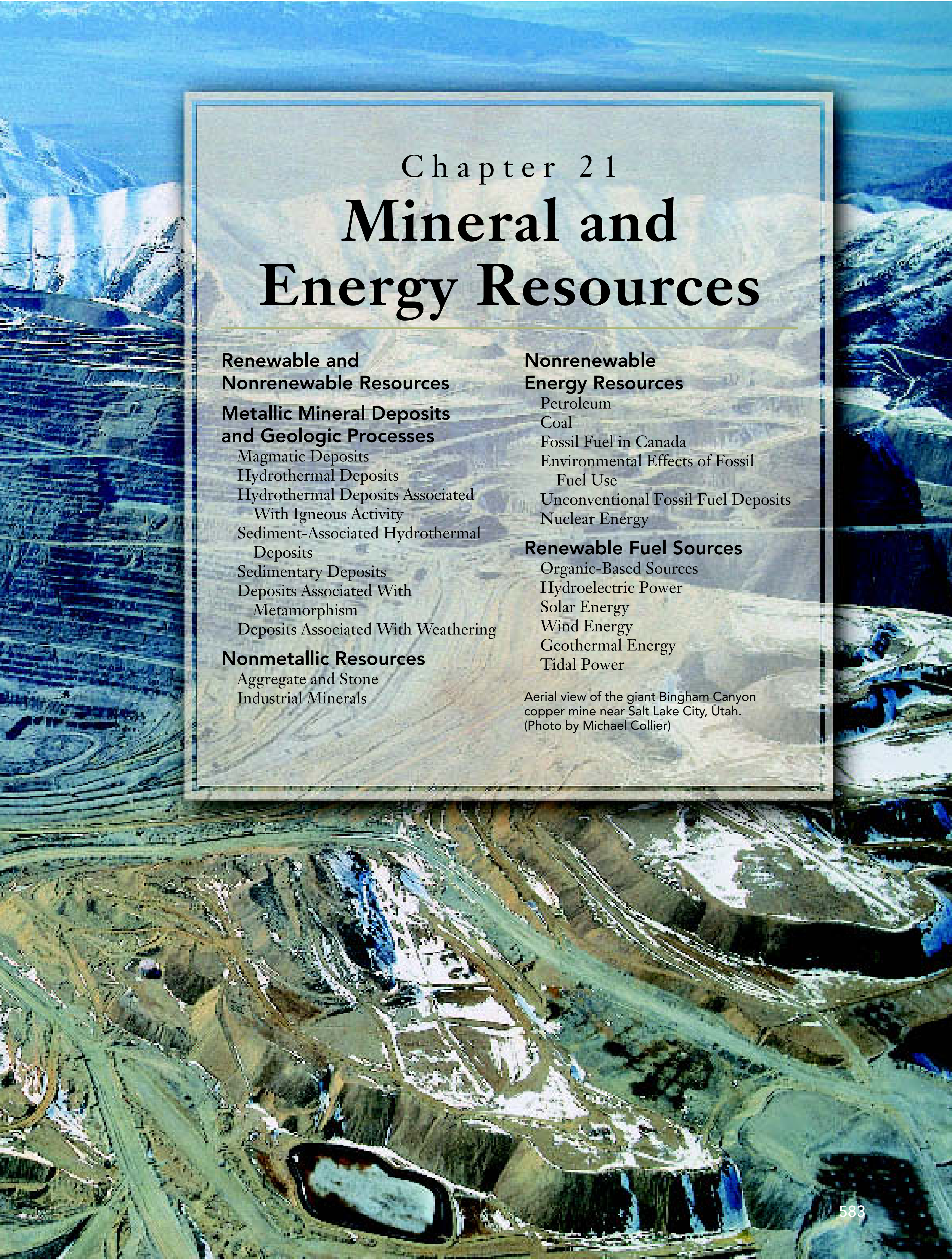

Chapter 21

Mineral and Energy Resources

Renewable and Nonrenewable Resources

Metallic Mineral Deposits and Geologic Processes
- Magmatic Deposits
- Hydrothermal Deposits
- Hydrothermal Deposits Associated With Igneous Activity
- Sediment-Associated Hydrothermal Deposits
- Sedimentary Deposits
- Deposits Associated With Metamorphism
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- Industrial Minerals

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- Fossil Fuel in Canada
- Environmental Effects of Fossil Fuel Use
- Unconventional Fossil Fuel Deposits
- Nuclear Energy

Renewable Fuel Sources
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- Geothermal Energy
- Tidal Power

