24 Earth's Resources

Our modern society is completely dependent on a wide variety of mineral resources. Often we take for granted that these resources will always be available. The sobering fact is that most of our natural resources are finite and nonrenewable. History records the fall of cultures and civilizations in which a depleted resource base played a major role. An example is the decline of Mesopotamia 1500 years ago. As the people of southern Asia began to irrigate their arid lands, salt became concentrated in the soil when irrigation waters evaporated. Agricultural production gradually diminished. The destruction of one of their most valued resources led to the decline of their entire civilization.

The image above is symbolic of yet another such cultural collapse following the destruction of an island society's resources. In this chapter, you will read about the rise and fall of the people of Easter Island who carved these great basalt statues. Although they did not depend on deposits of iron or reservoirs of petroleum, they did depend on certain palm trees, on good soil, and on animal life. Eventually, however, the small volcanic island became overpopulated and its resources were not sufficient to sustain its inhabitants.

Our problem is similar. It is not just one of finding more and more resources, but of balancing those resources with a burgeoning human population. In the early 1900s, Earth's total population is estimated to have been about 1.7 billion people. At the beginning of the new millennium, the population is more than 6 billion. Every 3 years the equivalent of the population of the United States is added to the planet. In 100 years, our numbers have increased more than threefold. The increase in population has not come without its costs.

During the next decade, we will use more oil, gas, iron, and other mineral resources than were consumed throughout previous human history. These facts lead us to ask a series of important questions. Is there really a finite supply of mineral resources? Will we completely consume the metallic resources discovered only in the last century? Will we be able to find and extract even deeper deposits? What about oil resources— will they be gone in another 30 years? Do we have enough agricultural lands to support ourselves? Will there be ample fresh water for billions of additional people? In short, what will be the fate of our resource-dependent civilization?

Ore deposits and other types of earth resources are not equally distributed around the world but are rare and only concentrated by very specific geologic conditions. All mineral resources develop slowly and eons pass before a new deposit forms. In this chapter we review the origin of these resources and examine some of the implications of our increasing rate of consumption of our natural resources.

Photograph by Val Brinkerhoff

MAJOR CONCEPTS

1. Mineral resources are concentrated by geologic processes operating in the hydrologic and tectonic systems. Many require long periods to form; these resources are finite and nonrenewable.
2. Ore deposits are formed by igneous, sedimentary, metamorphic, and weathering processes. Many metallic ores involve transport and deposition of metals in a hydrothermal fluid.
3. Earth's principal nonrenewable energy resources include coal, oil, natural gas, and nuclear power. Renewable energy resources include solar energy, wind power, hydroelectric power, tidal power, and geothermal energy. At present these renewable forms of energy provide only a small fraction of our energy needs.
4. The location and richness of most of Earth's natural resources are directly or indirectly controlled by plate tectonics.
5. There are limits to population growth on Earth imposed by the finite nature of many of our natural resources.

MINERAL RESOURCES

The present store of mineral resources has been concentrated very slowly by a variety of geologic processes related to the plate tectonic and hydrologic systems. Most mineral resources are therefore finite and nonrenewable.

Mineral resources range from the soils that support agriculture to metals such as silicon, which is used in high-technology applications such as computers. Though technically not minerals, oil, natural gas, coal, and some other sources of energy are also included as mineral resources because they are extracted from Earth. Mining worldwide produces about $500 billion worth of metallic ore each year; another $700 billion of energy minerals are produced.

Why are mineral resources distributed so unevenly throughout the world?

The world's valuable deposits of minerals and energy fuels were formed slowly by the major geologic systems during various periods in the geologic past (Table 24.1). Their formation required very long intervals of time and occurred under specific geologic conditions. Some metallic mineral deposits were formed in such restricted geologic settings that they approach uniqueness. For example, 40% of the world's reserves of molybdenum are in one igneous intrusion in Colorado; 77% of tungsten reserves are in China; more than 50% of tin reserves are in Southeast Asia; and 75% of chromium reserves are in South Africa. If mineral resources are depleted, we cannot just go out and find more. More of many deposits simply does not exist. Fortunately, most metals, unlike fossil fuels, can be **recycled.**

In contrast to some energy resources and most biological resources (such as agricultural crops and forest products), very few mineral resources are **renewable,** meaning they are replenished in a short period of time. The processes that form mineral resources operate so slowly (by human standards) that their rates of replenishment are infinitesimally small in comparison to rates of human consumption. For example, the generation of oil from sedimentary rocks may take more than 10 million years. Consequently, mineral deposits are finite and therefore are exhaustible or **nonrenewable.** Most of our mineral resources are like a checking account that will never receive another deposit. The faster we withdraw, or the larger the checks we write, the sooner the account will be depleted. Moreover, today, few areas remain completely unexplored for mineral deposits. Most of the continents have been mapped and studied extensively, so the inventory of natural resources is nearly complete. We can accurately estimate the extent of many of our mineral resources and their rates of consumption. With these estimates, projecting how long they will last is not especially difficult.

TABLE 24.1 The Major Geologic Processes That Form Mineral Resources

Process	Deposits Formed	Mineral Resource
Igneous processes	Magmatic segregation	Chromium, vanadium, nickel, copper, cobalt, platinum
	Pegmatites	Beryllium, lithium, tantalum
	Hydrothermal deposits	Copper, lead, zinc, molybdenum, tin, gold, silver
Sedimentary processes		
Clastic rocks	Stream deposits	Sand, gravel
	Placer deposits	Gold, platinum, diamonds, tin, ilmenite, rutile, zircon
	Dune deposits	Sand
	Loess deposits	Soil
Chemical precipitates	Evaporite deposits	Halite, sylvite, borax, gypsum, trona
	Marine sediment	Banded iron formation, phosphate, limestone
Organic precipitates	Hydrocarbon deposits	Oil, natural gas, coal
	Marine deposits	Limestone
Metamorphic processes	Contact metamorphism	Tungsten, copper, tin, lead, zinc, gold, silver
	Regional metamorphism	Gold, tungsten, copper, talc, asbestos
Weathering and groundwater	Soil	Agriculture
	Residual soils	Clay
	Residual weathering deposits	Nickel, iron, cobalt, aluminum, gold
	Groundwater deposits	Travertine, uranium, sulfur
	Brines in basins	Lead, zinc, copper
	Geothermal wells	Hot water, electricity
	Water	Drinking water, irrigation

(Modified from S. E. Kesler)

PROCESSES THAT FORM MINERAL DEPOSITS

The origin of most ore deposits is related to fundamental geologic processes. We recognize four major groups of mineral deposits formed by (1) igneous processes, (2) metamorphic processes, (3) sedimentary processes, and (4) weathering and groundwater processes.

The important minerals on which modern civilization depends are an extremely small part of Earth's crust. For instance, copper, tin, gold, and other metallic minerals occur in quantities measured in parts per million (and, in most cases, a very few parts per million). To form a mineral deposit, some metals must be concentrated thousands of times beyond their "normal" concentrations in rocks. In contrast, the rock-forming minerals (such as feldspar, quartz, calcite, and clay) are abundant and widely distributed. The important question, then, is how these very small quantities of important minerals are concentrated into deposits large enough to be used.

Below, we will consider some principles governing the concentration of rare minerals in ore deposits and the origin of some nonmetallic resources. It may surprise you to learn that essentially every geologic process—including igneous activity, metamorphism, sedimentation, weathering, and deformation of the crust—plays a part in the genesis of some valuable mineral deposits (Table 24.1). The occurrence or absence of most mineral deposits, therefore, is controlled by a region's specific geologic conditions and plate tectonic setting (Figure 24.1).

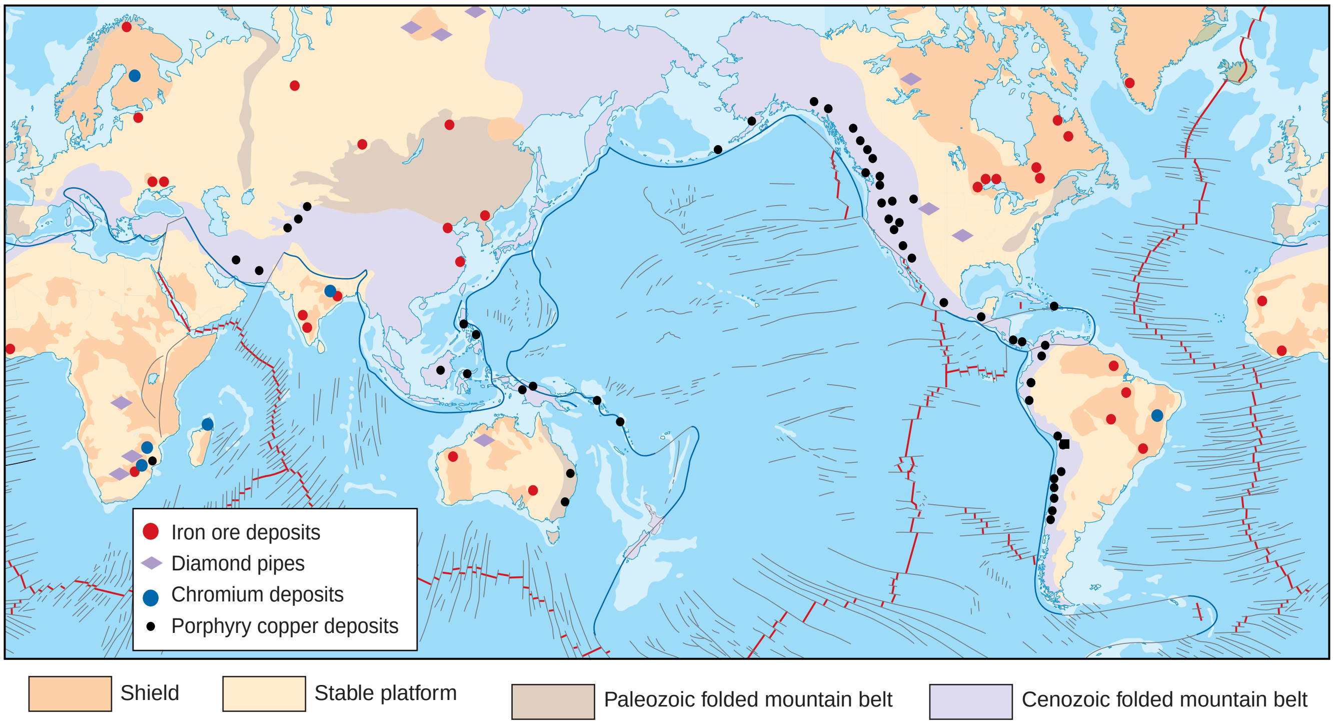


FIGURE 24.1 **Major ore deposits** are related to specific tectonic settings. Most important iron ores are in sedimentary rocks of Precambrian age exposed in the shields. Chromium and diamond deposits are also concentrated on the shields and formed in ancient basaltic intrusions related to mantle plumes or rifts. In contrast, many copper (and lead, zinc, and silver) deposits form around intrusions in young mountain belts at convergent plate boundaries.

Igneous Processes

Many mineral resources are formed by magmatic processes. Magmas have higher concentrations of some elements than most other rocks, and some minerals can reach even higher concentrations in specific areas of an igneous rock. Prime examples are the exotic ultramafic volcanic rocks that host diamonds. Diamond crystals were probably ripped from diamond-bearing wall rocks by magma rising through the deep mantle (Figure 24.2). Laboratory experiments show that diamond is stable at depths of at least 150 to 200 km. At low pressure, the stable form of carbon is the soft mineral graphite, but the reaction of diamond to form graphite proceeds very slowly at the low temperatures found at Earth's surface. Besides its use as a gem, diamonds have found industrial uses as abrasives and as strong coatings. Diamond deposits are limited to regions underlain by Precambrian crust (Figure 24.1). The richest deposits are found in South Africa and Australia, but diamonds have been discovered recently in the Northwest Territories. Diamond prospecting in the United States has identified diamond-bearing igneous pipes on the Colorado-Wyoming state line and in Arkansas, but none of these is currently economic to mine.

Why are there no diamond mines in Kansas?

Concentrations of other ores result when minerals forming in a magma have different temperatures of crystallization and density. One concentration process is **magmatic segregation,** in which dense mineral grains accumulate in layers near the base of an igneous body (Figure 24.2). To form ore, the layer must form when only one kind of mineral is crystallizing. This requirement calls for unusual conditions because most magmas have several different kinds of minerals crystallizing simultaneously. Once they crystallize, the dense minerals can sink to the bottom of the chamber to form layers. Deposits of chrome, nickel, vanadium, and platinum form in some mafic intrusions by this process (Figure 24.3). The largest of these are in the Bushveld Complex of South Africa. The rich nickel and copper sulfide ores of Sudbury, Ontario, also sank to the base of a very unusual, but large body of mafic magma. Some geologists have concluded that the magma formed because of a meteorite impact about 1.7 billion years ago.

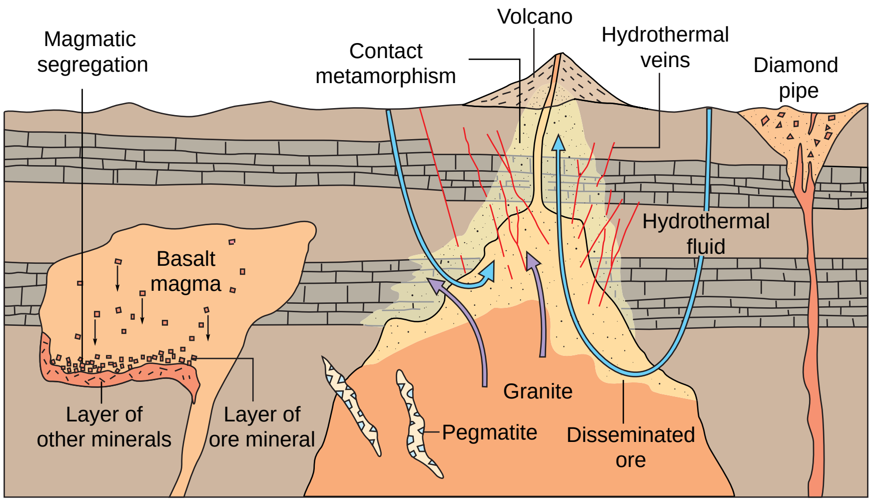


FIGURE 24.2 Igneous processes produce many metallic ore deposits as illustrated in this cross section. Magmatic segregation (left) occurs as heavy crystals sink through fluid magma and accumulate in layers near the base of a magma chamber. Ore in pegmatites consists of beryllium and lithium, which are concentrated in residual melts during fractional crystallization. Other elements, such as gold, silver, copper, lead, and zinc, are carried by hydrothermal fluids (blue and purple arrows) through fractures in the surrounding rock. Eventually, the metallic elements are precipitated as hydrothermal vein deposits. The concentration of ore deposits by contact metamorphism occurs as fluids from the cooling magma replace parts of the surrounding rock. Iron and tungsten deposits may be formed by this process. Diamonds, brought deep from the mantle,are mined from volcanic pipes in which the upper part is a complex breccia (right).

Late-stage segregation and crystallization is another process by which rare minerals are concentrated (Figure 24.2). In an original magma, many elements occur in amounts of only a few parts per million but do not fit readily into the crystalline structure of the rock-forming minerals. As a silica-rich magma crystallizes, these rare elements are concentrated in the last remaining melt. Examples of such rare element segregations include beryllium, lithium, uranium, and tantalum. These late-stage, water-rich magmas can then intrude into fractures in a pluton or in the surrounding rock. As they cool, the rare elements crystallize as minerals in a coarse-grained rock called **pegmatite.** Individual quartz crystals several meters long have formed in pegmatites. These rare elements have important uses in electronics, lightweight metal fabrication, and nuclear reactors. Several gemstones are found in granitic pegmatites, including topaz, beryl, and tourmaline. In addition, large masses of common silicate minerals, such as feldspar and mica, can be mined from pegmatites. Feldspars are used in ceramics, and muscovite mica is used in makeup, insulators, and various construction materials.

