of geology is an important step in your being able to help resolve moral dilemmas that we face to which there is no ideal solution.

Summary

Most people interact with the Earth primarily through their interaction with *geologic resources:* soil, water, metals, nonmetals, and fuels, most of which are *nonrenewable* and form under particular and transient natural conditions.

Coal, petroleum, and *natural gas* are fossil fuels that are the main sources of energy in the modern world. They are also important in nonenergy applications, such as making fertilizer, steel, and many other products. These resources are essentially ancient *solar energy,* unlocked by combustion in power plants after mining or drilling. *Coal beds* occur in areas of ancient swamps and marshes, and derive from the accumulation of dead land-based plant matter. *Oil* (petroleum) and natural gas derive from certain nearshore marine settings where dead, microscopic, floating organisms accumulate. Coal and oil both require heat and burial to develop. Oil and natural gas also need to be sealed into subsurface reservoirs as they percolate toward the surface. Anticlines, faults, and other structural traps provide this lid.

Reserves are known as deposits that can be legally and economically recovered now—the short-term supply. Resources include reserves as well as other known and undiscovered deposits that might be economically extractable in the future. There is evidence that the world's reserves of petroleum are nearing critical depletion, given the high level of demand. This will force the world into finding energy alternatives, including the burning of more coal and increased development of *nuclear power.*

Uranium-235 is the primary fuel of *nuclear reactors.* Through breeder designs, nuclear energy could provide us with electricity long into the future. But risk of accidents and waste-disposal issues raise questions about the long-term viability of this energy source.

Geothermal power benefits only a few localized areas around the world. This resource can be easily exhausted, and it is never likely to become a principal source of world energy, despite the enormous amount of heat contained inside the Earth.

Renewable energy strategies, such as *solar, wind,* and *wave power,* are an appealing, environmentally clean substitute for "conventional" energy sources. *Hydroelectric power* is the most successful and extensively used type of renewable energy, though it is localized to areas with abundant flowing water. Biofuels provide a carbon-neutral source of fuel for our vehicles, but the cost of producing the biofuel is more expensive food.

Metallic ores, which can be profitably mined, are often associated with igneous rocks, particularly their *hydrothermal fluids,* which can form in contact metamorphic deposits, hydrothermal veins, disseminated deposits, and submarine hot springs at divergent plate boundaries, on the flanks of island arcs, and in belts on the edges of continents above subduction zones.

Ores are mined at the surface in *strip* and *open-pit mining,* and in costly, potentially dangerous, and carefully executed underground mining. *Placer* mining takes advantage of the sedimentary reworking and concentration of ore minerals.

Nonmetallic resources, such as sand and gravel and limestone for crushed rock and cement, are used in huge quantities. Fertilizers, rock salt, gypsum, sulfur, and clays are also widely used.

Terms to Remember

active solar heating 548
biofuel 550
coal 535
coal bed methane 544
energy resources 535
fission 545
fossil fuels 535
heavy crude 544
hydrothermal veins 552
kinetic energy 535
natural gas 538
nonrenewable resources 533
oil field 540
oil (tar) sands 544
oil shale 544
ore 550
passive solar heating 548
petroleum 538
photovoltaic cells 548
placer deposits 553
potential energy 535
reserve 533
reservoir rock 538
resource 533
source rock 538
strip mining 537
structural (or oil) trap 539

Testing Your Knowledge

1. What is the difference between a reserve and a resource? Under what circumstances would a resource come to be regarded as a reserve?
2. Coal is often referred to as "clean coal." What is that in reference to? Is coal a truly clean energy source?
3. Is it likely that oil resources will be completely depleted one day? Are we likely to stop exploiting oil? What factors would contribute to us ceasing oil production, and what factors may lead to us continuing to exploit oil?
4. Contrast the geologic conditions responsible for the formation of coal, oil, and natural gas.
5. Describe how a nuclear reactor works.
6. Discuss the pros and cons of exploiting geothermal and hydroelectric power.
7. Discuss the ways in which solar, wind, wave, and tidal energy are harnessed.
8. Describe the ways in which igneous processes can form metallic ore deposits.
9. How can surface processes create ore deposits?
10. Describe two ways in which resources are mined, and discuss the pros and cons of each.
11. Discuss common uses for metallic resources and nonmetallic resources.
12. Discuss the tension between our need to exploit resources for energy and materials and the environmental impact of that exploitation.
13. Which is *not* a type of coal?
    a. lignite
    b. bituminous
    c. sulfite
    d. anthracite

14. Which metal would most likely be found in an ore deposit formed by crystal settling?
    a. copper
    b. gold
    c. silver
    d. chromium
15. Which metal would *not* be found in hydrothermal veins?
    a. lead
    b. aluminum
    c. silver
    d. gold
16. Coal forms
    a. by crystal settling.
    b. through hydrothermal processes.
    c. by compaction of plant material.
    d. on the ocean floor.
17. The world's largest oil reserves are found in
    a. Venezuela.
    b. the Middle East.
    c. the United States.
    d. Canada.
18. What factors can increase reserves of Earth resources (choose all that apply)?
    a. decrease in cost of extraction
    b. increased demand
    c. price decreases
    d. new mining technology
19. The largest use of sand and gravel is
    a. glassmaking.
    b. extraction of quartz.
    c. construction.
    d. ceramics.
20. Oil accumulates when the following conditions are met (choose all that apply):
    a. source rock where oil forms
    b. permeable reservoir rock
    c. impermeable oil trap
    d. shallow burial

Expanding Your Knowledge

1. Many underdeveloped countries would like to have the standard of living enjoyed by the United States, which has 6% of the world population and uses 15% to 40% of the world's production of many resources. As these countries become industrialized, what happens to the world demand for geologic resources? Where will these needed resources come from?
2. If driven 12,000 miles per year, how many more gallons of gasoline per year does a sport utility vehicle or pickup truck rated at 12 miles per gallon use than a minicompact car rated at 52 mpg? Over five years, how much more does it cost to buy gasoline at $4 per gallon for the low-mileage car? At $8 per gallon (the price in many European countries)?

Exploring Web Resources

www.NRCan.gc.ca/

Natural Resources Canada. Use this site to get information on Canada's mineral and energy resources.

http://minerals.usgs.gov/

U.S. Geological Survey Mineral Resources Program. Provides current information on occurrence, quality, quantity, and availability of mineral resources.

www.eia.doe.gov/

U.S. Energy Information Administration. Provides data, analysis, and forecasts of energy and issues related to energy.

www.api.org

American Petroleum Institute. Information on all aspects of petroleum from the industry's perspective.