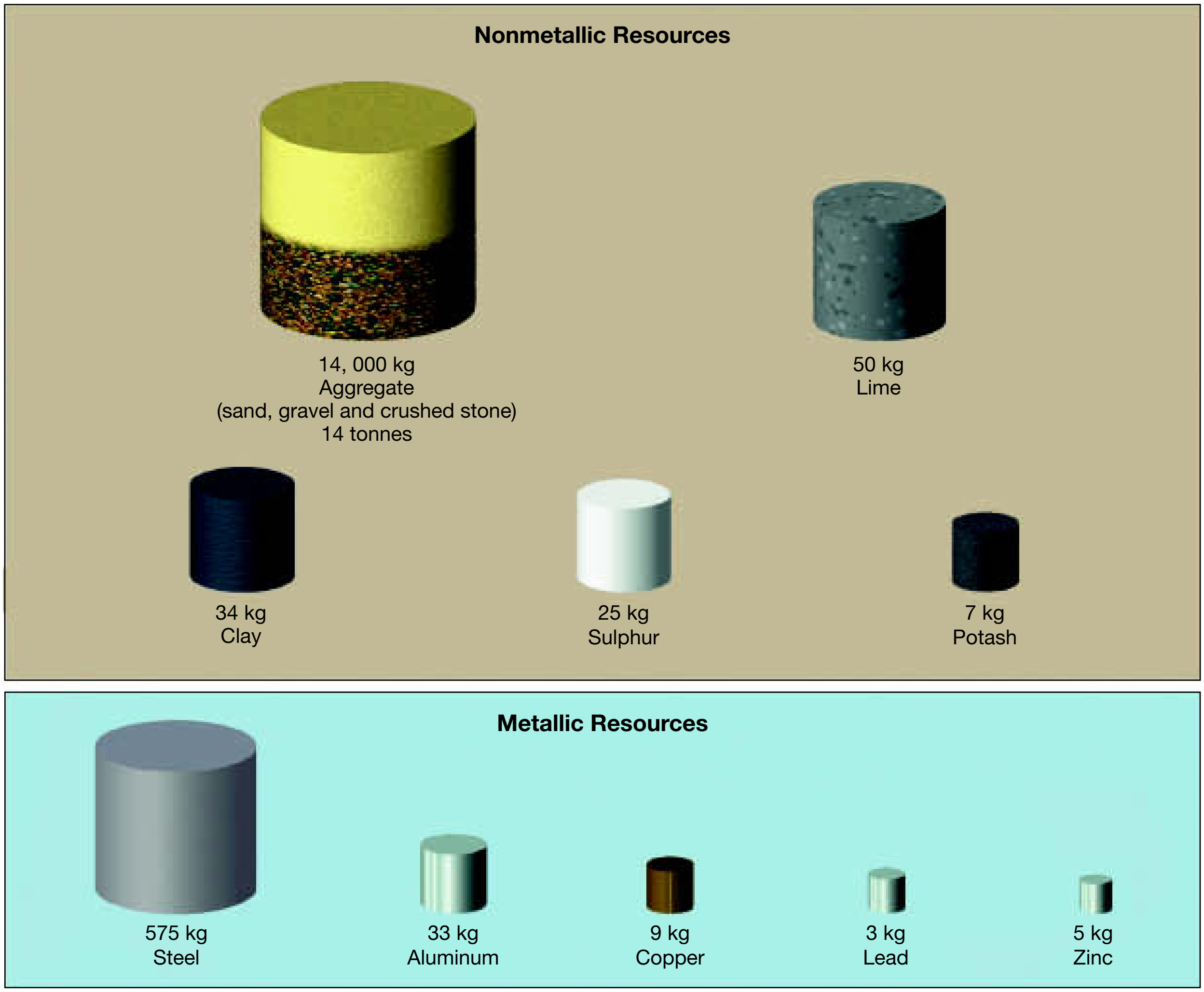
Aerial view of the giant Bingham Canyon copper mine near Salt Lake City, Utah. (Photo by Michael Collier)

A popular saying among geologists is "if it can't be grown, it's gotta be mined." Materials extracted from the Earth are the basis for modern civilization (Figure 21.1). Everything we use in our lives that is not derived from living things comes from the solid Earth. We so depend on the Earth's resources that we generally take this fact for granted. Chances are that most of the metals, plastics and energy sources that you are using today are derived from Earth resources that were ultimately discovered and developed with the help of geoscientists. For example, when you turn on your television or computer, you are actually using materials derived from the Earth. From the silicon chips to the copper in the wires, and from the glass screen to the energy that powers the computer, nearly all aspects of these high-tech devices are linked to mineral and fuel resources. The economic uses of several minerals, both metallic and nonmetallic are indicated in Table 2.4 (page xx).

The mining industry is a vital contributor to the Canadian economy. In 2001, the mining and mineral processing industries contributed $35.1 billion to the Canadian economy, amounting to $622 per person. Canada is also one of the world's largest exporters of minerals and mineral products. At least 80 percent of Canada's mineral and metal production is exported. Canada ranks first in the world for the production of potash and uranium, is the second largest producer of nickel and asbestos, and ranks in the top five for the production of zinc, cadmium, titanium concentrate, aluminum, platinum group metals, salt, gold, molybdenum, copper, gypsum, cobalt and lead. The five most important minerals in Canada with respect to production value are gold ($2.1 billion), nickel ($1.8 billion), potash ($1.6 billion), copper ($1.5 billion), and zinc ($1.4 billion).

The number of different **mineral resources** required by modern industries is immense (Figure 21.2),

◆ **Figure 21.1** Toronto at night. As this scene reminds us, mineral and energy resources are the basis of modern civilization.



◆ **Figure 21.2** The annual per capita consumption of selected mineral resources for Canada. (Data courtesy of Statistics Canada, Aggregate Producers of Canada, and Steel Producers of Canada)

and although some countries, like Canada and the United States, have rich supplies of many important minerals, no nation is completely self-sufficient. Consequently, resources of the Earth have long been the basis of world trade, have driven great waves of immigration, and have even generated wars.

Geoscientists are indispensable in many aspects of mineral and fuel resource discovery and management. These include: predicting where an economically important resource might occur, determining the most effective way of extracting them, and determining the conditions of mineral deposit formation to aid in the discovery of similar deposits. At the same time, geoscientists are mindful of the great responsibilities nations face in their exploitation and utilization of natural resources (Box 21.1) and play crucial roles in assessing the possible environmental impacts of mineral extraction and developing techniques for environmental remediation.

Renewable and Nonrenewable Resources

Resources are the endowment of materials held in reserve that are useful to humans and are ultimately available commercially. Resources are commonly divided into two broad categories—renewable and nonrenewable.