As some magmas cool and crystallize, hot water-rich solutions are concentrated and released. These hot fluids are one type of **hydrothermal fluid** and can become laden with high concentrations of soluble materials, including many economically important elements. Deposits from these fluids are part of a large

FIGURE 24.3 Layers of dense minerals such as chromite may form by the crystallization and settling to the floor of large mafic igneous intrusions. Shown here is the Bushveld Complex, South Africa. The black layers are chromite and the tan layers are made of olivine. *(Spence Titley/Peter L. Kresan Photography)*

category of ores known as **hydrothermal ore deposits** (Figure 24.2). Hydrothermal fluids can be injected into fractures in the rock surrounding an intrusion to form **veins** with minerals containing gold, silver, copper, lead, zinc, molybdenum, and other elements. The fluids can also permeate small fractures and grain boundaries in the already-solid part of the intrusion to form metallic minerals distributed in the intrusion. This process produces large deposits of low-grade ore (0.2% to 2% copper); much of the pluton may be mineralized. If the intrusion is exposed near the surface, these low-grade deposits can be removed profitably by open-pit mining. An important example of this type of mineral deposit is the copper found in some porphyritic igneous intrusions, often of dioritic or granitic composition. **Porphyry copper** deposits currently account for more than 50% of the world's copper production. Utah's Bingham copper mine is one the largest of this type in the world (Figure 24.4).

Earth Resources

Other types of hydrothermal fluids are formed by a variety of processes and tectonic settings; not all hydrothermal fluids are released directly from magmas. Intrusions may heat groundwater, causing it to convect and carry ore metals that may become concentrated in veins. The penetration of water along faults in rift zones into the deep and hot parts of the crust can also create hydrothermal solutions that carry gold and other metals (Figure 24.2).

A variety of igneous materials are also used as **industrial minerals**—generally nonmetallic minerals or rocks that are used in industry. The cost per ton for these materials is generally low. Building stone, for example, is commonly quarried from homogeneous unfractured plutons exposed at the surface. Road aggregate with very specific properties is sometimes formed by crushing intrusive igneous rocks of known strength, especially in areas where gravel is not common.

Metamorphic Processes

Metamorphism changes the texture and mineralogy of rocks and in the process can form important new mineral resources.

Regional Metamorphism. Important deposits of industrial minerals, such as asbestos, talc, and graphite, have formed during the metamorphism of large regions in the roots of mountain belts. Marble and serpentine are commonly used to face buildings and in other construction projects. Corundum (Al_2O_3) and garnet are

FIGURE 24.4 **Porphyry copper deposits** form around shallow igneous intrusions where hydrothermal fluids deposit copper and alter the surrounding rocks. Most are mined as large open pits with huge tailing (waste rock) piles like these near Bingham, Utah.

common metamorphic minerals used as industrial abrasives. On the other end of the value scale, these same two minerals also form gems—ruby and sapphire are colored varieties of corundum, and garnet is a semiprecious gem. Colombian emeralds (gem form of beryl) appear to have formed during metamorphism of sedimentary rocks.

Metallic ore deposits are also created by regional metamorphic processes. Gold, copper, and tungsten bearing hydrothermal fluids are also expelled from rocks during regional metamorphism of the continental crust. Fault zones, formed deep in the crust and now exposed in the continental shields, have been mineralized when such fluids flowed along them.

Contact Metamorphism. Some ore deposits form by contact metamorphism—metamorphism along the contact between an igneous intrusion and the surrounding rocks. In this process, heat and the flow of chemically active fluids from a cooling magma alter the adjacent rock by adding or removing elements. Limestone surrounding a granite pluton is particularly susceptible to alteration by hot, acidic hydrothermal solutions related to the intrusion. For example, large volumes of calcium can be replaced by iron in a hydrothermal fluid to form valuable ore deposits that contain tungsten or tin (Figure 24.2).

What important ore deposits are formed by metamorphic processes?

Seafloor Metamorphism. Hot hydrothermal fluids circulating through the oceanic crust cause seafloor metamorphism. These fluids leach metals (such as manganese, iron, copper, zinc, lead) and sulfur from the crust and transport these elements to hotspring vents on the ocean floor. Minerals precipitate when the hydrothermal fluids mix with seawater and cool. Mounds of sulfide ores collect on the seafloor where the hot waters are released.

Sedimentary Processes

A significant result of the erosion, transportation, and deposition of sediments is the segregation and concentration of mineral grains according to size and density (Figure 24.5). As emphasized in Chapter 12, soluble minerals are transported in solution; silt and clay-sized particles are transported in suspension, and sand and gravel are moved mostly as bed load by strong currents. Each of these forms of sediment transport may create mineral deposits.

Clastic Sediments. Sand and gravel are concentrated in river bars, beaches, and alluvial fans. These deposits, both modern and ancient, are valuable resources for the construction and glass-making industries. In the United States alone, more than $1 billion worth of sand and gravel is mined each year, making it the largest mineral industry not associated with fuel production in the country.

Clastic sedimentary processes also concentrate gold, diamonds, and tin oxide. Originally formed in veins, volcanic pipes, and intrusions, these minerals are eroded and transported by streams. Because they are much denser than most silicate minerals, they are deposited and concentrated where current action is weak, such as on the insides of meander bends or on protected beaches and bars (Figure 24.5). Such layers and lenses of valuable minerals are known as **placer** deposits, and they are mined from both modern and ancient rivers and beaches. Some placers in modern rivers have been traced upstream to the source of the ore in vein deposits higher in the drainage basin. Placer ore deposits include gold and diamonds; some ancient placers also contain uranium minerals.

How can diamonds be concentrated in both igneous and sedimentary processes?

Chemical Precipitates. Chemically precipitated sediments are also important sources of minerals. Chemical precipitates from seawater form the great bulk of iron ore mined today. **Banded iron formations** of Precambrian age are especially significant because of their abundance (Figure 24.6). These deposits consist of

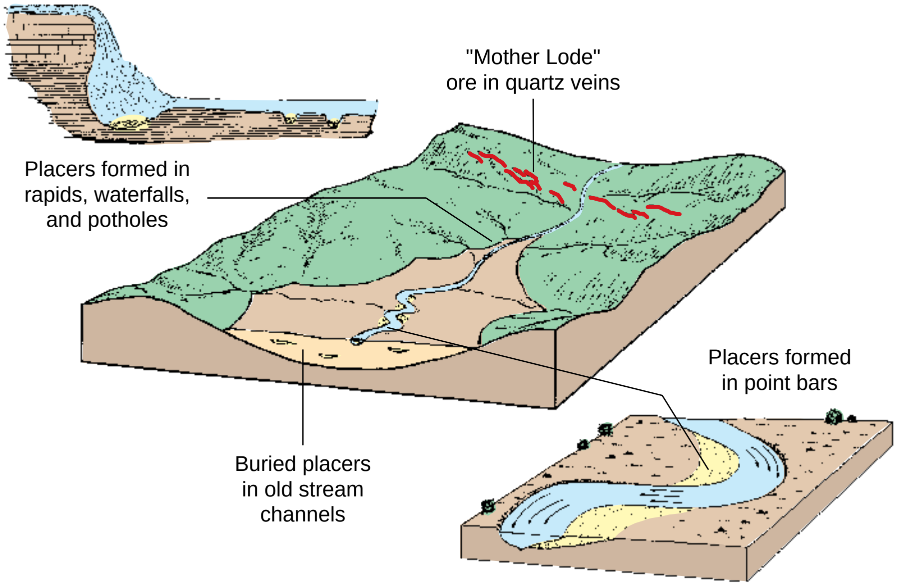


FIGURE 24.5 The concentration of heavy minerals in placer deposits occurs by stream action. Gold, diamonds, and tin, for example, if eroded from their original deposits, will accumulate in areas where stream currents are weak, such as at the base of a waterfall or inside a meander bend.

alternating layers of iron oxide and chert, formed during a unique period of Earth's history, from 1.8 to 2.2 billion years ago, when the oxygen in Earth's atmosphere was building up to modern levels. Consequently, much iron was removed from solution in seawater. They cannot form under present environmental conditions. Many of these sedimentary sequences were subsequently metamorphosed.

Another way in which sedimentary processes concentrate valuable minerals is in the evaporation of saline waters in restricted embayments of the ocean or in large lakes where little clastic sediment is deposited. Valuable evaporites are formed in many playa lakes. As evaporation proceeds, dissolved minerals are concentrated and eventually precipitated as solid crystals. These **brines** and **evaporite** deposits include elements of commercial value, such as potassium, sodium, and magnesium salts, sulfates, borates, and nitrates (Figure 24.7). Gypsum is a common sulfate mineral formed by evaporation and is an especially important industrial mineral used in home construction as wallboard and as the base for plaster of paris.

FIGURE 24.6 Banded iron formations formed as iron minerals interlayered with chert precipitated from shallow Precambrian oceans. Today, they form our major source of iron. These banded iron formations are in Australia. *(Jean-Marc La Roque/Auscape International)*

FIGURE 24.7 Brines form by strong evaporation. These ponds on the shores of Great Salt Lake are sources of magnesium as well as salt.

Less exotic chemical precipitates are also important mineral resources. Limestone, deposited by organic and inorganic processes, is a key component of agricultural lime, concrete, and other building materials. Limestone is crushed to make aggregate for roads and as a flux in steel smelting. The phosphate mineral apatite precipitates from upwelling seawater and is also mined to make fertilizers. Carbon-rich organic deposits are discussed below as energy minerals.

Sedimentary Fluids. Hydrothermal fluids may also form in sedimentary basins as the strata subside to deeper and deeper levels in the crust. If meteoric water penetrates these deep basins, it may be heated to as high as 300°C. At this temperature, soluble elements may be extracted from the rocks and then concentrated by crystallizing out of the fluid at shallower and cooler levels of the crust. There, ore minerals may precipitate in cavities and veins. Important deposits of lead and zinc in Paleozoic limestone of the upper Mississippi Valley of Missouri and Wisconsin formed in this way.

Weathering and Groundwater Processes

The simple process of chemical weathering also concentrates valuable minerals (Table 24.1). For example, water removes soluble material such as sodium, potassium, calcium, and magnesium from rocks, leaving insoluble compounds as a residue. Weathering, therefore, can enrich ore deposits that were originally formed by other processes (Figure 24.8). For example, gold may occur as small inclusions in the sulfide mineral pyrite. Weathering may destroy the pyrite, concentrating the gold in a surface layer.

Chemical weathering can also concentrate, in the regolith, an element that was originally dispersed throughout a rock body. For example, extensive weathering of granite in tropical and semitropical zones commonly concentrates relatively insoluble metallic oxides and hydroxides in the thick regolith as it removes the more-soluble material. Because aluminum is relatively insoluble in groundwater, deposits of aluminum called *bauxites* may form in this way. Aluminum ores form where other elements are efficiently flushed out by a combination of high rainfall and good drainage due to high relief. Ophiolites exposed to deep tropical weathering may concentrate residual deposits of nickel, cobalt, and iron.

Perhaps the most important resource formed by weathering is agricultural soil. As discussed in Chapter 10, both physical and chemical weathering processes, as well as biological activities, are important in soil formation. Physical weathering

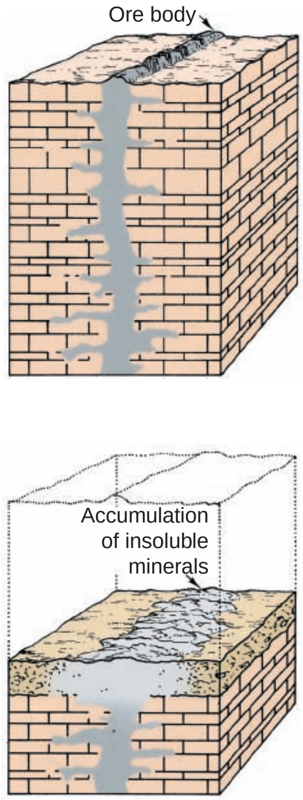


FIGURE 24.8 The concentration of ore deposits by weathering processes occurs as soluble rock, such as limestone, is removed in solution, leaving insoluble minerals concentrated as a residue.

breaks rocks up into small fragments; chemical weathering attacks minerals in these fragments and produces new clay minerals. The voids around the fragments allow nutrients and water to seep into the ground, and the clays absorb water and nutrients so that plants can gradually use them. A mixture of clay and silt with decayed organic materials creates productive agricultural soil. In many places, however, soil is being stripped away by erosion much faster than it is being formed. Even in a humid climate, it may take thousands of years to produce a few centimeters of good soil.

Even the clay formed by chemical weathering is a valuable resource and may be used in ceramics and to make tile and bricks (Table 24.1).

Another important resource controlled by surface processes is the groundwater itself. As discussed in Chapter 13, groundwater is an important source of drinking and irrigation water in many regions of the world. In many of the world's aquifers, groundwater is a nonrenewable resource. In these aquifers, recharge rates are so slow that groundwater is pumped out much faster than it can be replenished. We are therefore essentially mining these groundwater resources, and once depleted, they cannot be replenished in a human time frame. Elsewhere, aquifers behave more like reservoirs used to temporarily store water for later use. Recharge occurs over the course of the year, and the water table remains essentially constant.

ENERGY RESOURCES

Renewable energy resources include solar energy, hydropower, tidal energy, wind energy, and geothermal energy. Together they cannot be expected to fulfill our long-term energy needs. Fossil fuels form slowly from sedimentary rocks and are being rapidly depleted. Nuclear energy may become a major energy source in the future.

Modern society's technological progress and standard of living are intimately related to energy consumption. Until recently, energy resources and the capacity for growth seemed unlimited. Now, we are beginning to appreciate that energy sources are limited. Understanding the sources of energy and how they can be used most effectively will be among the most pressing problems of the twenty-first century.

Our sources of energy are found in both renewable and nonrenewable forms. A renewable energy source is either one that is available in unlimited amounts, for all practical purposes, or one that will not be appreciably diminished in the foreseeable future. Solar energy, tidal energy, and geothermal energy are the most important examples. In contrast, nonrenewable energy sources, such as mineral resources, are finite and exhaustible. They cannot be replaced once they have been consumed. Coal and petroleum, the fossil fuels on which modern culture relies so much, are nonrenewable. These energy sources have been concentrated by geologic processes that operated over vast periods of geologic time. Although the same processes function today, they operate too slowly to replenish these fuels.

Are oil production and consumption increasing in the United States?

An important aspect of today's energy picture is that more than 90% of the energy we use is produced from nonrenewable fossil fuels (Figure 24.9). The exponential growth in consumption of the world's fossil fuels has brought on the present energy crisis. Few technical analysts—whether economists, geologists, or engineers—doubt that the problem exists. They see the trends and events that indicate, in the near future, difficulties ranging from an awkward situation to disaster and economic peril. By contrast, most of the general public—if we are to accept the results of public opinion polls—do not believe that a problem exists.

The energy crisis, however, was accurately predicted more than 40 years ago. In 1956 M. King Hubbert, an eminent research geologist for Shell Oil Company, analyzed the reserves, production, and rate of consumption of petroleum in the United States. From these data, he predicted a continuous decline in U.S. production beginning in 1971 (Figure 24.10). Take a moment and study these curves and observe that they show the decline actually started about 1975. If our actual reserves exceeded this estimate by a third, the huge increase would postpone the day of reckoning by only 5 years. More recent forecasts of world oil production also generally paint a gloomy picture. Most geologic forecasts predict that world oil production will peak sometime between 2005 and 2020. From then on, there will be less available in each year than in the previous year. Petroleum production could decline to near exhaustion by 2070. Obviously, if these predictions are correct, oil prices will rise. The U.S. Department of Energy forecast, on the other hand, sees no drop in world oil production until sometime after the end of the period they scrutinized (ending in 2020). Obviously, predicting any future events is difficult.