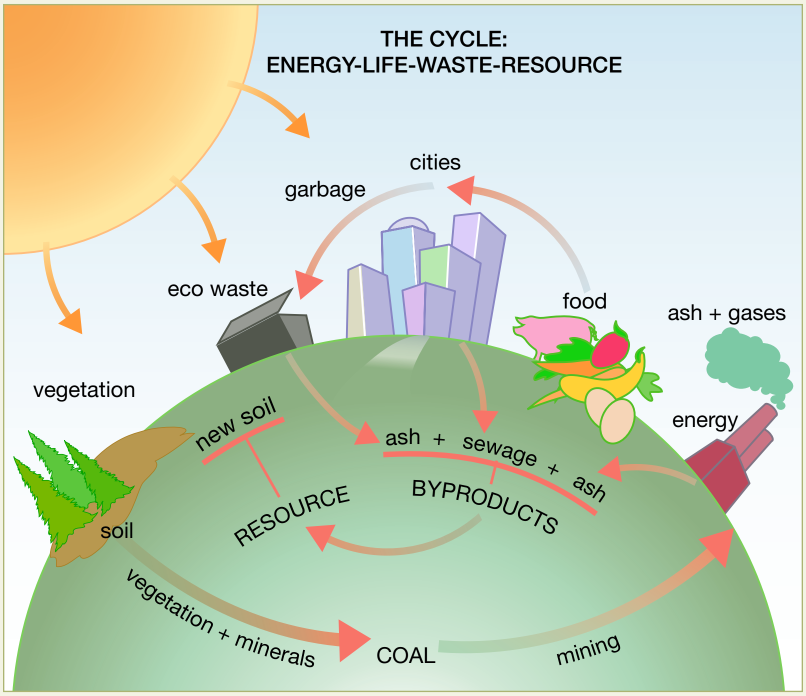
Renewable resources can be replenished over relatively short time spans such as months, years, or decades. Common examples are plants and animals for food, natural fibres for clothing, and trees for lumber and paper. Energy from flowing water, wind, and the Sun are also considered renewable. By contrast, **nonrenewable resources** continue to be formed in the Earth, but the processes that create them are so slow that significant deposits may take millions of years to accumulate. For human purposes, the Earth contains fixed quantities of these substances.

BOX 21.1

People and the Environment

Resource Consumption and Sustainability: A Global Perspective

In a global context, resources not only include minerals and fuel, but also anything else held in reserve that can be used in the future. For many of us, resources are those things that we use in excess to maintain our quality of life, or high standard of living (consumables, energy, etc.); this is a view embraced mainly by people living in "developed" countries. However, for most of the world's population, locally available resources are those things that simply maintain life on a daily basis (food, shelter, etc.). Many small countries possess a single resource (e.g., sandy white beaches or a pleasant climate), which translates into tourism dollars. From a global perspective, resources include the vast reservoirs of less tangible commodities such as air, water and soil quality, and extinction of plant and animal species. Global resource consumption is not equitable or evenly distributed on a per capita basis. The vast majority of worldwide resources are channelled into economies that have the financial capacity to buy commodities.



◆ **Figure 21.A** Uses of "waste" resources from by-products.

Planet Earth can be thought of as a single mixed reservoir of all resources that are consumed mostly by a single compartment (humans). The rate of resource consumption is a product of population size and rate of consumption. The rate of population growth has accelerated exponentially throughout history. It took over 100,000 years for Earth to reach the 1 billion population mark, but it only took 13 years to add the 5th billion, and it will take only 12 years to reach the 6th billion. Increases in economic activity worldwide show that the richest 20 percent of people consume 85 percent of the resources while the poorest 25 percent use less than 1.5 percent. To put this into perspective, consider a scenario where China consumed resources at the same rate as North America. Conservatively, China would use the entire worldwide production of nearly all resources each year! Another interesting perspective is to consider how long the total static resources would last if all the people in the world used resources at the same rate as North Americans—not very long, not even a generation.

Energy is the single most important resource. Per capita consumption is a measure of quality of life (and life expectancy) and industrial status worldwide. Approximately 25 percent of the global population use 75 percent of the total energy produced annually. North America (5 percent of the total population) uses twice as much energy as all developing countries combined and Western Europe (9 percent of the total population) uses about the same amount. On a per capita basis, people in developed countries use between 10 and 30 times as much energy as people in developing countries. Canada (6th largest consumer worldwide) uses 3.7 percent of the world's total generated electricity for a population of only 32 million. India (7th largest consumer worldwide), with a population of over 1 billion, uses less.

How long global resources will last depends on future population growth and consumption trends. Even at a conservative across the board increase of 1 percent most of our proven mineral and energy reserves will last for less than 200 years. If the rate of consumption increases to 2 percent, static levels of resources will last for less than 100 years. So, whether or not we use resources in a "sustainable" way will be a complicated issue in the future, and one of the greatest problems facing future generations. The question remains: can we keep adding 100 million people to the surface of Planet Earth each year and still pretend that resource consumption can be tailored to "sustainability"? Figure 21.A shows the relationship between some types of waste and the need for new resources.

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When the present supplies are mined or pumped from the ground, there will be no more. Examples are fuels (e.g., coal, oil, natural gas) and many important metals (e.g., iron, copper, uranium, gold). Some of these nonrenewable resources, such as aluminum, can be used over and over again; others, such as coal, cannot be recycled. Some resources can be placed in either category, depending on how they are used. Groundwater is one such example. Where it is pumped from the ground at a rate that can be replenished, groundwater can be classified as a renewable resource. However, in places where groundwater is withdrawn faster than it is replenished, the water table drops steadily. In this case, the groundwater is being "mined" just like other nonrenewable resources.

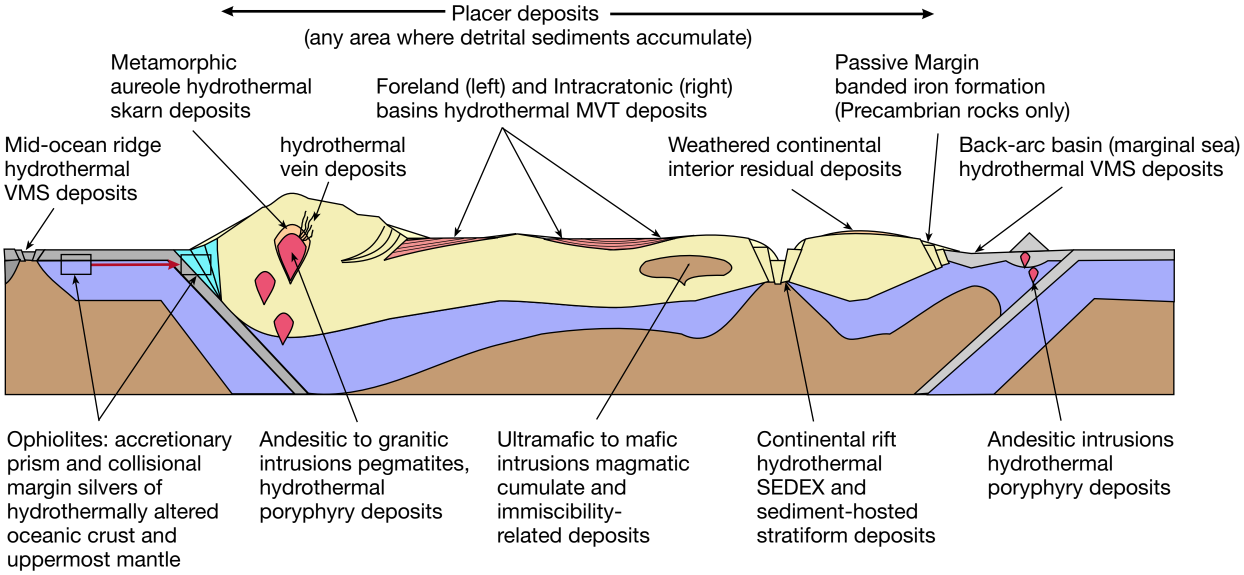
Resources include **reserves**, the already identified deposits from which minerals and fuel materials can be extracted profitably, and known deposits that are not yet economically or technologically recoverable. Resources may also include deposits that have not yet been discovered, but are inferred to exist by some evidence.