Visualizing the volume of a natural resource buried beneath the ground in limited parts of the world can be difficult. To get some idea of the finite nature of the world's petroleum, imagine the Great Lakes drained of water. Then imagine pouring into those basins all the oil we know of or anticipate ever finding. A small puddle in the Lake Superior basin—less than 5% of the lake's volume—would represent the world's oil for all time. In the future, coal might be expected to replace petroleum as the main hydrocarbon resource, but natural gas, solar energy, and hydrogen fusion will certainly be needed (Figure 24.11). It is quite clear, therefore, that we must greatly curtail our reliance on fossil fuels and replace them with other energy sources.

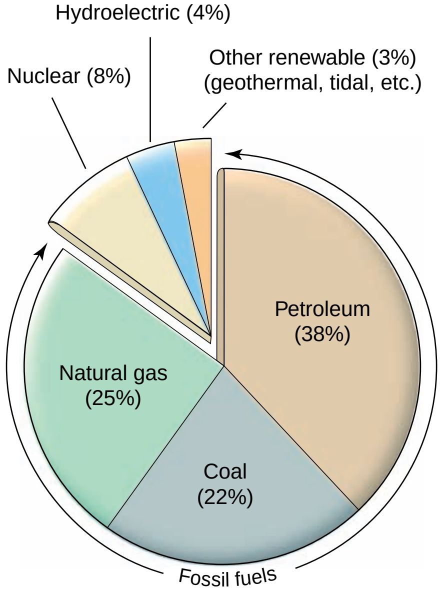


FIGURE 24.9 The energy consumed in the United States is provided from a variety of resources, but is predominantly from petroleum. Over the last two decades, however, our reliance on oil has diminished and the use of coal and natural gas has increased.

Renewable Energy Sources

Solar Energy. Solar radiation is the most important renewable, or sustained-yield, energy source. It has the added benefits of being clean. If our present understanding of the evolution of stars is correct, the Sun will continue to shine for the next several billion years. The major problem, of course, is that **solar energy** is distributed over a broad area. To be used effectively in our urban societies, it must first be concentrated in a small control center, where it can be converted to electricity and then distributed.

Solar energy can be converted to electricity in several ways. One technology uses a very large array of mirrors and lenses to focus the Sun's energy to heat water, turn it into steam, and use the steam to turn turbines that generate

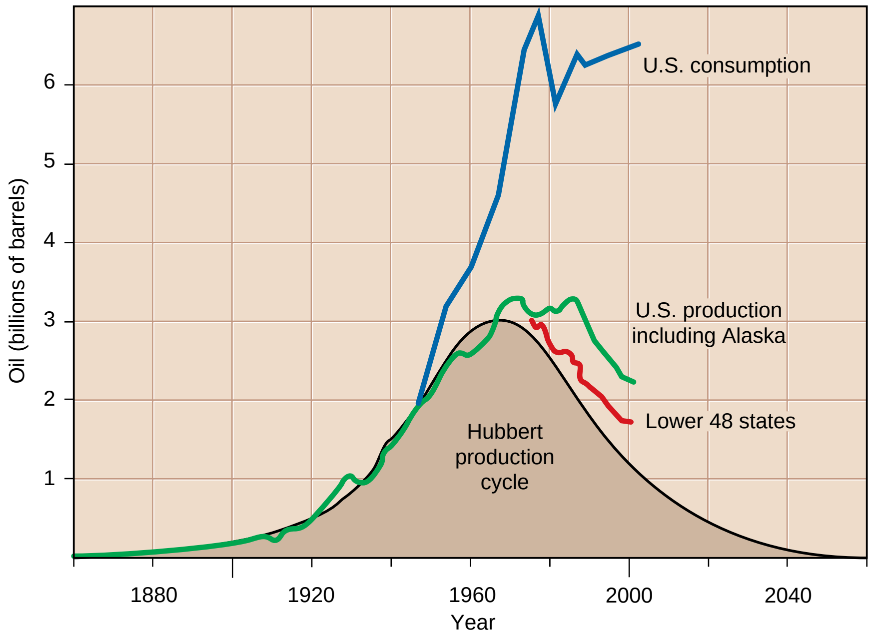


FIGURE 24.10 Projected rates of petroleum consumption in the United States were calculated in 1956 by M. King Hubbert. His analysis of reserves, production, and consumption rates predicted a decrease in production beginning in 1970, with supplies declining to near exhaustion by the year 2070. The major oil crisis that occurred in 1974 substantiates his remarkable projections. U.S. production (green and red curves) decreased soon after 1970.

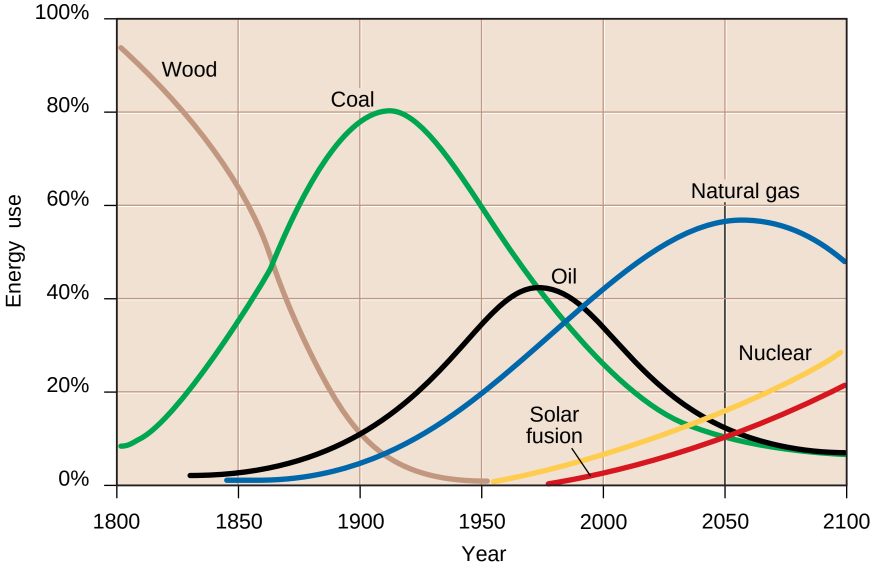


FIGURE 24.11 A world without oil. The history of energy sources for humans is marked by changes from wood, to coal, to oil. Future sources may be natural gas, hydrogen, solar, and fusion.

electricity. A more familiar, but technically more advanced, method involves the use of **photovoltaic cells** to convert sunlight directly into electricity (Figure 24.12). A variety of familiar electronic devices, especially calculators and outdoor lights, are powered by small arrays of these cells. The same technique is used to generate electricity for space satellites. Larger panels with many individual cells for collecting solar radiation have been mounted on buildings to provide some of the electrical needs of a household, but collecting systems for large-scale solar energy use, although technically feasible, are not yet economical. Although the technology is improving, photovoltaic cells are relatively inefficient, and large collectors are still necessary. For example, to satisfy the present needs for electrical energy in the United States, a collecting system covering 7000 km^2 (about twice the size of the state of Rhode Island) would be required. Experimental systems with many solar panels have been built in California. Moreover, experimentation with new materials may lead to more efficient photovoltaic cells. Currently, solar cells

FIGURE 24.12 Solar energy can be converted directly to electricity in photovoltaic cells, but the process is still quite inefficient. Large arrays of cells must be used to produce electricity for modern urban societies. This experimental array of solar cells in California is being used to test the technology for large-scale production of electricity. *(John Mead/Science Photo Library/Photo Researchers, Inc.)*

can extract only about 10% to 15% of the energy that falls on them, but theory suggests that more efficient cells could be developed to extract as much as 30% of the energy that falls on them.

More passive uses of solar power are becoming increasingly important for heating homes and businesses and producing hot water. Solar collectors can be mounted on south-facing roofs. These solar collectors consist of black panels filled with narrow tubes through which fluids circulate to collect heat from the Sun. Water can be heated and piped into the home, or air can be warmed by heat from the fluid in the collector.

What are the principal sources of renewable energy?

Limitations on the usefulness of solar energy include the number of sunny, cloud-free days in an area. More critical is the inefficiency of the current solar collectors. Large-scale solar energy use, therefore, is a long way away, although local use in individual homes and buildings reduces the need for other forms of energy.

Biomass—materials of biological origin—provides another way to collect, store, and use solar energy. Crops can be grown specifically for the production of fuel. For example, corn can be converted into liquid alcohol for use in automobiles. Alternatively, woody plants, grains, and even municipal garbage can be combusted to drive electrical generating plants. This technology has the added benefit of reducing the amount of landfill needed for waste, but on the other hand, combustion and fuel production facilities create pollutants, including carbon dioxide, that enter the biosphere.

Hydroelectric Power. **Hydroelectric power** is another sustained source of energy. In a sense, this is also energy extracted from the Sun, because the gravitational potential energy acquired by water is provided by the Sun as it heats the ocean surface to produce buoyant air laden with water vapor. Subsequently, the kinetic energy of water flowing downhill is used to turn turbines that generate electricity. The power plants are usually built in dams or at waterfalls on rivers (Figure 24.13). Hydroelectric power is relatively inexpensive and clean. As a side benefit, the dams are important flood-control devices and the reservoirs behind them serve as sources of irrigation water. Hydroelectric power constitutes about 4% of U.S. energy consumption, but it has been developed in the United States to approximately 25% of its maximum capacity. With full development, hydroelectric power would still provide only about 15% of the energy needed in the United States. To reach this level of production, however, large areas of wilderness and farmland would have to be flooded. A problem with hydroelectric generators is that, when a river system is modified by a dam, many unforeseen side effects may occur, including the destruction of natural habitats upstream and downstream from the dam (see the discussion of the Nile River in Chapter 12). Moreover, the reservoir behind the dam is only a temporary feature, destined to become filled with sediment. The useful life expectancy for most large reservoirs is only 20 to 200 years, so this source of energy is, in reality, limited.

FIGURE 24.13 **Hydroelectric power** is produced by channeling dammed rivers through turbines inside dams such as this one. Hoover Dam impounds the Colorado River to form Lake Mead in Nevada and Arizona. *(Lowell Georgia/Photo Researchers, Inc.)*

Wind Energy. Another indirect form of solar energy can be extracted from the wind. Windmills have been used for centuries to drive grain mills and pump water from shallow aquifers. Only recently, however, has the wind been used to generate electricity on a significant scale. For example, Denmark has embarked on a vigorous plan to exploit **wind energy.** Some parts of the country currently derive as much as 7% of their electrical energy in this way. Individual generators are scattered across the countryside. Elsewhere, large wind farms, consisting of as many as several thousand windmills, have been constructed in remote areas as in eastern California (Figure 24.14). Passes between mountains that funnel winds to high velocities are particularly favorable locations. California intends to eventually generate about 8% of its energy in this way.

Like many other solar-based energy sources, wind power has many advantages. It is pollution-free, releases no carbon dioxide or other greenhouse gases, requires no mining or processing of fuel, and has no radiation dangers. Moreover, virtually every country has plentiful wind resources that are free. However, individual

FIGURE 24.14 **Wind energy** can be extracted to produce electricity using modern propeller-driven turbines but has been used for centuries to drive windmills to pump water and grind wheat into flour. This field of turbines is in California.

windmills are moderately expensive, so wind energy is not an immediate solution to energy problems in developing countries. Moreover, much of our energy consumption is as portable fuels for automobiles and other transportation vehicles. Like all forms of solar energy, no portable fuel is a direct product of wind power, although electricity could be used to hydrolyze water and create gaseous hydrogen fuel. Wind power could also be used for electric vehicles if they become accepted and technical advances allow them to compete with gasoline-powered vehicles. In more-developed countries, the unseemly appearance, noise pollution, and large tracts of land set aside for power generation are of concern. If people come to accept these as trade-offs for a clean source of energy, wind power may become an increasingly important part of a diverse set of energy sources.

What limits the potential for wind energy to become an important energy source?

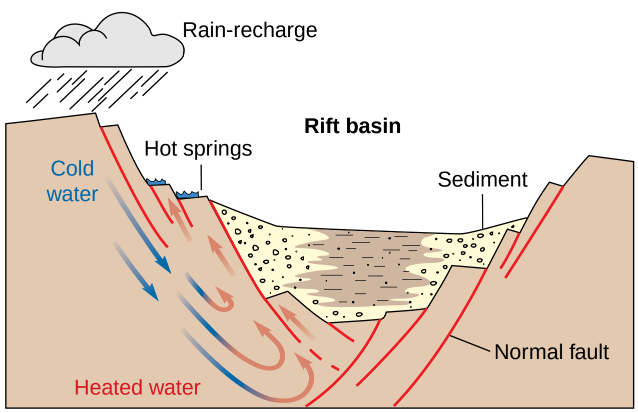
Geothermal Energy. Earth has its own internal source of heat, which is expressed on the surface by hot springs, geysers, and active volcanoes (Figure 24.15). In general, temperature increases systematically with depth, at a rate of approximately 3°C/100 m at shallow levels. Temperatures at the base of the continental crust can range from 400° to 1000°C, and at the center of Earth they are perhaps as high as 4500°C. Unfortunately, most of Earth's heat is far too deep to be artificially tapped, and the heat we can reach by drilling is typically too diffuse to be of economic value. Like ore deposits, however, **geothermal energy** can be concentrated locally and has been used for years in Iceland and in areas of Italy, New Zealand, and the United States. In most cases, this thermal energy is focused by hot groundwater or steam circulating at shallow levels in permeable rocks (Figure 24.16). Geothermal energy is concentrated where magma is relatively close to the surface. In addition, deep circulation of groundwater along normal faults in rifts produces concentration of hot springs used to produce electricity. Geothermal systems are similar to hydrothermal fluids that produce ore deposits. Hot springs and geysers are common manifestations of buried geothermal systems. These geothermal areas are most abundant above subduction zones, along continental rifts, and above mantle plumes.

Geothermal systems require a combination of special conditions. In addition to a large source of concentrated heat, such as a shallow magma chamber, a commercial geothermal system typically has to have a large reservoir of permeable rock with ample fractures and other pore spaces filled with water and steam. The heated water convects through the pore spaces, becoming hot as it nears the heat

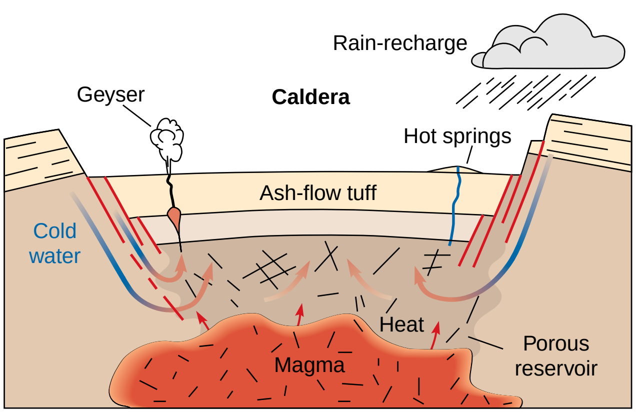
FIGURE 24.15 Geothermal energy stored in heated groundwater is extracted in facilities such as this one in New Zealand to generate electricity.

source, then rising and eventually cooling. In the most favorable settings, the permeable zone is capped by rocks of low permeability. This seal helps to contain the fluid, so that all of the energy is not expelled by convection of the water to the surface. Where geothermal water temperatures are above 150°C, electricity can be produced by pumping the fluids to the surface, where they flash to steam at low pressures. This energy can be used to drive a turbine and produce electricity. Cooler geothermal waters can be used for space heating. The homes in Reykjavik, Iceland, for example, are heated by geothermal water piped throughout the city. Elsewhere, geothermal water is used to heat greenhouses for growing vegetables and flowers year-long.

The United States, Philippines, Mexico, and Italy lead the world in the production of electricity from geothermal power plants. A few large geothermal systems, such as the Geysers of northern California or the Lardarello field of Italy, produce enough energy to power a large city, but geothermal energy currently accounts for less than 0.2% of that produced by oil and gas worldwide. Estimates indicate that, at its maximum worldwide development, geothermal energy would yield only a small fraction of the world's total energy requirements.



(A) In a fault-bounded rift basin, cold, near-surface water flows to great depth, where it is heated, and eventually returns to the surface along faults.



(B) In a large caldera, cold descending groundwater is heated when it gets near a hot magmatic intrusion. Hot springs and geysers form where the water returns to the surface.

FIGURE 24.16 Geothermal energy can be extracted from subsurface hot water tapped by drilling. The hot water forms by the deep circulation of water along normal faults in rifts or by heating above shallow, still-molten magma bodies.

Geothermal energy has several advantages over more traditional sources of energy. First, electricity produced by geothermal systems is relatively nonpolluting. Geothermal plants do not produce air pollution or carbon dioxide as do plants that burn oil or gas. Second, geothermal energy is renewable in the sense that the heat source is typically long-lived. A large magma chamber may take thousands of years to cool below the temperature needed to sustain an active geothermal system. A more immediate cause of the death of a geothermal system may be artificial or industrial extraction of the groundwater or steam faster than it can be resupplied. A diminishing supply of steam related to overproduction in the Geysers geothermal system of northern California limits the energy output of the power plants there. On the negative side, hot geothermal fluids carry high concentrations of dissolved salts and metals and are very corrosive to the pipes and other equipment that contains them. The discharge of the hot geothermal fluid can pollute neighboring streams, lakes, or aquifers. Moreover, as in any case where groundwater is removed, the withdrawal of geothermal fluids can cause subsidence of the surface over the circulating system.

Can geothermal energy provide all of our future energy needs?

Tidal Energy. Another sustained energy source is the ocean tides. **Tidal energy** can be harnessed by a dam built across the mouth of a bay where the tidal range is high. At the narrowed entrance to the bay, the rise and fall of the tides produce a strong tidal current that can be channeled through the dam and used to turn turbines that generate electricity. Tidal power cannot be generated along most continental margins, however. It is practical only where the tidal range is large, greater than 8 m or so. Large tidal ranges are enhanced by narrow, nearly enclosed bays. Tidal power plants have been built along the Bay of Fundy in Nova Scotia (Chapter 15), in Russia, and in China; the largest facility is in France at the mouth of the Rance River. No tidal power plants exist in the United States. Even with maximum development, however, tidal power could supply only 1% of the energy needed in the United States. Tidal power is renewable, as long as the Moon continues its gravitational tug-of-war with Earth's oceans. Moreover, it can be extracted without air or water pollution.

Fossil Fuels

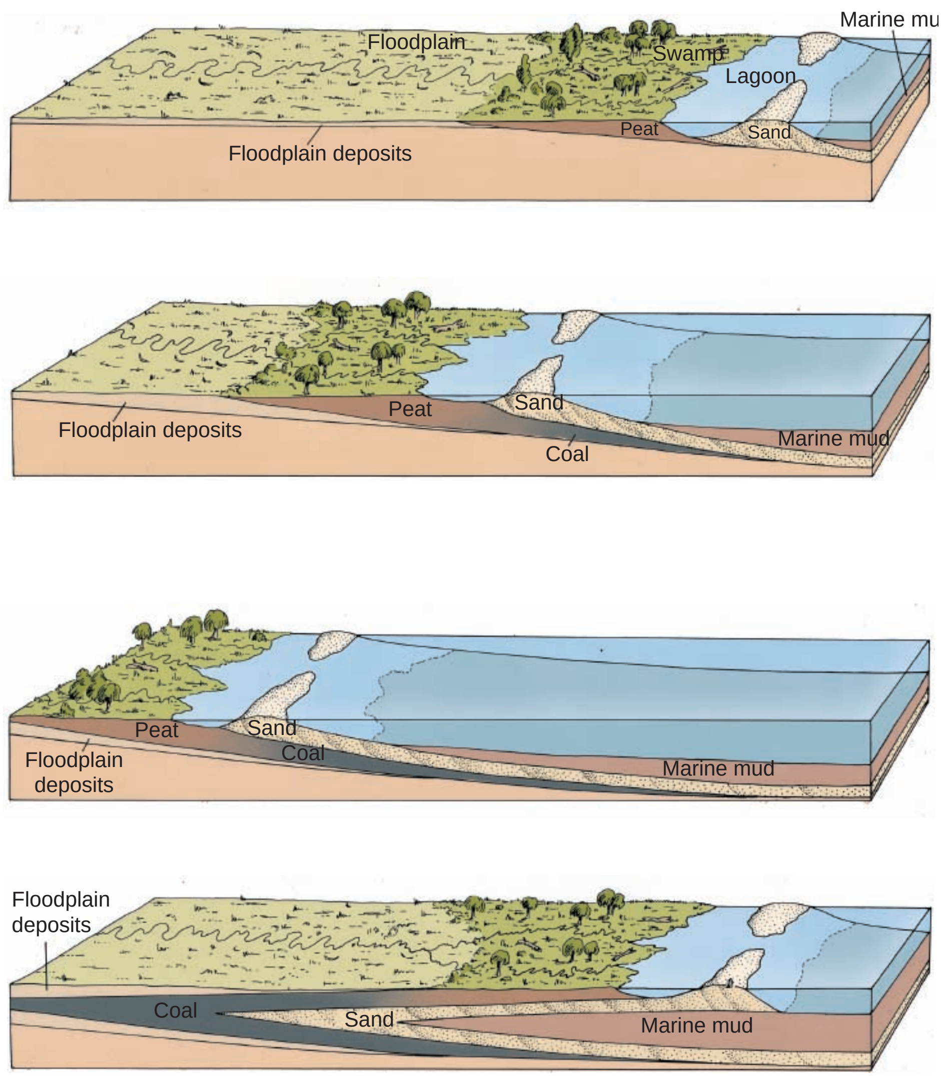
Coal, petroleum, and natural gas commonly are called **fossil fuels** because they contain solar energy preserved from past geologic ages. The idea that we currently use energy released by the Sun more than 200 million years ago may seem remarkable. Energy from the Sun is converted by biological processes into combustible, carbon-rich substances (plant and animal tissues). This organic matter may be subsequently buried by sediment and preserved. Only small proportions of all the organic matter in the biosphere is buried with the potential to become a natural resource. Most organic materials decay by combining with the oxygen in the atmosphere to produce carbon dioxide and water. In a manner of speaking, the storage of this ancient solar energy is a type of savings account we inherited from the distant past.

Petroleum

Coal. Extensive **coal** deposits originate from plant material that flourished in ancient temperate swamps, typically found in low-lying floodplains, deltas, and coastal barrier islands. Modern examples include the coastal swamps of Sumatra and the Great Dismal Swamp along the coast of Virginia and North Carolina. In this area, the lush growth of vegetation has produced a layer of **peat** more than 2 m thick, covering an area of more than 5000 km^2. In this environment, the layer of peat will eventually be covered with sand and mud from an adjacent lagoon and beach, as sea level slowly rises (Figure 24.17). Because of increased temperature and pressure from the overlying sediment, water and organic gases are cooked and squeezed out of the plant debris, causing the percentage of carbon to increase. By this process, peat is compressed and is eventually transformed into coal in a series of steps (Figure 24.18). The sequence lignite, subbituminous, bituminous, and anthracite marks this increase in rank, or metamorphic grade, of coal. Experimental studies show that this process proceeds at about 200° to 300°C; some anthracite coals have experienced even higher temperatures during tectonic folding and low-grade metamorphism. The coal itself is a complex mixture of graphitic carbon and more complicated hydrocarbons—hydrogen-carbon compounds made of molecular chains and rings. Some coals contain abundant plant fossils, including bark, leaves, and wood. If sea level rises and falls repeatedly, a series of coal beds can develop, interbedded with beach sand and near-shore mud.

Coal deposits are restricted to the latter part of the geologic record, when plant life became plentiful. The most important coal-forming periods in Earth's history were the Pennsylvanian and Permian Periods about 300 million years ago. Great swamps and forests then covered large parts of most of the continental platforms. (The Western industrial nations, such as Great Britain, Germany, and the United States, developed with energy from these coals.) Other important periods of coal formation were the Cretaceous and Tertiary. Coal deposits are nonexistent in Precambrian rocks.

Coal is an important energy resource because there are large reserves of it. With the completion of at least reconnaissance geologic mapping of most of the continents, all of the major coalfields are believed to have been discovered



(A) The sequence of sedimentary environments along a coast grades seaward from floodplain to swamp and lagoon, to barrier bar, to offshore mud.

(B) As the sea expands inland, each sedimentary environment shifts landward. Swamp vegetation is deposited over previous floodplain deposits, the sand of the barrier island is deposited over the previous swamp (peat) muck, and marine mud is deposited over the coastal sand. The heat and pressure of the overlying sediment change the peat to coal.

(C) Continued expansion of the sea superposes swamp deposits over floodplain sediments, beach sand over swamp material, and mud over beach sand.

(D) As the sea recedes, the sequence is reversed: The sand of the barrier island is deposited over offshore mud, coal is deposited over the sand, and floodplain sediments are deposited over coal. By expansion and contraction of the sea, layers (lenses) of sediments and coal are thus deposited in an orderly sequence.

FIGURE 24.17 **Coal deposits** are commonly formed by the expansion and contraction of a shoreline and involve the associated movement of a swamp and barrier bar.

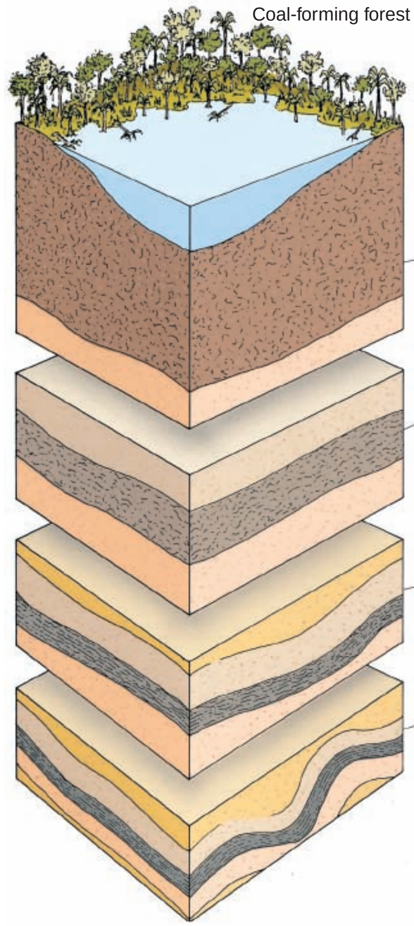


FIGURE 24.18 The origin of coal involves burial, compaction, and induration of plant material. The process begins in extensive swamps. Plant material produced in the swamp decomposes to form peat (about 50% carbon). Subsidence causes the peat to be buried with sediment, and the resulting increase in temperature and pressure compacts the peat, expelling water and gases and thus forming lignite and brown coals (about 72% carbon). With continued subsidence and deeper burial, the lignite is compressed into bituminous coal (about 85% carbon). Further compression (commonly induced by tectonism) drives out most of the remaining hydrogen, nitrogen, and oxygen, producing anthracite coal, which is about 93% carbon.

(Figure 24.19), and therefore a reasonably accurate inventory of the world's coal reserves can be made. Most of the reserves are found in the United States and Russia, so developing nations are not likely to grow by using vast amounts of coal. Coalfields in the United States can probably sustain our current rate of energy consumption for several hundred years.

Just over 20% of U.S. energy needs are met by using coal (Figure 24.9). In the early part of this century, coal played a much more important role as an energy source, providing more than three-quarters of the country's needs. With the technological developments that allowed oil and natural gas to be exploited, the importance of coal diminished. However, with the depletion of oil and gas, we are again witnessing a shift to reliance on coal. Coal is used largely to generate electricity. Undoubtedly, increased use of coal will bring with it serious environmental problems related to **strip mining** and acid rain produced by burning sulfur-rich coals.

What problems result from relying more and more on coal as an energy source?

Coal is probably the dirtiest of all fossil fuels. Considerable quantities of sulfur compounds are emitted by burning. Left unchecked, this sulfur is released into the atmosphere and there combines with water to make sulfuric acid. This acid is an important component of acid rain. Two highly industrialized portions of the world, eastern North America and northern Europe, have rain with pH of less than 4.2. Normal precipitation has a pH of about 5.7. Where the acid precipitation is not neutralized by reaction with carbonate rocks, the pH of streams and lakes also drops. Acid buildup is blamed for the near extinction of fish populations in southern Scandinavia. Fortunately, new technologies allow sulfur to either be removed from coal before it is burned or scrubbed from smoke before it is released to the atmosphere. Environmental acids are also created by the mining of coal. Pyrite is a common mineral in many coal layers. When it is exposed to oxygen-rich groundwater in open mines, it dissolves to create sulfuric acid that enters stream drainages (Figure 24.20). Present mining regulations in the United States and Canada have

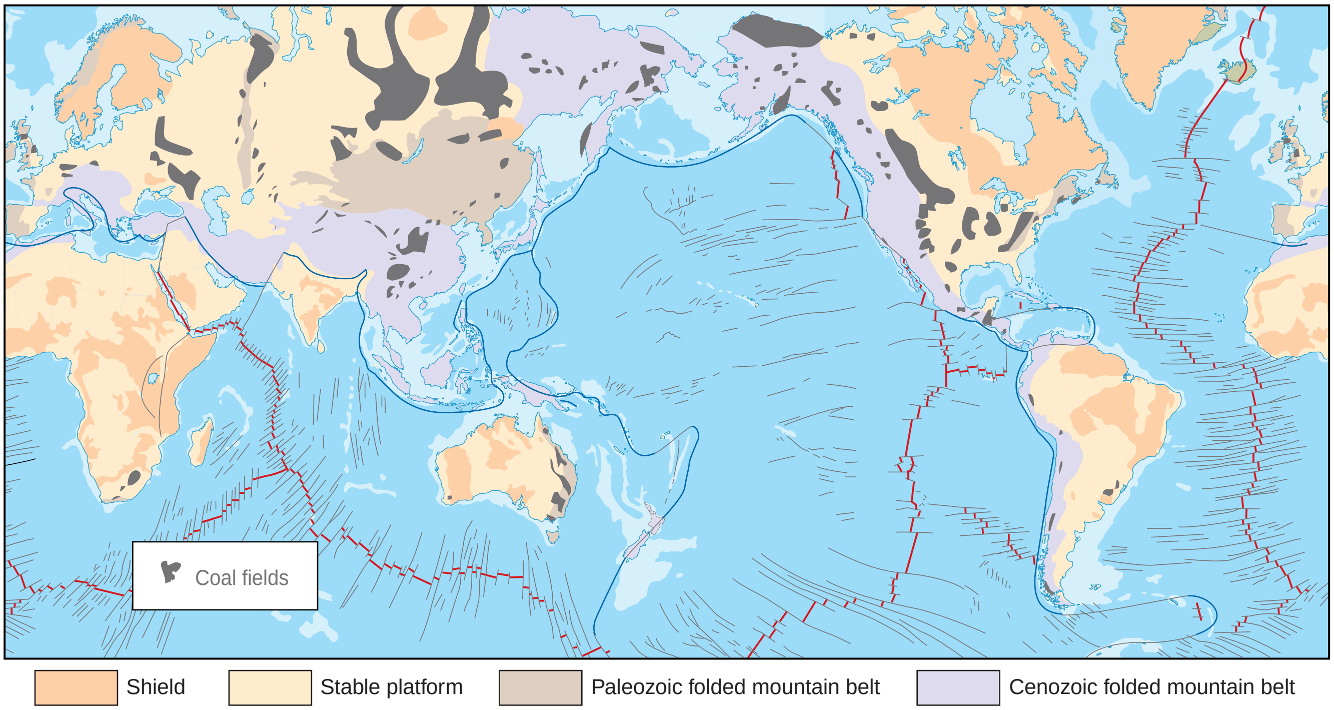


FIGURE 24.19 **The principal coal deposits** are concentrated in fluvial and deltaic sedimentary rocks on the continental platforms.

largely alleviated this problem. Another problem with the use of coal as a source of energy is that large volumes of ash are left after burning. Ash may be as much as 30% of the coal. It consists of clastic material such as clay and quartz that were included in the ancient swamps. Large quantities of gypsum sludge are also created in removing sulfur from the smokestacks. Other problems with coal mining are related to the destruction of the natural landscape in strip mines and subsidence over some underground mines.