Metallic Mineral Deposits and Geologic Processes

An important point to be made about Earth's resources concerns the natural abundance of elements sought after; even the common metals such as aluminum and iron comprise less than 10 percent of average continental crust. Next, when one examines the distribution of mines and the primary mineral resources they extract, it becomes obvious that the various metals and other resources we rely on are not uniformly distributed across the globe—they are naturally concentrated only in particular areas. This uneven distribution is inherent to the Earth system. Not only does the composition of crust vary in different regions, but the effects of tectonic processes, weathering, sedimentation rates, the movement of fluids, and various other factors are expected to be subdued in some areas and enhanced in others. These circumstances, combined with the economics of extracting the resources, limit the localities on Earth where the mining of particular materials is practical.

Most of us have heard the term **ore**. This term is generally used to denote those useful metallic minerals (and a few nonmetallic minerals such as fluorite and sulphur) of sufficient concentrations to be mined at a profit. It is emphasized that a rock body may be considered an ore one day and not the next due to economic factors. These can include fluctuations in the price of the material sought after, the price of fuel required for the running of machinery and the efficiency of mining equipment. It should be noted that the term ore is not applied to all materials of economic interest. Most nonmetallic minerals used for such purposes as building stone, aggregate, abrasives, ceramics, and fertilizers are not usually called ores but are generally classified as **industrial minerals**.

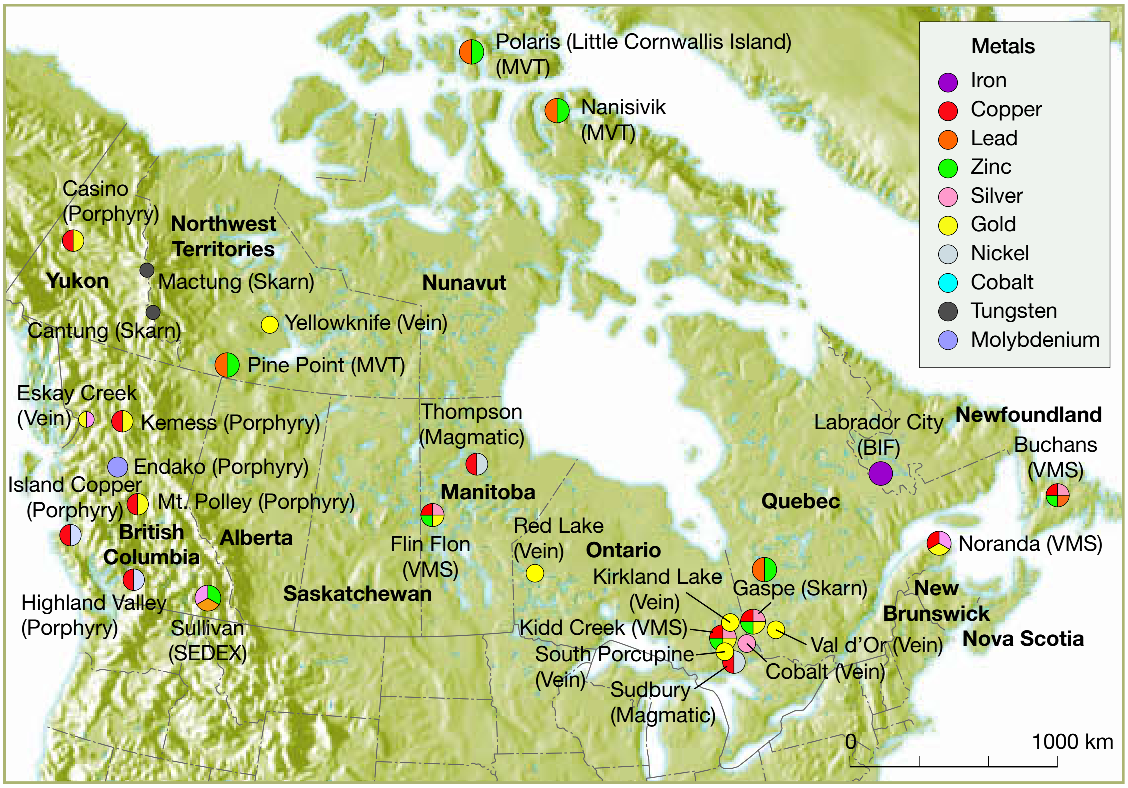
In this section, a few of the most important types of metallic mineral deposits are discussed. The primary types of deposits discussed in this section and their contained metals are summarized in Table 21.1, and depicted in the context of plate tectonic environments in Figure 21.3. Canadian metallic mineral deposits of present and historical significance are shown in Figure 21.4.



◆ **Figure 21.3** Distribution of common mineral deposit types and their contained metals with respect to plate tectonic environments.

TABLE 21.1 **Occurrence of Metallic Minerals**

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



◆ **Figure 21.4** Locations of important metallic resources and mining centres in Canada.

Magmatic Deposits

Many of the world's most valuable metallic mineral resources are directly associated with magma that ultimately forms igneous rocks. Certain metals are naturally enriched in certain magmas, but most only reach economically viable concentrations upon further enrichment during the cooling process. In both cases, it is the characteristics of the magma itself that are responsible for the formation of mineral deposits.