Petroleum and Natural Gas. Petroleum and natural gas are hydrocarbons. Natural gas consists largely of the simple organic molecule known as methane (CH_4). Crude oil is made of larger and more complex molecules composed only of hydrogen and carbon linked together in chains and rings. In contrast to coal, the hydrocarbons forming oil and gas deposits originate largely from microscopic algae and other plants and animals that once lived in the oceans and in large lakes. The remains of these organisms accumulated with mud on the seafloor. Because of their rapid burial, they escaped complete decomposition.

Deposits of oil and gas form if several basic conditions are met. *First,* the source beds must have sufficient organic material in fine-grained sediments. The environment of deposition must be poor in oxygen to prevent destruction of the organic materials before burial. *Second,* the beds must be buried deep enough (usually at least 500 m) for heat and pressure to compress rock and cause the chemical transformations that break down organic debris in the **source rocks** to form hydrocarbons. Oil generation usually begins when temperatures reach 50° to 60°C. At about 100°C, methane is produced as the complex molecules break down to form simpler ones. *Third*, the materials must migrate from the scattered pores in the source beds to become concentrated. Once formed, the hydrocarbon fluids are squeezed by compaction out of the shales. Because of their low densities, these fluids generally migrate upward from source beds into more porous and permeable rock (usually sandstone or porous limestone or dolomite) called **reservoir rocks.** *Fourth,* as the oil and gas migrate through the reservoir beds, a physical barrier, or **hydrocarbon trap,** must cause the oil or gas to accumulate. If the reservoir beds provide an unobstructed path to the surface, the oil and gas seep out at the surface and are lost.

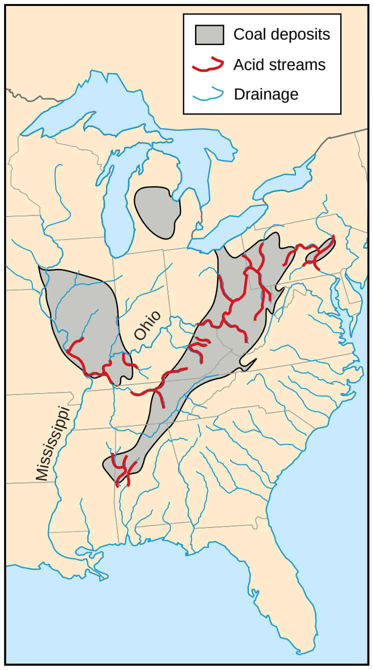


FIGURE 24.20 **Streams in the eastern United States became acidic** when pyrite was oxidized during the weathering of coal mines. Modern environmental regulations have returned these streams to more normal conditions.

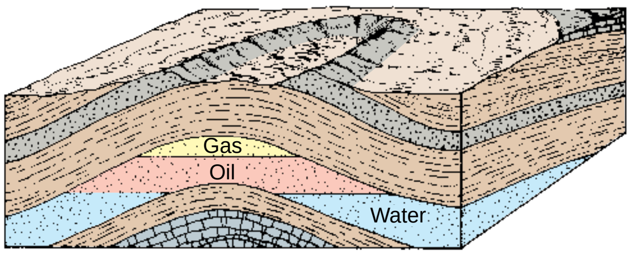
This is one reason why most oil and gas deposits are found in relatively young rocks. In older rocks, there has been more time for erosion and Earth movements to provide a means for the oil and gas to escape. Traps in the path of oil's upward migration can result from a variety of geologic conditions, such as those shown in Figure 24.21. Most traps involve some sort of permeability barrier. For example, shales are much less permeable than sandstones and provide effective cap rocks for many oil and gas deposits. Exploration for oil and gas, therefore, is based on finding sequences of sedimentary rocks that provide good source and reservoir beds and then finding an effective trap. Gas, oil, and water all migrate together, but once trapped, they separate from one another on the basis of their densities. Natural gas is the lightest and fills the pore spaces in the uppermost part of the reservoir; oil occupies an intermediate position and floats on water (Figure 24.21).

Why can't we find oil deposits in the shields?

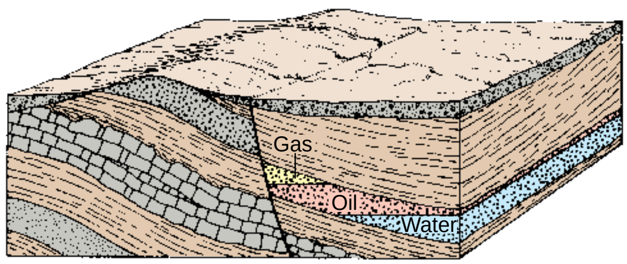
If any component of this sequence is missing, a hydrocarbon deposit will not form. For example, only about 250 of the 800 sedimentary basins produce oil or gas (Figure 24.22). Some basins may not have organic-rich source rocks. Others have adequate organic materials, but the sediments have not yet been buried deep enough for oil and gas to form. In many others, oil and gas formed but have subsequently leaked from the rocks because traps were inadequate. Groundwater may permeate a basin and strip the reservoirs of oil. The age of source rocks is not as critical as for coal deposits, but because of progressive leakage, young sedimentary rocks are more productive than older ones. Algae, the principal source of oil, have been on Earth for a very long time and oil of Precambrian age is known.

Oil and gas are commonly extracted from Earth through holes drilled through the trap rock and into the permeable reservoir. This simple fact makes oil and gas much more economical to produce than many types of solid mineral resources. The fluids may be under sufficient pressure to flow to the surface on their own, or they may be pumped out (Figure 24.23). In some fields, water, natural gas, or even steam is pumped into the subsurface to flush more oil or gas from a reservoir.

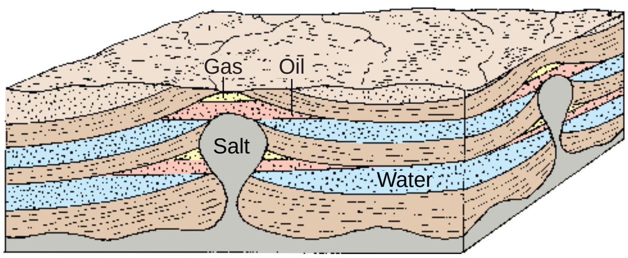
Environmental problems associated with oil and gas production are not as severe as for coal mining. However, oil extraction can lead to subsidence, just like that



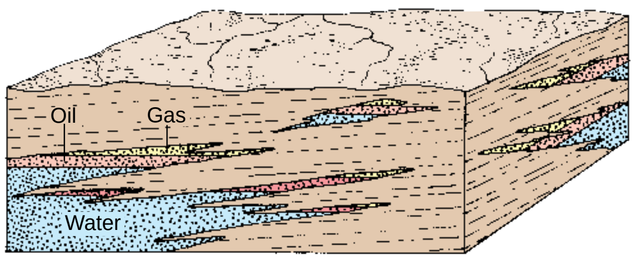
(A) Anticline. Oil, being lighter than water, migrates up the dip of permeable beds and can be trapped beneath a relatively impermeable shale bed in the crest of an anticline.



(B) Fault trap. Impermeable beds can be displaced against a permeable stratum and then trap the oil as it migrates up dip.



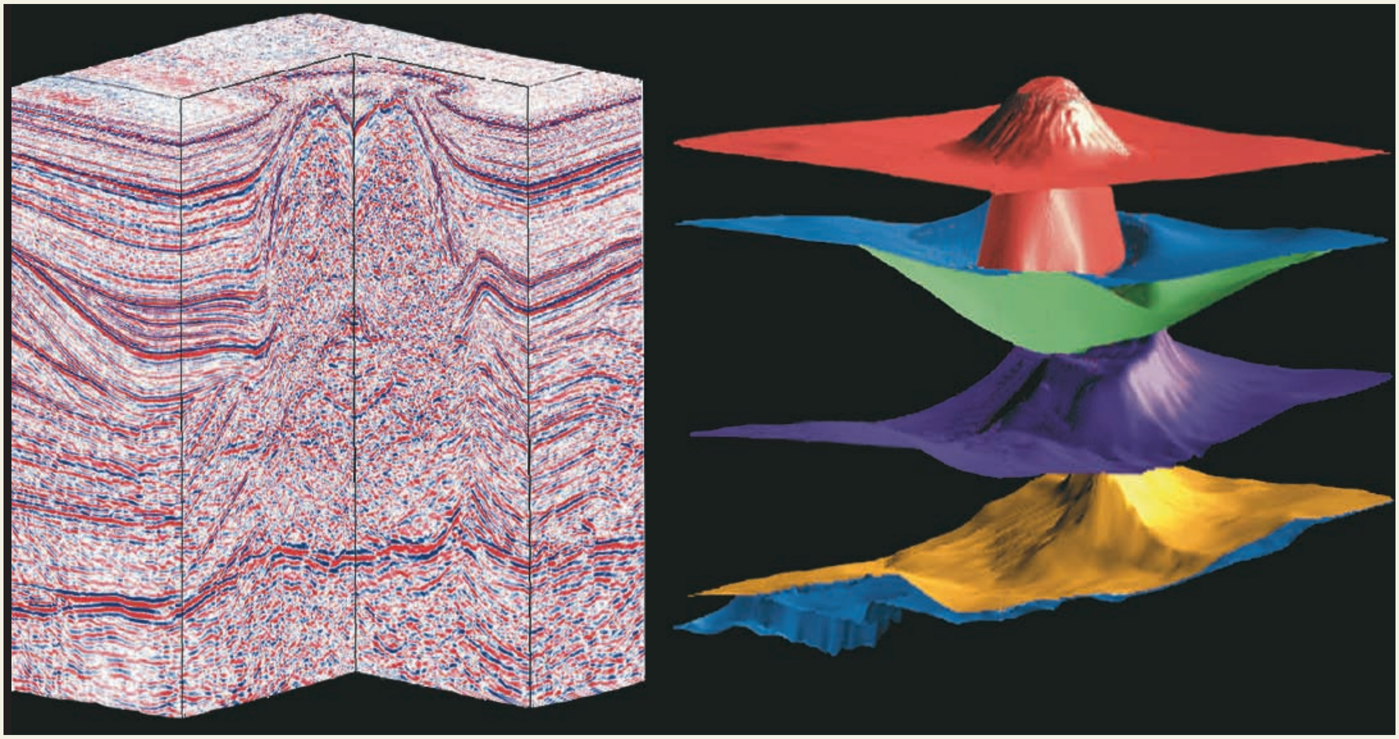
(C) Salt dome. Oil and gas may accumulate near the flanks of salt diapirs that pierce and arch up sedimentary layers.



(D) Stratigraphic trap. Shale surrounding a sandstone lens can form and prevent the oil from escaping.

FIGURE 24.21 **The accumulation of oil and gas** requires (1) a reservoir rock (a permeable formation, such as a porous sandstone) into which the petroleum can migrate and (2) a barrier (an impermeable cap rock) to trap the fluids. Some of the geologic structures that trap oil and gas are shown here.

STATE OF THE ART — *Three-Dimensional Seismic Imaging*



(Courtesy of Compagnie Generale de Geophysique, data from BEB)

Geologists are trained to look at a two-dimensional surface, such as a landscape or road cut, and construct a mental image of the third dimension. For example, a team of geologists may make a geologic map showing the distribution of various geologic units on the surface—a two-dimensional view (see p.179). They may then, by a process of interpretation, draw a vertical cross section showing how the outermost layers, faults, and folds extend below the surface where no one can see. Every geologist longs for a type of "X-ray vision" that would reveal what the structure of the interior is really like. Seismic investigations are one way that this can be done.

Seismic geophysicists specialize in these techniques and their skills are widely employed in oil exploration. A marine survey is conducted on a ship with an air gun that sends a series of acoustic (sound) pulses toward the bottom of the sea. This energy travels as compressional waves to the seafloor, where some of it enters the sediment and rock as seismic waves. Portions of this seismic energy are reflected back to the surface by the layers of sediment. Sensors towed behind the ship detect the reflected energy and time its arrival back at the surface. In this way, an image of the discontinuities (usually faults and sedimentary layers) in the crust can be constructed. Such information is usually shown as a vertical cross section—a *seismic section*—much like one that might be constructed from interpretation of a map. Figure 19.2 is a vertical seismic profile.

In the last 10 years, the capabilities of computer processing have increased so rapidly that a single vertical section is no longer the goal of a seismic survey. Instead, the surveyors make a series of traverses across a region to create an array of sections that can be combined in a computer to construct a three-dimensional image that reveals the subsurface geology.

Using powerful computers, these blocks can be sliced anywhere and at any angle to allow a geologist to see the structure from any perspective. Multiple "maps" can be viewed; vertical sections can be stacked together and played back like a movie while a geologist traces faults or distinctive beds through the three-dimensional image. In fact, some oil companies have developed special rooms with multiple projectors that allow teams of geologists with special headsets to "walk through" a virtual-reality model of the crust. They explore details of the structures that might help them find deposits of oil that can later be drilled and exploited. The diagram above is a three-dimensional seismic image sliced to show the subsurface structure of a salt dome in Germany. The layers of sedimentary rock show up as red, blue, and white stripes, cut by the irregular dome. The colored planes to the right show the configuration of several deformed layers as revealed by the seismic image. The "surface" of this block is actually a horizon at depth. These tools have dramatically changed the way an oil company looks for new deposits and increased their success rate.

caused by the extraction of groundwater. For example, parts of Long Beach, California, subsided by as much as 8 m by 1967. Subsequently, water injection has stopped the subsidence. Injection is a common practice in other fields now. Oil spills are another form of environmental problem, but they are associated more with the transportation of oil in large tankers than with production.

In some geologic environments, the hydrocarbons remain as solids in the shale in which the organic debris originally accumulated. These deposits are known as **oil shales.** They are reservoirs of oil that may become important in the future. There are huge reserves of oil shale (Figure 24.22). The United States has more than 10 times more oil that could be recovered from shale than it does from conventional wells. Most of the oil shale in North America lies in the Green River Formation of Colorado, Wyoming, and Utah. The shale was deposited in a series of shallow Tertiary lakes. The problem with all oil shale is that it must be mined and heated to extract the oil. This process requires considerable energy and water resources and is not yet economically feasible. Reclamation of strip mines and the safe disposal of processing wastes are also costly.