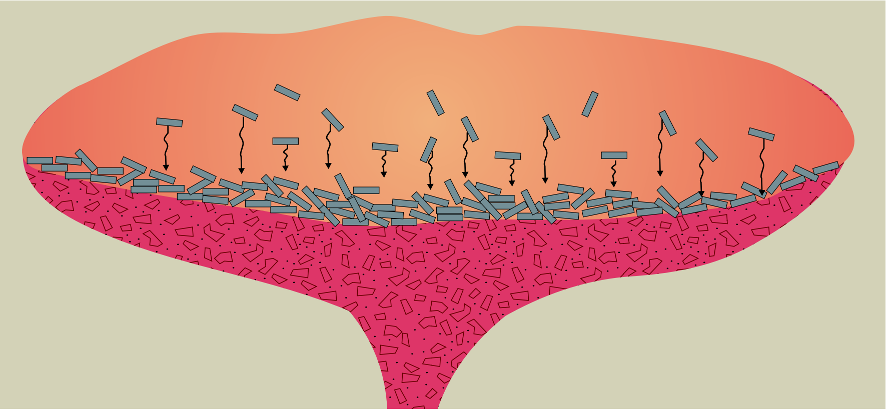
Gravitational Settling The igneous processes that generate some metal deposits are fairly straightforward. For example, some economically important minerals are concentrated by simple gravitational settling within a magma chamber. In essence, crystals of heavy minerals that form during early stages of crystallization settle at the bottom of a magmatic body such as a pluton or sill, concentrated layers of minerals (Figure 21.5). Such deposits, commonly called *cumulate deposits*, are important sources for chrome (in the mineral chromite), iron (in the mineral magnetite), and platinum. They typically form from mafic igneous magmas that are naturally enriched in these elements. Examples of mafic intrusions that host such deposits are the Stillwater Complex of Montana, Bushveld Complex of South Africa, and the Bird River Sill of Manitoba.

Immiscibility Some metal deposits, such as the nickel deposits of Sudbury, Ontario and Voisey's Bay, Newfoundland and Labrador, are probably produced by the separation of liquid components of magma in a manner similar to the separation of oil and water in salad dressing left to stand on a kitchen counter. Such nonmixing of liquid phases is called immiscibility.

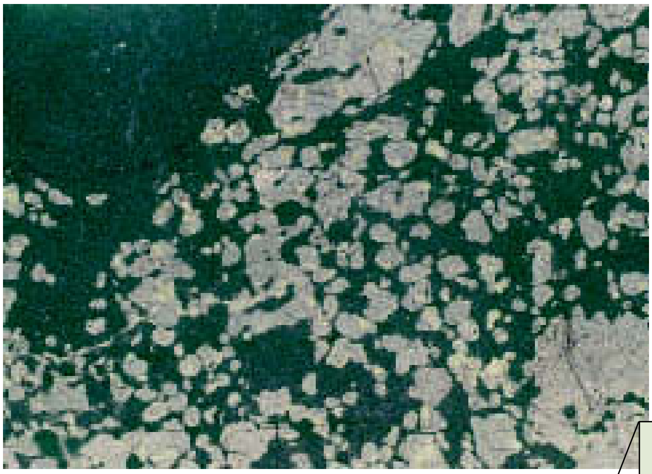
Mantle-sourced magmas of mafic to ultramafic composition are naturally enriched in elements such as nickel and copper, relative to felsic magmas. Because these elements are readily incorporated into silicate minerals such as olivine and pyroxene, substituting for atoms of iron and magnesium, they are usually too dispersed within mafic intrusive rocks to be mined at a profit. In some cases, however, these elements can be scavenged from the melt by small droplets of immiscible iron sulphide liquid that eventually sink to the base of the intrusion and accumulate to form an orebody. The resulting deposit (Figure 21.6A) is dominated by the iron sulphide mineral pyrrhotite with intergrowths of the nickel-bearing sulphide mineral pentlandite $(Ni,Fe)_9S_8$, as well as chalcopyrite $(CuFeS_2)$ and some precious metals such as platinum.

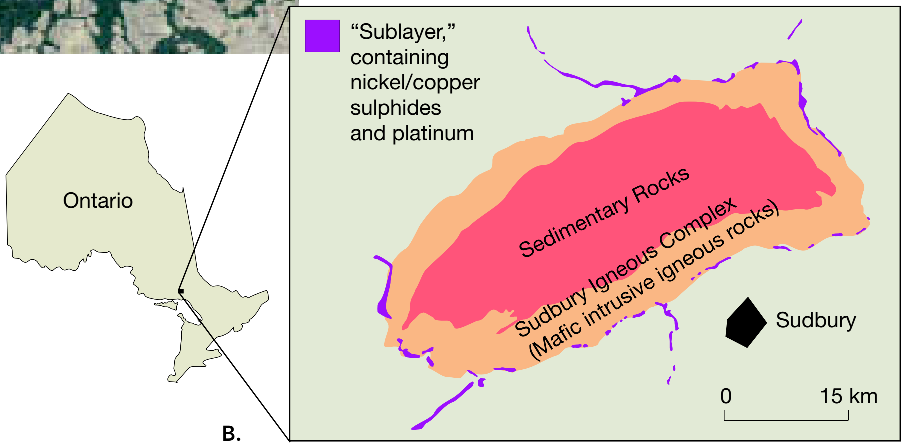
Although the nickel deposits of Sudbury and Voisey's Bay share similar origins from mantle-derived magma, the mechanisms believed to have triggered igneous activity in each case differ markedly. In Sudbury, the generation and emplacement of mafic magma is linked to the impact of a large meteorite that occurred about 1.9 billion years ago. The impact is believed to have produced fractures that penetrated into the mantle and acted as passageways for magma containing the required sulphide droplets. The Sudbury orebody occurs at the base of a mafic igneous intrusion, and is exposed at the surface as an oval ring-shaped structure (Figure 21.6B). In contrast, the Voisey's Bay orebody occurs at the base of a mafic igneous intrusion that appears to have been fed by mantle-penetrating fractures generated by an ascending mantle plume.