Oil and gas are convenient forms of energy because they are easy to handle and transport. Currently, about 40% of the U.S. total energy needs comes from petroleum, and another 25% comes from natural gas. Unfortunately, at the present rate of consumption, the known reserves of oil will be depleted in about 50 years. In the United States, reserves are only about 10 times our annual consumption. World gas reserves are not projected to last much longer at current usage rates. Obviously, the real lifetime of our oil reserves will depend upon the actual price of oil in the future, upon world politics, and upon the further development of technology and energy conservation efforts. If the current trends continue, we will soon be forced to begin large-scale gasification and liquefaction of coal and oil shale deposits and to rely more on coal-fired electrical plants combined with nuclear and solar energy. Clearly, we can expect to pay a great deal more for petroleum in the future and should use alternative sources of energy whenever possible.

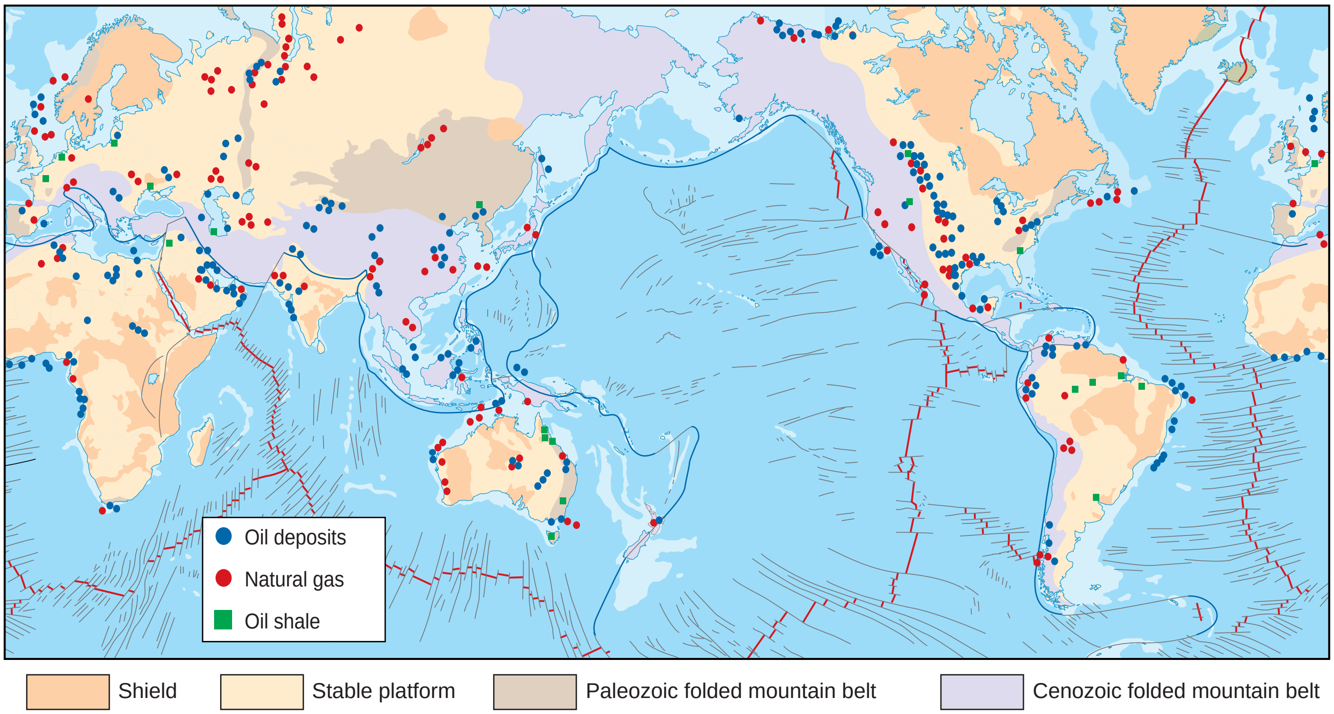


FIGURE 24.22 **Major oil and gas fields and deposits of oil shale** are found on all of the continents except Antarctica. Most form in thick sedimentary deposits on continental crust. The rifted margins of Africa, South America, and Europe are important oil-producing environments. Other important fields lie in the sedimentary basins of the platform and the flanks of folded mountain belts.

FIGURE 24.23 **Oil wells** such as this in the North Sea are important symbols of our modern society. About $600 billion of oil and gas are produced each year. Oil is the most expensive basic commodity of our modern society. *(Keith Wood/Tony Stone Images)*

Methane Hydrates. This icy substance forms where rising bubbles of methane gas, given off as bacteria digest organic matter in mud, react with cold seawater (Figure 24.24). The ices are concentrated in a layer about 100 m thick where pore spaces between sediment particles are filled with the hydrate. Gaseous methane is trapped beneath this impermeable cloak.

Methane hydrates were first discovered on the seafloor in the 1970s. They are now known to cover vast areas of the seafloor where the water is deep and cold enough. These ices may contain twice as much carbon as all other petroleum, coal, and natural gas sources put together. However, the highly volatile hydrates will be very difficult to mine. The gas cannot simply be drilled into and then pumped on shore. Even if a way can be devised to economically extract these valuable materials from the seafloor, there are concerns about the effect of releasing methane into the atmosphere, either during mining or if seawater warms by continued global warming.

What are the limitations of using oil shale as an energy source?

Methane is a greenhouse gas and decomposition of hydrates may contribute to global warming. In turn, release of methane gas from the icy hydrates could be triggered by warming of the seafloor related to climate change. Several large submarine landslides may have been triggered when hydrates decomposed as the ocean warmed at the end of the last ice age. One landslide on the continental slope off Norway slid 800 km and probably induced a large tsunami that inundated Scotland. Elsewhere, craters as large as 700 m across pockmark the floor of the polar Barents Sea and may mark places where methane gas vented explosively to the surface as climate changed. It is conceivable that a large gas release could warm the planet further and help to create other landslides and release more gas from the seafloor, forming a complicated feedback cycle. Some scientists have speculated that a sharp rise in sea temperatures, extinctions of tiny marine animals, and fossil composition changes were all related to a massive release of seafloor methane 55 million years ago.

Nuclear Energy

The ever-increasing demands for energy and the decreasing supply of fossil fuels naturally put the spotlight on nuclear power as an answer to our energy requirements. The technology of **nuclear energy** production is well developed. Nuclear energy is commonly generated by the controlled fission of uranium-235 in what is known as a nuclear reactor. The fission is produced by bombarding the uranium

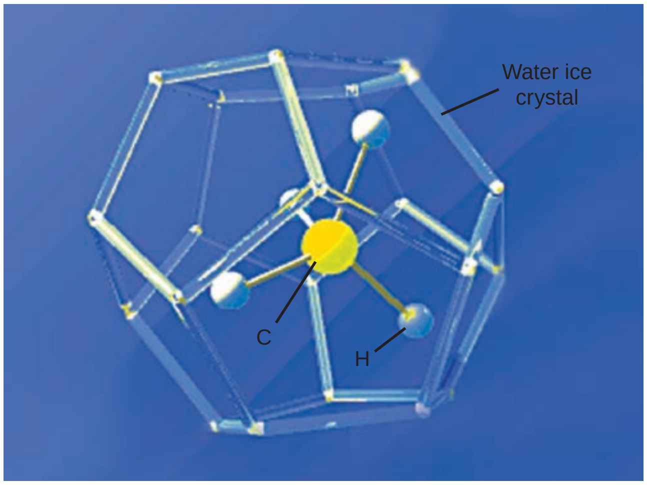


FIGURE 24.24 **Methane hydrates** consist of a methane molecule (CH_4) trapped inside a crystalline "cage" of frozen water (left). They form on the deep seafloor as methane released by bacteria bubbles upward and is trapped in ice. They may be abundant enough to form an important source of natural gas and will burn if ignited with a match (right). However, they will be difficult to mine and pose environmental hazards because methane is a greenhouse gas. *(Illustration courtesy of J. Booth, USGS, Woods Hole, MA; photograph by John Pinkston and Lama Stern/USGS, Menlo Park, CA)*

in a fuel rod with neutrons. As a result of the splitting of the uranium nucleus into lighter isotopes of other elements, a small mass is converted to heat energy. This heat is used to drive steam turbines that generate electricity.

Contemporary society, however, has hesitated to move toward large-scale production of nuclear energy because of the possibility of environmental problems and potential for cataclysmic accidents. Radiation hazards during mining and energy production, problems of waste disposal, and thermal pollution of fresh and marine waters, as well as potential terrorist activities, are among the greatest concerns. For example, if the rate of fission is not carefully controlled, the reaction may become a rapid and destructive chain reaction. Enough heat may be released to melt the floor of the reactor, dropping hot radioactive materials to the water table. If the water table is shallow, steam explosions, like those generated by magma-water interactions, may shower radioactive debris over a large area. Even small releases of steam from small accidents can release harmful doses of radioactive materials. Increasing costs for government-mandated safety regulations, combined with a small accidental leak of radioactive materials at the Three Mile Island reactor in Pennsylvania in 1979, turned public opinion against the use of nuclear energy in the United States and much of the rest of the world. As a result, the price of uranium dropped precipitously, and uranium production has also dropped. The nearly catastrophic failure of the Chernobyl reactor, in what is now the Ukraine, showed even more people about the potential dangers associated with nuclear reactors. A partial meltdown at this reactor in 1986 released a cloud laden with radioactive by-products across much of central Europe.

Only when these hazards and disposal problems are solved will nuclear energy become a more important source of energy. France is the one country that has moved toward large-scale production of electricity from nuclear energy. About 75% of its electricity is produced in nuclear reactors. Belgium (60%), South Korea (49%), Sweden (46%), Switzerland (43%), Spain (38%), Taiwan (38%), Bulgaria (36%), and Finland (35%) all produce major proportions of their electricity in nuclear reactors. In contrast, the United States produces only about 20% of its electricity in this way and Canada only about 14%. A few countries, most notably Italy, have complete bans on the production of nuclear energy.

The key element in the development of nuclear energy is uranium. The average uranium content in the rocks of Earth's crust is only 2 parts per million. At current prices, uranium concentrations must be as high as 5000 parts per million before the ore can be mined profitably. Uranium is concentrated by a variety of igneous, metamorphic, and sedimentary processes. For example, uranium is concentrated in rhyolitic magma by fractional crystallization. Explosive eruptions may shower the rhyolite as ash over large areas, where it weathers by reactions with the atmosphere and water. As the glassy ash reacts with oxygen, the uranium becomes oxidized and water-soluble. The uranium is then leached out of the rock and transported by surface water and groundwater. It can later be deposited and highly concentrated if a barrier to its transport is encountered. In this case, the barriers are usually chemical rather than physical. In permeable sedimentary rocks, uranium may be absorbed by clay minerals and reduced to its insoluble state by carbonaceous organic matter. The rich uranium deposits in the Colorado Plateau of the western United States probably formed in this way and are concentrated in ancient stream channels, especially where fossil wood is found. Other important uranium deposits form as vein deposits in granite and as placers of heavy uranium oxides in ancient (older than about 2.2 billion years) stream channels. Canada, Russia, the United States, Australia, Namibia, and France are all important producers of uranium ores (Figure 24.25).

What are the advantages of nuclear energy?

PLATE TECTONICS AND MINERAL RESOURCES

Earth's system of plate tectonics creates many different environments favorable for the creation of mineral deposits and accumulations of fossil fuels. Understanding these associations has led to the discovery of new deposits that sustain a high standard of living for many people.

Plate tectonics is important to understanding the genesis of and exploration for new mineral resources. Plate margins are where many of Earth's dynamic processes prevail, including magma intrusion, faulting, and folding. Moreover, the tectonic setting determines the type of sedimentary rocks that accumulate in a region. Even weathering and stream processes are controlled by a continent's climate belt, a product of plate movement. Following, we briefly review some of the most important types of mineral resources found in each of the four types of tectonic settings discussed earlier.

Divergent Plate Margins

Basaltic volcanism, normal faulting, and sedimentation in closed basins are the products of continental rifts. A distinctive suite of ore deposits forms because of these geologic processes (Figure 24.26).

For example, the great intrusions of mafic magmas developed in rifts have produced magmatic segregation deposits of sulfide ore rich in platinum and copper. Basaltic lavas erupted in continental rifts are also rich in copper that can be extracted by groundwater circulating on deep faults and later deposited in enriched zones as native copper. Many native copper deposits of northern Michigan formed in a rift that is more than 1 billion years old. Proterozoic rifting in what is now the Yukon and the Northwest Territories of Canada also produced native copper deposits. In this narrow rift, more than 3 km of basaltic flows are overlain by 4 km of clastic sediments including conglomerates. The entire sequence is capped by evaporites to form a classic rift sequence of rocks.

In other continental rifts, the evaporites are the principal mineral resource. Rifts may contain evaporites related to playa lakes. Deposits of salt, soda, potash, and gypsum, as well as mineral-laden brines, are extracted from rifts in East Africa and the Basin and Range Province of the western United States.

Divergent boundaries on the ocean floor also have a characteristic suite of mineral resources that owe their origin to basaltic magmatism, high heat flow, deep fractures, and abundant seawater. For example, pods or layers of chromium and platinum minerals form in or below oceanic-ridge magma chambers. A slice of mineralized oceanic crust that is thrust onto a continent as an ophiolite may become an ore deposit.

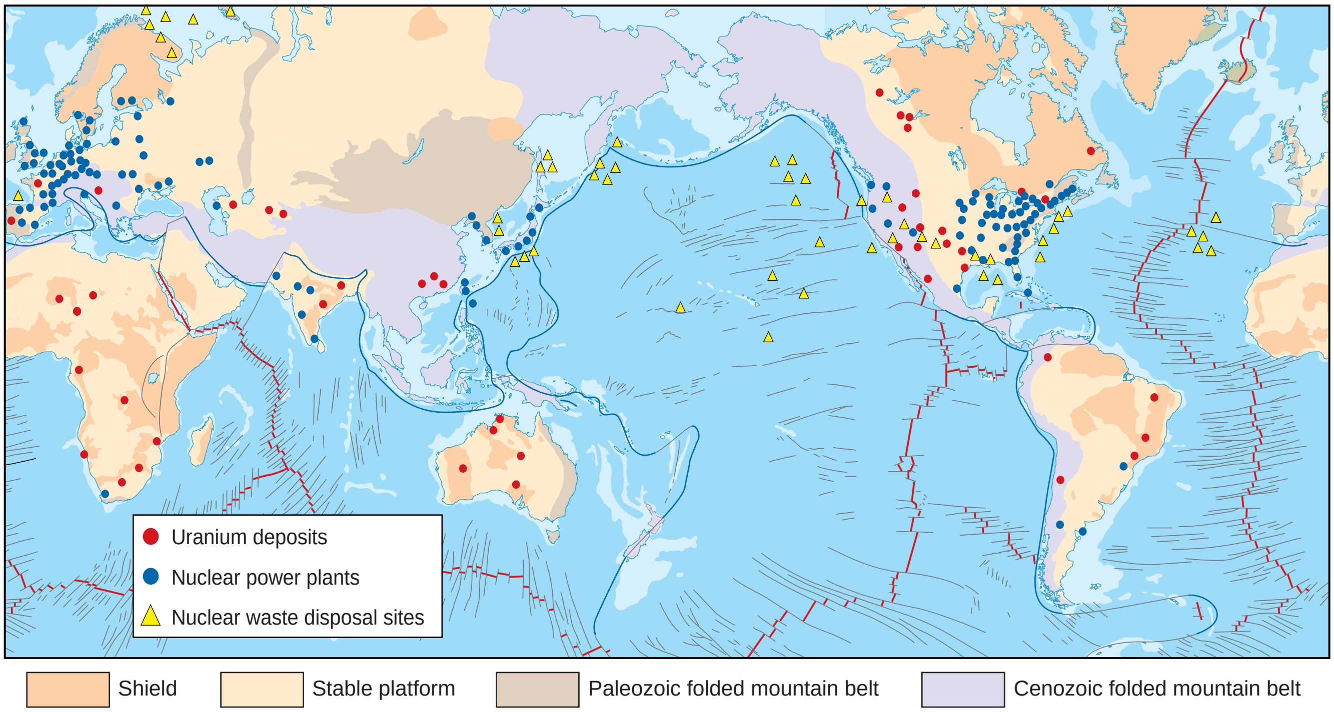


FIGURE 24.25 Uranium deposits and nuclear reactors may become a key part of the future production of energy, but only if the public becomes convinced that nuclear reactors are safe and that their waste products can be safely stored in repositories for long periods of time.