Pegmatites As an igneous body cools, the most abundant components of the magma that are able to crystallize are removed from the magma. The melt remaining during the very last stages of cooling becomes enriched in volatile components (e.g., water) and rare elements that are not readily incorporated into common igneous minerals. Minerals that crystallize from such a melt may therefore be very unusual in their chemical composition, containing some of the least abundant elements found in Earth's crust. Because the melt is very fluid, it is readily injected into cracks surrounding the cooling igneous body and allows the growth of unusually large crystals (see Box 3.1, p. xx).



◆ **Figure 21.5** High-density minerals such as chromite and magnetite crystallize during the early stages of magma crystallization. The crystals can sink to the bottom of the magma chamber, forming concentrated layers of these minerals.





◆ **Figure 21.6** **A.** A sample of nickel-bearing rock from Sudbury. The nickel occurs in the rounded bodies of bronze-coloured sulphides that crystallized from immiscible fluid. Dark coloured mafic silicate minerals surround the metal sulphide bodies. Scale bar: 5 mm (Photo by Bob Hodder) **B.** In Sudbury, Ontario, nickel-bearing liquid separated from mafic magma, eventually settling to form a "sub-layer" beneath a silicate-dominated, mafic intrusive body and becoming injected into faults that emanated from the impact structure. The magmatic materials are believed to have escaped from the mantle due to a meteorite impact during the Proterozoic. The Sudbury Basin impact structure has since been deformed into an oval shape.

The resulting rocks, called **pegmatites**, typically occur in dykes and small veins within and around plutons (Figures 21.7, 21.9) and are generally felsic in composition. Elements of economic value that are mined from pegmatites include uranium, thorium, beryllium, lithium, tantalum, and niobium. Industrial minerals mined from pegmatites include feldspar and muscovite.

◆ **Figure 21.7** Vertical pegmatite dykes cut through biotite gneiss at Severn Bridge, north of Orillia, Ontario. Pegmatites, formed during the late stages of crystallization in felsic magmas are rich sources of rare earth metals. (Photo by Bob Hodder)

Hydrothermal Deposits

Among the best-known and most important ore deposits are those generated from **hydrothermal (hot-water) solutions**, which may be produced during the late-stage cooling of magma, by the heating of groundwater or seawater, or by metamorphic processes. A critical factor in the ability of hot water to dissolve metals appears to be the presence of dissolved salts, such as sodium chloride, potassium chloride, and calcium sulphate. Whereas metals are effectively insoluble in pure water, salt-rich *brines* are capable of dissolving at least small amounts of metallic elements (e.g., gold, silver, copper, lead, zinc, and mercury). High temperatures further increase the ability of brines to hold metals in solution. Because of their mobility, brines can migrate great distances before they eventually cool, lose their ability to keep metals in solution, and deposit the metals (usually in the form of sulphide minerals).

Companies mining hydrothermal ores must take great care in managing the waste materials (tailings) as the sulphide minerals contained in the ores readily react with water and produce substances that can be harmful to living things if released into the environment (Box 21.2).

Hydrothermal Deposits Associated With Igneous Activity

Studies of modern hydrothermal systems have shown that igneous activity serves as a powerful heat engine that drives the production and circulation of mineral-rich fluids. As is evident in the hot springs of Yellowstone National Park, the ordinary groundwater can invade a zone of recent igneous activity and be heated to increase its capacity to dissolve minerals. In such an environment, migrating hot waters can remove metallic ions from intrusive igneous rocks and carry them upward, where they may be deposited as an ore body.

The role of igneous activity in producing ore deposits is also evident in the depths of the oceans. Since the mid-1970s, active hot springs and metal-rich sulphide deposits have been detected at several sites, including study areas along the East Pacific Rise and Juan de Fuca Ridge. The deposits are forming where heated seawater, rich in dissolved metals and sulphur, gushes from the seafloor as particle-filled clouds called *black smokers*. As shown in Figure 21.8, seawater infiltrates the hot oceanic crust along the flanks of the ridge. As the water moves through the newly formed material, it is heated and chemically interacts with the basalt, extracting and transporting sulphur, iron, copper, and other metals. Near the ridge axis, the hot metal-rich fluid rises along faults. Upon reaching the seafloor, the spewing liquid mixes with the cold seawater and the sulphides precipitate to form massive sulphide deposits.

Vein Deposits Hydrothermal fluids generated by cooling magmas can rise to the surface through fractures, faults, and other features resulting from the brittle deformation of the overlying rocks. Fluids passing through the fractures eventually cool, allowing minerals to precipitate (Figure 21.9). The precipitated minerals, generally dominated by quartz and/or calcite, but sometimes including metallic minerals, fill the fractures to produce veins (Figure 21.10) that can range in width from a few centimetres to a few metres. The fluids can also react with the rocks immediately adjacent to the fractures to produce new minerals. Mineral deposits that occur in veins, or at least intimately associated with vein systems, are called **vein** (or *lode*) **deposits**. These are important sources of valuable ore minerals, such as native gold and silver, as well as copper and zinc sulphides. The hydrothermal environment in which some vein deposits were formed probably resembled that of Yellowstone. However, networks of metal-rich veins are also associated with fractures systems of other hydrothermal environments.

Mineral deposits of particular importance in Canada are vein gold deposits, which occur throughout the Archean greenstone belts of the Superior and Slave Provinces of the Canadian Shield. Well over 4000 tonnes of gold have been extracted from the many individual deposits in these areas. Among the most famous producers are the mines of the Porcupine, Red Lake, Kirkland Lake, Malartic-Val d'Or, and Yellowknife districts. Vein silver deposits are also important in some parts of Canada, particularly British Columbia. Historically significant to Canada are the lode silver deposits of Cobalt, Ontario, which spawned a remarkable mining boom in the early 1900s.

Disseminated Deposits Another important type of accumulation generated by magma-sourced hydrothermal fluids is called a **disseminated deposit**. Rather than being concentrated in well-defined veins, these ores are distributed in small masses throughout a large rock body. Most of the world's copper and molybdenum, and smaller quantities of other metals such as gold and silver, are mined from disseminated deposits called *porphyry deposits*. These are so named because of their close association with porphyritic igneous rocks.

When silicate minerals, such as feldspars, crystallize around the edges of an intrusion during the early cooling of a pluton, the water content of the remaining melt increases to the extent that steam pressure shatters the already crystallized rock, and in some cases, the surrounding host rock.

BOX 21.2

People and the Environment

Acid Mine Drainage (AMD) in Canada

Base and precious metal mining in Canada (and globally) is focused on the recovery of metals (e.g., nickel, copper, or gold) from geologic deposits. In an existing mine, rock is blasted and brought to the surface or removed from an open pit, crushed in rod and ball mills, and then undergoes a series of floatation steps leading towards metal purification. After the minerals of economic interest (e.g., millerite (NiS) or chalcopyrite ($Cu\text{-}FeS_2$)) are recovered, the gangue materials (waste rock) are disposed of in massive holding/tailings (waste) ponds. These wastes include silicates, base metals containing sulphide minerals that were not recovered during floatation, and typically, pyrite. Mining can also result in the generation of waste rock possessing pyrite. Upon removal, this waste rock is usually stored above ground in large free-draining piles.

The disposal of sulphide-bearing mine wastes (rock and tailings) as open deposits results in the formation of unique acid generating ecosystems (Figure 21.B). Acid formation is biocatalysed by acidophilic ("acid loving") bacteria, (e.g., *Acidithiobacillus ferrooxidans*), which oxidize sulphide minerals generating dilute solutions of sulphuric acid containing soluble, toxic heavy metals. This acid mine drainage (AMD) seeps into and damages surrounding aquatic and terrestrial environments.

While abiotic, chemical oxidation of pyrite can occur (see Reaction 1), it is slow and on its own will not lead to the formation of AMD. Under normal, natural water conditions ($pH \cong 7$), the iron that's released from Reaction 1 will oxidize (Reaction 2) to Fe^{3+}, which will subsequently hydrolyze water producing three protons (acid; Reaction 3). The net acid generating capacity of reactions 1–3 (4 protons) additionally cannot produce AMD.

$$FeS_2 + 3\tfrac{1}{2}\,O_2 + H_2O \rightarrow Fe^{2+} + 2\,SO_4^{2-} + 2\,H^+ \tag{1}$$

$$Fe^{2+} + \tfrac{1}{4}\,O_2 + H^+ \rightarrow Fe^{3+} + \tfrac{1}{2}\,H_2O \tag{2}$$

$$Fe^{3+} + 3\,H_2O \rightarrow Fe(OH)_3 \text{ (iron hydroxide; the rust colour)} + 3\,H^+ \tag{3}$$

Under acidic conditions (i.e., $pH < 4$) Fe^{2+} is generally stable and soluble (Reaction 2 slows down). Therefore, the net acid generation should slow as well but it doesn't! This is where the acidophilic, lithotrophic (lithos=rock; trophic=food or eating) bacteria become important. The key to the formation of acid mine drainage is the bacteria's ability to oxidize iron under acidic conditions. (They can also catalyze Reaction 2!; Singer and Stumm, 1970.) In the presence of water and acid conditions, Fe^{3+} will "attack" pyrite (Reaction 4), producing lots of Fe^{2+} (more food for the bacteria) and lots of acid.

$$FeS_2 + 14\,Fe^{3+} + 8H_2O \rightarrow 15\,Fe^{2+} + 2\,SO_4^{2-} + 16\,H^+$$

The chemical oxidation of pyrite (Reaction 4) occurs extremely quickly under acid conditions—typically faster than the bacteria can oxidize the Fe^{2+}. Therefore, the rate-limiting step in the formation of AMD is the oxidation of Fe^{2+} by the bacteria (biocatalysed Reaction 2). It should be noted that Fe^{3+} can also chemically "attack" other base metals (e.g., Cu_2S) that will, in turn, release soluble toxic heavy metals (e.g., Cu^+).

The Canadian mineral industry generates one million tonnes of waste rock and 950,000 tonnes of tailings per day, totalling 650 million tonnes of waste per year. In Canada, there are an estimated 351 million tonnes of waste rock, 510 million tonnes of sulphide tailings, and more than 55 million tonnes of other mining sources which have the potential to cause AMD.[1]

Once in a tailings pile, they get their O_2 and CO_2 from the air (they're autotrophic, similar to plants) and their energy from the sulphide minerals (e.g., pyrite), ultimately forming AMD. Acid Mine Drainage is the mining industry's greatest environmental problem and its greatest liability.[2] The water pollution resulting from the bio-oxidation of mine wastes may need to be managed for centuries after mine closure and the cleanup at existing acid-generating mines in Canada will cost billions of dollars.

◆ **Figure 21.B** Metal mine tailings, which appear benign at first glance were revealed to be highly oxidized immediately below the surface (inset). This zone of oxidation extended approximately 40 centimetres down into the tailing. (Photos by Gordon Southam)

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1. Government of Canada, *The State of Canada's Environment*. Ottawa: Ministry of Supply and Services, 1991, p. 11–19.
2. Singer, P.C. and W. Stumm. 1970. Acidic mine drainage: the rate determining step. Science 167:1121–1123.