In addition, seawater becomes a hot brine when it circulates through the oceanic crust and then vents onto the seafloor. Ancient hydrothermal mounds, such as those described in Chapter 19, have formed important sulfide deposits sought for their copper and zinc. Only those brought to the surface in ophiolite complexes can be mined today. The copper deposits of the ophiolite on the island of Cyprus are a characteristic example of this seafloor mineralization.

Rifted continental margins gradually evolve into broad submarine shelves where shallow-marine sediment collects. The cooling and subsidence of the once-hot elevated margins are the important geologic controls here. Many of Earth's most important resources are formed in this divergent margin environment. Large deposits of oil, gas, and coal form in sediments deposited in tropical or subtropical environments such as this. During the Proterozoic, banded iron formations formed as sedimentary precipitates along continental shelves. At other times, ocean upwellings formed phosphorus deposits on the shelves that are now mined as fertilizer on the coastal plains of the eastern United States.

Many important beach placer deposits also form on rifted continental margins. Erosion of a continental shield and concentration by longshore drift have formed ore deposits of dense minerals with titanium, niobium, zirconium, and rare earth elements.

Convergent Plate Margins

The role of convergent margin processes in producing many deposits is exemplified by the distribution of porphyry copper deposits (Figure 24.1). Many hydrothermal deposits of copper and other metallic ores (molybdenum, lead, zinc, silver, and gold) are associated with diorite to granite intrusions formed above subduction zones. Porphyry copper deposits are found in island arcs and in continental volcanic arcs (Figure 24.26). In some cases, the volcanoes themselves host the ore deposits. The copper ores of western North and South America, Iran, Pakistan, Philippines, and New Guinea are examples of relatively young porphyry copper deposits.

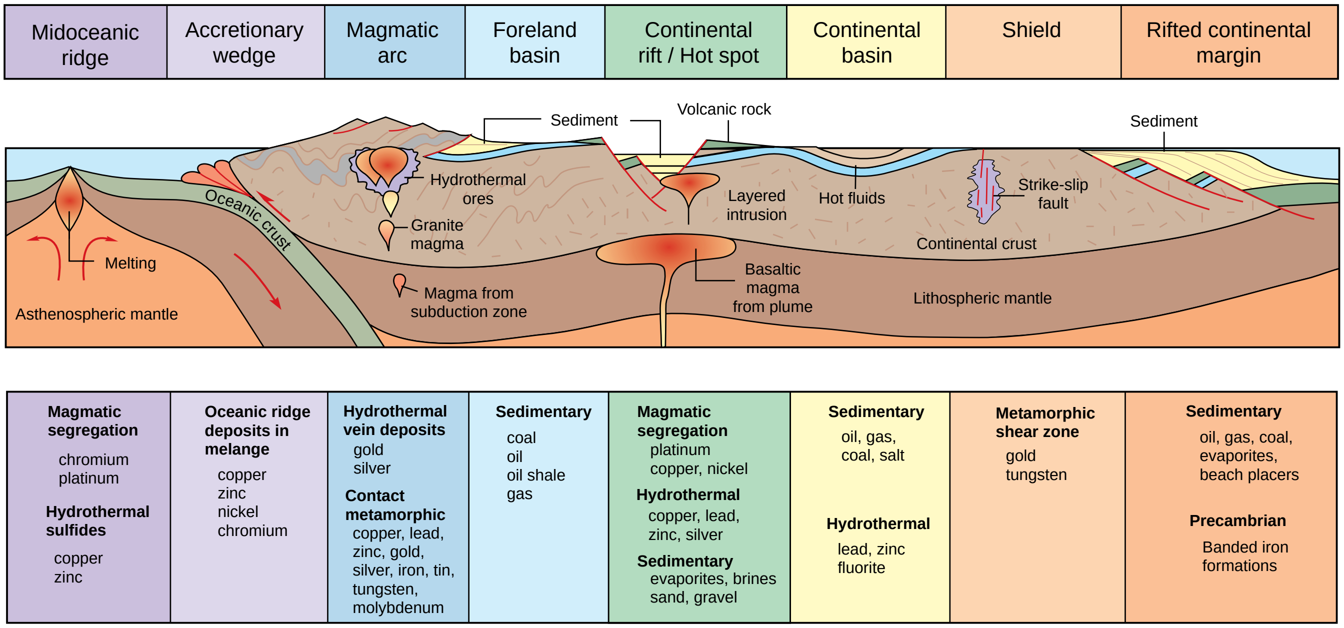


FIGURE 24.26 **Mineral resources are intimately related to the plate tectonic system.** Some of the major ore-forming environments are shown on this schematic cross section. Plate tectonics controls igneous, sedimentary, and metamorphic processes and even the climate; it therefore exerts a major control on the types of ore deposits formed at any location and time.

The collision of two continents produces fewer ore deposits, but distinctive granites do form by partial melting of the continental crust. Hydrothermal and placer deposits of tin form in and near these granites. The tin deposits of Malaysia, Indonesia, and southeastern China may have formed in this tectonic setting.

Oil and gas deposits are commonly related to convergent plate boundaries. As noted above, organic-rich sedimentary rocks are deposited on rifted continental margins. In time, many of these rift-margin sequences become involved in plate collisions of various sorts. Convergent margin thrust systems may bury organic-rich sedimentary rocks to sufficient depths to cause oil or gas formation in sediments that otherwise would remain cool and unproductive. Deformation also creates pathways for the oil and gas to migrate and, ultimately, become trapped. The most obvious of these structures are found in fold belts, where anticlines may be natural petroleum traps.

What mineral resources would you expect to find in the area where you live?

Transform Plate Boundaries

Mineral resources along transform boundaries are represented by the oil and gas fields of southern California. Small pull-apart basins between offsets in the strike-slip faults of the San Andreas transform fault system are ideal for accumulation of clastic sedimentary rocks rich in organic materials. Continued faulting, subsidence, and sedimentation bury these strata to depths where oil and gas can form and migrate to a variety of stratigraphic and structural traps.

A few deep shear zones in the continental shields may be ancient transform faults (Figure 24.26). Some have gold deposited by hydrothermal fluids that passed along the permeable fault zones. Otherwise, metallic ore deposits are rare along transform plate boundaries, mainly because igneous rocks are also rare.

Intraplate Settings

Mineral deposits found in plate interiors are also distinctive. Two different types are worth considering here. The first type is found in stable platforms where sedimentary rocks accumulate in broad, slowly subsiding basins. Hydrothermal fluids formed here may concentrate a variety of elements, including lead, zinc, and fluorine. Important deposits of this type are found in Paleozoic sedimentary rocks of Missouri, Wisconsin, and Tennessee and in the Pine Point region of the Northwest Territories of Canada. Other sedimentary basins, such as the Witwatersrand of South Africa, contain ancient placer deposits of gold and, if old enough, uranium minerals. Intracontinental basins also contain many of the world's important evaporite deposits, including those in the Michigan Basin, central Europe, and the Paris Basin. These same sedimentary basins, if they were also filled with sufficient organic materials, may lead to coal, oil, and gas deposits.

The second type of resource is associated with hotspots or mantle plumes—in either oceanic or continental settings. The vast magma bodies formed from plume heads have been important sources of some metallic resources. For example, the large Noril'sk ore deposit of Siberia formed at the same time that the flood basalts of the Siberian traps erupted. The ores formed by magmatic segregation of nickel, copper, and platinum.

Mantle plumes beneath continents may also produce granites that have hydrothermal deposits of tin. Such granites are important sources of tin minerals that were further concentrated in placer deposits in Nigeria, for example.

LIMITS TO GROWTH AND CONSUMPTION

> Rapid population growth and the associated industrial expansion cause consumption of natural resources to increase at an exponential rate. We are finding that there are limits to growth. These limits will probably be reached through the depletion of natural resources.

The consumption of natural resources is proceeding at a phenomenal rate. The rapid population growth that has prevailed during the last few hundred years is unprecedented (Figure 24.27). There are currently about 6 billion people on the planet. It took history until about A.D. 1830 to reach a population of 1 billion. The population doubled in the next 100 years and doubled again in the next 45 years.

Just how many people can Earth hold? Estimates range widely, but most hover near 10 to 15 billion people, surprisingly close to the estimate of Leeuwenhoek, the Dutch naturalist famous for his use of early microscopes. In 1679 he suggested that Earth could sustain no more than 13.4 billion people. He based his estimate on the population and area of the Netherlands and extrapolated that population density over two-thirds of Earth's land area. Obviously, this must be an upper limit, because the Netherlands sustains such a high population density by importing many of its resources. However, if the growth rate for the last century persists, the population will reach his estimated limit in the next century.

The challenge is basically one of changing from a period of growth to a period of nongrowth. This change will require a fundamental revision of current popular economic and social thinking, which is based on the assumption that growth must be permanent and the even more basic assumption that growth must occur for society to prosper. It is important, therefore, to consider how resources are used and the rates at which they are being depleted. Perhaps the most critical point to make is that the rate of resource consumption increases exponentially. The exponential rate results both from population growth and from the growth of the average annual consumption per person, which increases yearly. In other words, growth is exponential because of an increasing population and a rising standard of living.

Studies show that the limits of population growth probably will not be imposed by pollution. The limits will be established by the depletion of natural resources. The projected interaction of some major variables, as the population grows to its ultimate limits, is shown in Figure 24.28. Food, industrial output, and population will continue to grow exponentially until the rapid depletion of resources forces a sharp decline in industrial growth.

On our finite Earth, unlimited population growth is impossible. In fact, the transition to a stable or declining phase has already begun. This does not pose insurmountable technological, biological, or social problems. It does, however, require some fundamental adjustments in our present growth culture. If we can achieve appropriate cultural adjustments, a steady-state population could be one of humanity's greatest advances. The alternative could be catastrophic.

What are the limits to growth?

EASTER ISLAND, EARTH ISLAND

The history of Easter Island shows the effects of overuse of natural resources and disregard for the limitations of a natural environment.

Three thousand kilometers from the western shores of South America lies Easter Island (Rapa Nui), a small volcanic island that is part of a long chain of hotspot islands and seamounts in the South Pacific (Figure 24.29). Easter Island formed like many other hotspot islands. Submarine basaltic eruptions gradually built a large volcano that eventually rose above the crashing waves. The most recent eruptions formed several small cinder cones that are less than 1 million years old.

The subtropical climate of the island ensures that it is warm and wet. The mean temperature is 20°C, and the island receives about 120 cm of rain annually. Weathering of the basaltic lavas created a rich volcanic soil. Eventually, the island was colonized by plants and animals floating or flying to this lonely island paradise. By the time the first Polynesians landed on the island between A.D. 400 and 700, Easter Island was richly forested. Several species of trees, notably the date palm, bushes, and other plants blanketed the landscape. However, 1000 years later, when the first European visitors arrived, the landscape and environment of Easter Island were

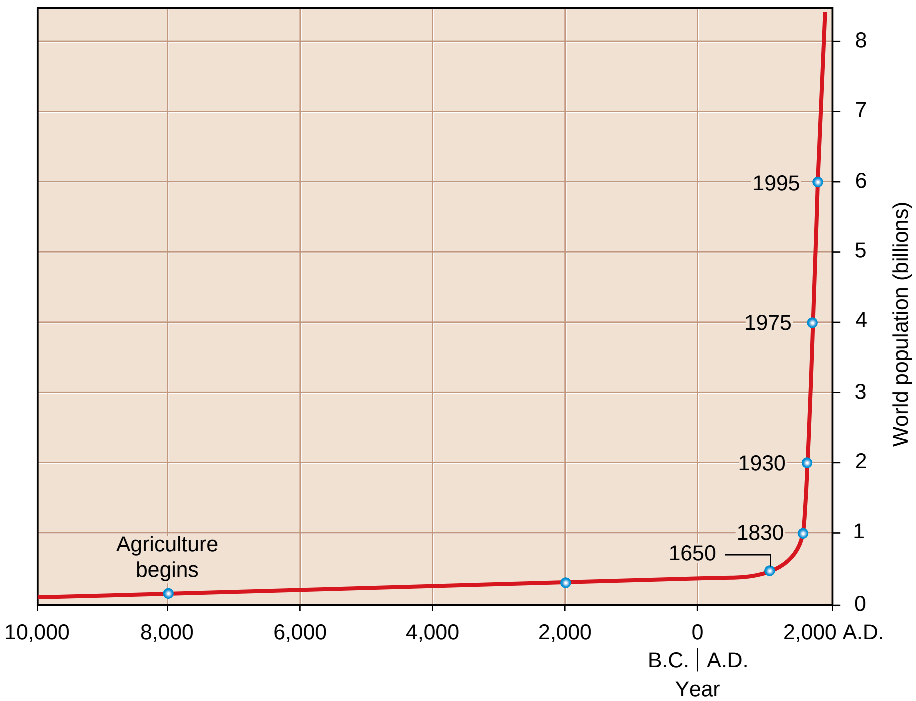


FIGURE 24.27 Earth's human population has grown exponentially. This growth has resulted in a similar increase in the rate of consumption of our natural resources.

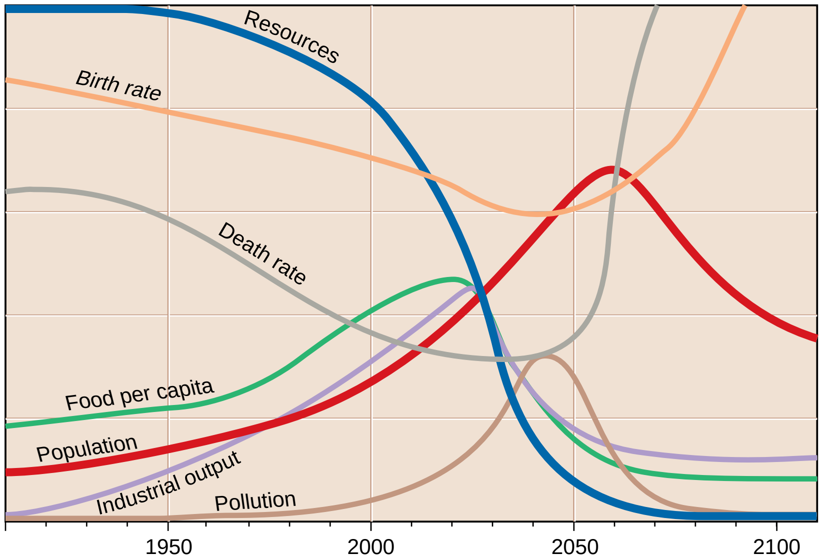


FIGURE 24.28 A computer model of resource consumption and its influence on other variables assumes no major changes in the physical, economic, and social relationships that historically have governed the development of the world system. All variables plotted here follow historical values from 1900 to 1970. Food, industrial output, and population grow exponentially until the rapidly diminishing resource base forces a slowdown in industrial growth. Because of natural delays in the system, both population and pollution continue to increase for some time after the peak of industrialization. Population growth is finally halted by a rise in the death rate due to decreased food and medical supplies. *(After D. H. Meadows and others)*

quite different. The climate had not changed. The basic geologic processes that shaped the island, produced soil, and allowed abundant rain to fall had not changed. But, apparently, its human population had heedlessly consumed its resources.

All of the European accounts describe Easter Island as a desolate place, lacking forests and having poor soil. The only animals larger than insects that early European visitors found were chickens. The island people, who came from a great seafaring culture, met early explorers in leaky canoes or by swimming. Jacob Roggeveen, a Dutch explorer and the first European to encounter the island, in 1722, described what he saw: "Withered grass, hay, or other scorched and burnt vegetation . . . its wasted appearance could give no other impression than of a singular poverty and barrenness." And there were, of course, the ominous stone carvings (p. 690), knocked over, some left in the middle of construction.

The location of the island and its volcanic rocks, which normally weather to produce fertile soils, should produce a rich environment that would provide a healthy and prosperous life for human inhabitants. Detailed studies have shown that 1500 years ago, when the first Polynesians came to Easter Island was a subtropical paradise. Seed, spores, and pollen found in ancient soils show that palms, tree daisies, ferns, herbs, and grasses grew in abundance. Bones uncovered in the same sediments show that more than 25 species of nesting birds used to be found on the island (more than on any other Polynesian island). In addition, the fossil evidence shows that many sea birds bred on the island.

What happened to this island and its people? Ancient pollen found in the layers of soil give a detailed account. Recorded in the soil is the destruction of an entire ecosystem and the demise of a culture. The first Polynesians reached the island between A.D. 400 and 700. The early colonizers enjoyed an abundance of food and lumber; in their abundance, the population increased. But the pollen records show dramatic changes in the plant life on the island as early as A.D. 900 (Figure 24.30). In only a few centuries, the islanders had begun the process of overharvesting the forests, one of their most important natural resources. The fossil pollen shows that by the 1400s the Easter Island palm had disappeared, probably consumed by humans and unable to regenerate itself because introduced rats devoured the palm seeds. Other trees that were needed by the islanders to make ropes and fibers show a similar decline, although they took longer to disappear.

There were several reasons the inhabitants deforested the island and many unalterable consequences. People on the island used wood both for construction materials to make canoes and houses and for fuel. In addition, they cleared land so that they could plant crops to feed the growing population. Statue construction, which required logs and ropes made from tree fibers to transport the huge basalt images up to 10 km, was at a peak during the years 1200 to 1500. Deforestation led to destruction of plant and animal habitat. Land birds, which provided food for the islanders, disappeared with the forests. Soil erosion increased with the destruction of the forests, and, in turn, growing crops became difficult and ultimately impossible.

With dwindling forest resources, islanders appear to have turned to exploiting the bounties of the sea. Archeological remains suggest a shift in the islander's diets—from porpoise (which could be harpooned from good seafaring canoes), to sea birds and shellfish, to small sea snails, chickens, and rats. As food supplies declined and warfare broke out, the people of Easter Island fell to cannibalism—a fact recorded in the archeological remains and oral traditions of the people.

Hand in hand with the environmental degradation came the demise of the island's society. Excessive consumption within the society depleted the small island's natural resources and intensified deforestation. Resources decreased and food became scarcer; canoes could no longer be constructed, so people could not escape to other islands. A complex centralized society was apparently replaced with feuding and chaos. Warrior societies formed and, between 1770 and 1864, the huge stone statues were toppled by rival gangs. It is estimated that the human population of the island fell to between one-quarter and one-tenth of its prior size.

Some have asked, Why didn't the Easter Islanders understand what they were doing and stop before it was too late? What were *they* thinking when they cut down the last palm tree? But a better question might be, "What can *we* learn from the history of Easter Island?" In myriad ways, the history of Easter Island is a microcosm of our own planet. Viewing Earth as our island in the vastness of space, we can see a potential repeat of the disasters that happened on this lonely Pacific island. Today, we see a human society that largely disregards the long-term effects of its actions and increasingly consumes many of its natural resources. The people of Easter Island had nowhere to go once they exhausted most of their resources. And where do we, the inhabitants of "Earth Island," have to go if we exhaust our resources and change our global environment?

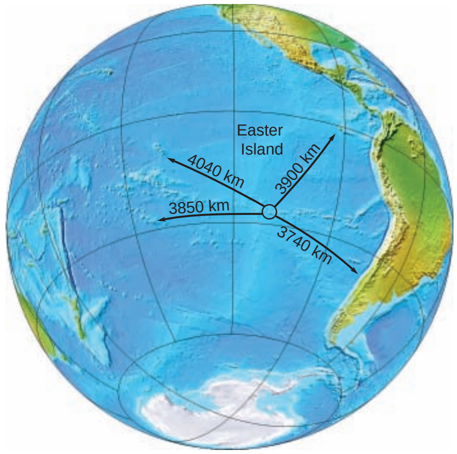


FIGURE 24.29 **Easter Island** provides lessons about the potentially catastrophic impact of humans on their environment. Easter Island is a small hotspot island that lies in the subtropical part of the South Pacific, about 3000 km from South America.

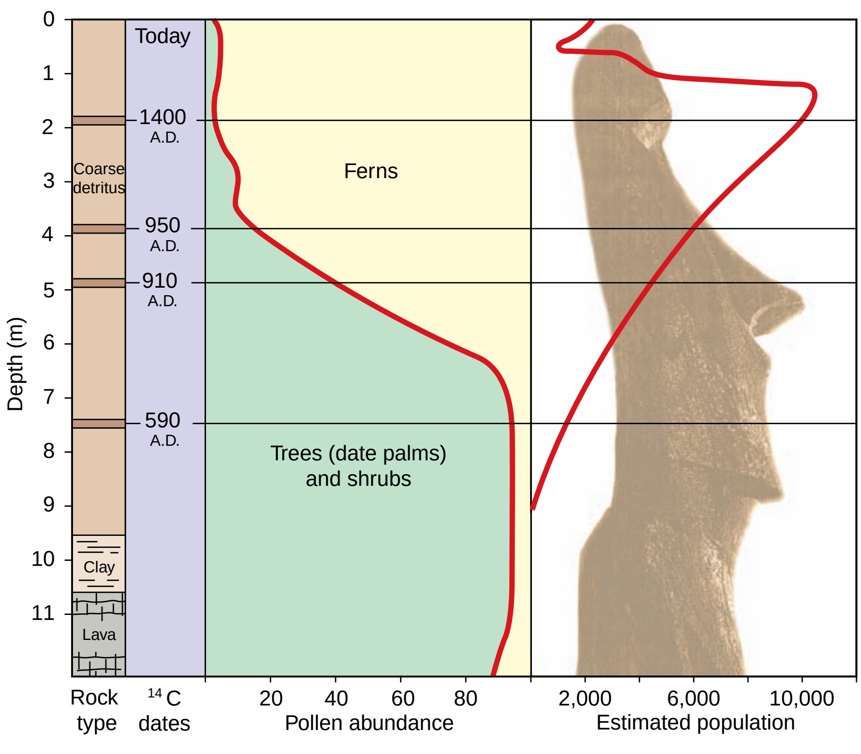
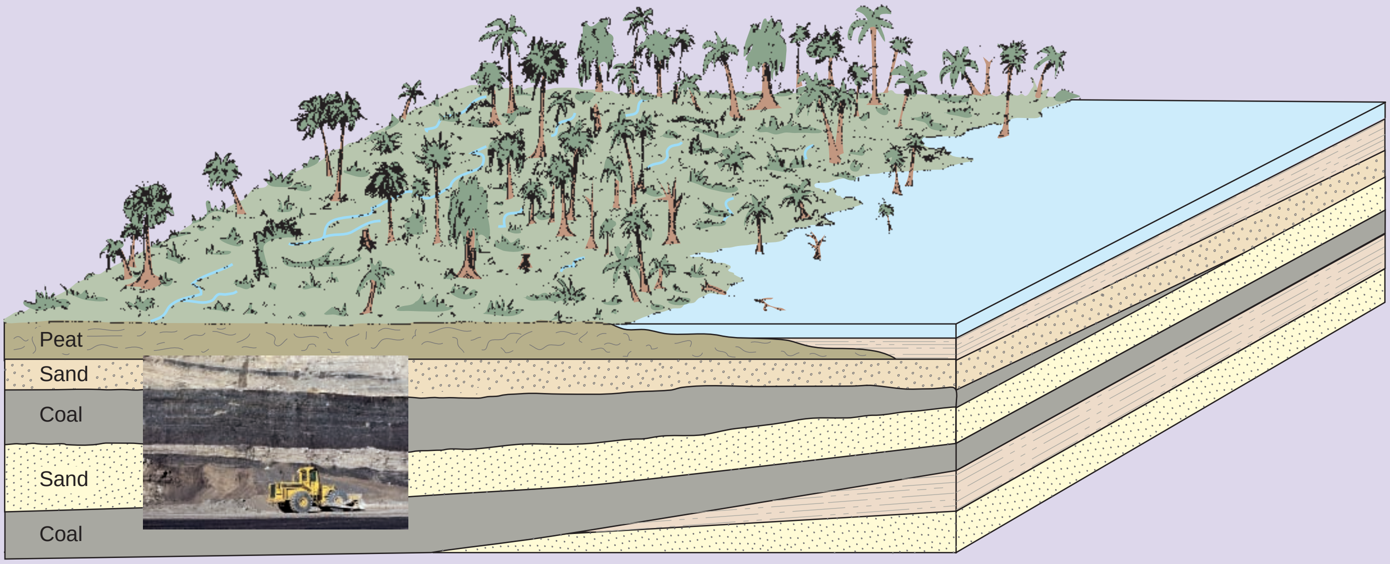


FIGURE 24.30 **Pollen fossils collected from Easter Island** paint a grim picture of the demise of the natural resource base for the people of Easter Island. Pollen was collected from cores taken from sediments that accumulated in a small volcanic crater. The record suggests that when people colonized the island about A.D. 400, date palms were abundant, as indicated by the amount of palm pollen preserved in sediment. By A.D. 1000, pollen records show, the island was nearly devoid of date palms. By the time Europeans visited the island in the 1700s, there were none. As a result of the overuse of their primary resources such as the date palm, the population of the island probably collapsed from a high of about 10,000 to as few as 1000 in the course of a few generations.

GeoLogic *The Origin of Coal*



Thick layers of black coal are some of our most valuable resources. Many also preserve abundant evidence of their origin. Careful observations of the character of the coal and its enclosing rocks allow us to understand the sequence of events involved in its formation

Observations

1. Coal is made of the carbon mineral graphite mixed with a variety of organic molecules, many of which have counterparts in still living materials.
2. Hosts of plant fossils are still clearly visible in most coal layers–tiny grains of pollen, leaves, bark, and wood from large trees related to those found today in tropical and temperate rain forests.
3. Coal beds are universally contained within layers of sedimentary rock, clearly indicating their formation and accumulation at the surface.
4. The thicknesses of the overlying strata show that coal beds were buried to depths of several kilometers.

Interpretations

With these facts in mind, what do geologists see when they look at a coal seam like that mined here? Many envision a vast nearly impenetrable swamp with closely spaced trees with their roots standing in water. Rotting plant material forms a black organic-rich mud in the ponds. Fallen trees clog the forest and thick layers of leafy litter are everywhere. The ocean is not far away and the quiet lapping of the waves can be heard. Nearby, a slow-moving river wends its way to the ocean and some of its banks are lined with white sand.

The fossils and organic molecules show that coal is plant derived. The sands and shales that enclose coal deposits were formed in beach, delta, and shallow marine environments. They typically show the shoreline was moving back and forth across a subsiding continental margin when the coal layer was deposited. Eventually, as burial depths increased, the organic material was converted by metamorphism to coal of various grades. Tectonic uplift and erosion brought the coal beds back to the surface where they could be mined to support our energy-hungry modern lifestyle.

KEY TERMS

banded iron formation (p. 697)
biomass (p. 703)
brine (p. 698)
coal (p. 706)
evaporite (p. 698)
fossil fuel (p. 706)
geothermal energy (p. 704)
hydrocarbon trap (p. 709)
hydroelectric power (p. 703)
hydrothermal fluid (p. 695)
hydrothermal ore deposit (p. 696)
industrial mineral (p. 696)
magmatic segregation (p. 694)
mineral resource (p. 692)
nonrenewable (p. 692)
nuclear energy (p. 713)
oil shale (p. 712)
peat (p. 706)
pegmatite (p. 695)
photovoltaic cell (p. 702)
placer (p. 697)
porphyry copper (p. 696)
recycle (p. 692)
renewable (p. 692)
reservoir rock (p. 709)
solar energy (p. 701)
source rock (p. 709)
strip mining (p. 708)
tidal energy (p. 706)
vein (p. 696)
wind energy (p. 703)

REVIEW QUESTIONS

1. List the ways in which mineral resources are concentrated.
2. Why are most mineral resources considered nonrenewable if their formation processes are continuing?
3. Explain how magmatic segregation concentrates ores such as chromium.
4. How are minerals concentrated by streams?
5. Explain how some mineral resources are concentrated by weathering processes.
6. List five different ways in which hydrothermal fluids can be generated.
7. Which energy sources are renewable? Which are nonrenewable?
8. Contrast the advantages and disadvantages of solar power, hydroelectric power, and wind energy.
9. What are fossil fuels?
10. Explain how coal originates.
11. Describe various kinds of petroleum traps.
12. What kinds of strata serve as (a) source beds and (b) reservoir beds for petroleum?
13. Are there similarities between the reservoir rocks for oil and for geothermal fluids?
14. Why is oil rarely found in the center of a syncline?
15. Compare Figures 24.22 and 24.19. Why are coal and oil commonly found in the same regions?
16. What are the major problems with nuclear energy?
17. What hydrocarbons may become more important fuel sources in the future?
18. Give an example of an important mineral resource whose origin is strongly controlled by plate tectonics.
19. Hydrothermal deposits formed on oceanic crust are rich in copper and nickel, whereas similar deposits formed in continental crust are poor in nickel but richer in lead and zinc. Speculate about the causes of this association between metal deposits and kinds of crust.
20. List the mineral resources that you have used today. Which were renewable and which were not?
21. Discuss the factors that limit the growth of population and industrialization.

ADDITIONAL READINGS

Bongaarts, J. 1994. Can the growing human population feed itself? *Scientific American* **271**(3): 36–42.
Brimhall, G. 1991. The genesis of ores. *Scientific American* **268**(5): 84–90.
Cohen, J. E. 1995. *How Many People Can the Earth Support?* New York: Norton.
Department of Energy. 1991. *National Energy Strategy.* Washington, D.C.: Government Printing Office.
Energy for Planet Earth. 1990. Special issue. *Scientific American* **267**(9).
Evans, A. M. 1995. *Introduction to Mineral Exploration.* Oxford: Blackwell Scientific.
Kesler, S. E. 1994. *Mineral Resources, Economics, and the Environment.* New York: Macmillan.
Suess, E., G. Bohrman, J. Greinert, E. Lausch, Flammable ice. *Scientific American* **279**(11): 76–83

MULTIMEDIA TOOLS

Earth's Dynamic Systems Website
The Companion Website at **www.prenhall.com/hamblin** provides you with an on-line study guide and additional resources for each chapter, including:

- On-line Quizzes (Chapter Review, Visualizing Geology, Quick Review, Vocabulary Flash Cards) with instant feedback
- Quantitative Problems
- Critical Thinking Exercises
- Web Resources

Earth's Dynamic Systems CD
Examine the CD that came with your text. It is designed to help you visualize and thus understand the concepts in this chapter. It includes:

- Animation of how petroleum forms
- Animation of oil exploration techniques
- Slide shows of ore deposits
- A direct link to the Companion Website