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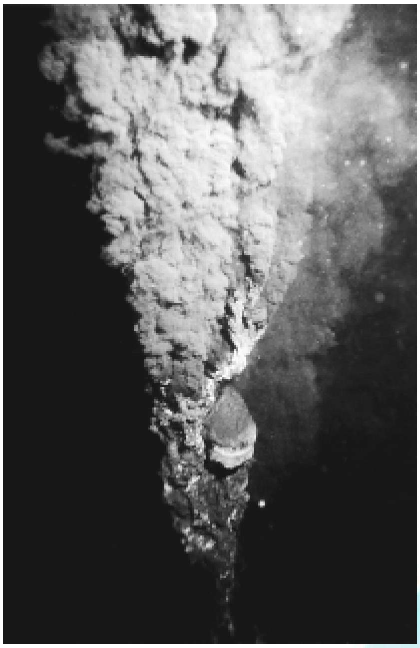
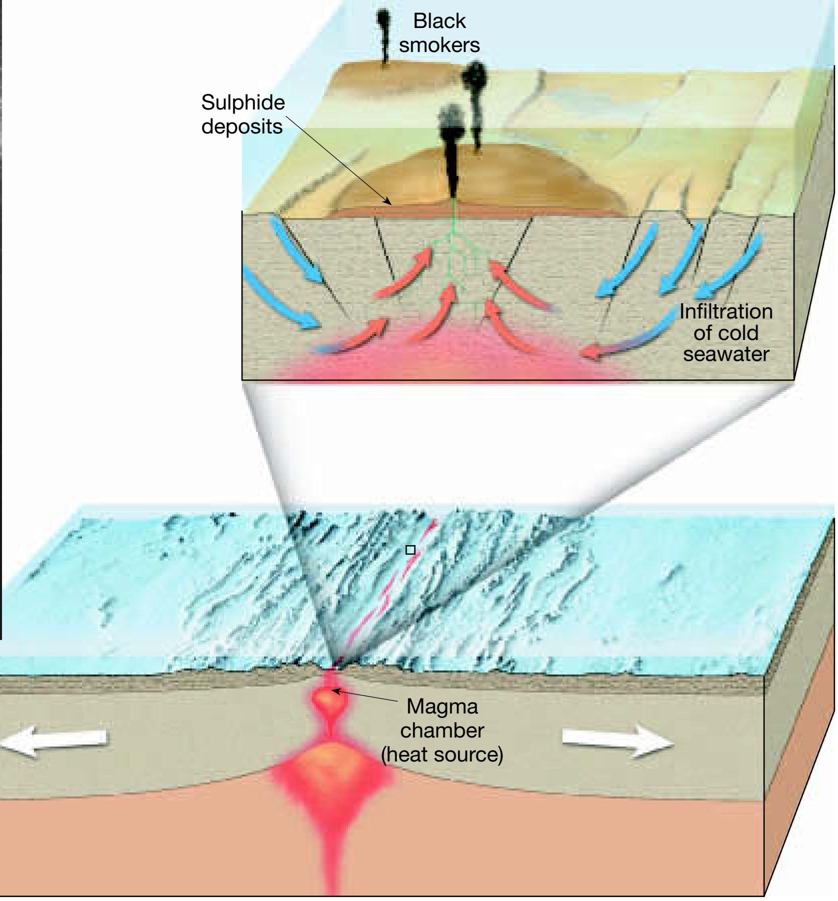
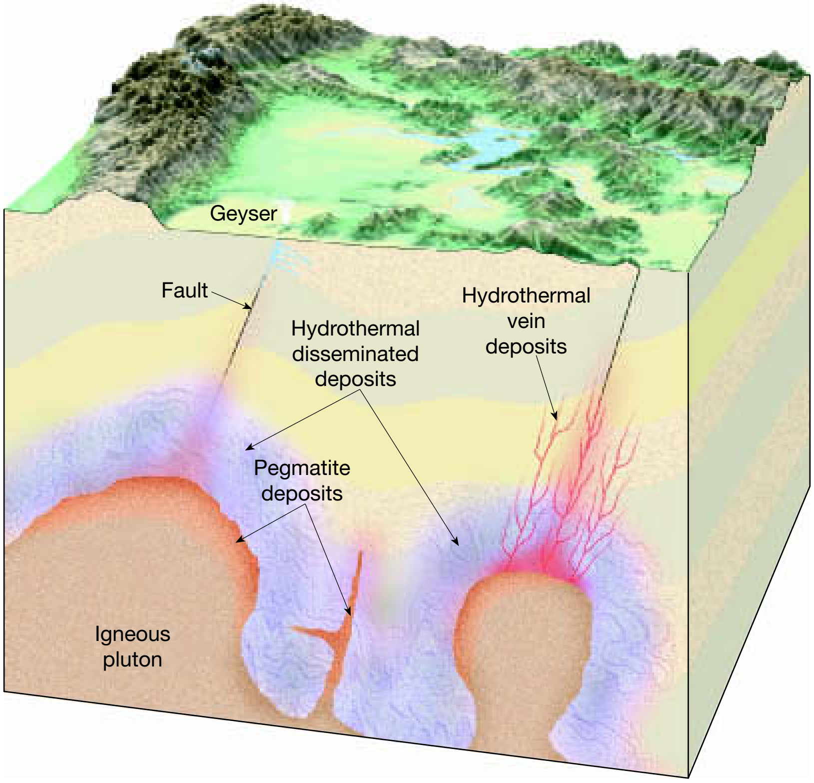




◆ **Figure 21.8** Massive sulfide deposits can result from the circulation of seawater through the oceanic crust along active spreading centres. As seawater infiltrates the hot basaltic crust, it leaches sulphur, iron, copper, and other metals. The hot, enriched fluid returns to the seafloor near the ridge axis along faults and fractures. Some metal sulphides may be precipitated in these channels as the rising fluid begins to cool. When the hot liquid emerges from the seafloor and mixes with cold seawater, the sulfides precipitate to form massive deposits. Photo shows a close-up view of a black smoker spewing hot, mineral-rich seawater along the East Pacific Rise. (Photo © Robert Ballard, Woods Hole Oceanographic Institution)



◆ **Figure 21.9** Illustration of the relationship between a parent igneous body and the associated pegmatite and hydrothermal deposits.

◆ **Figure 21.10** Gneiss laced with quartz veins at Diablo Lake Overlook, North Cascades National Park, Washington. (Photo by James E. Patterson)

The fractures thus produced are then filled with the hydrothermal fluid condensed from the steam and, in turn, are filled with metal sulphides precipitated from the fluid. This cycle can be repeated several times until the plutonic rock and some of the host rock is riddled with minute sulphide-filled fractures rarely exceeding a few millimetres in thickness. The result is a swarm or *stockwork* of thin (at times microscopic) metal sulphide veinlets scattered throughout porphyritic rocks of the cooled pluton as well as in the surrounding host rocks (Figures 21.9, 21.11). Porphyry deposits are generally associated with magma chambers that feed stratovolcanoes and are found accordingly in convergent margin settings.

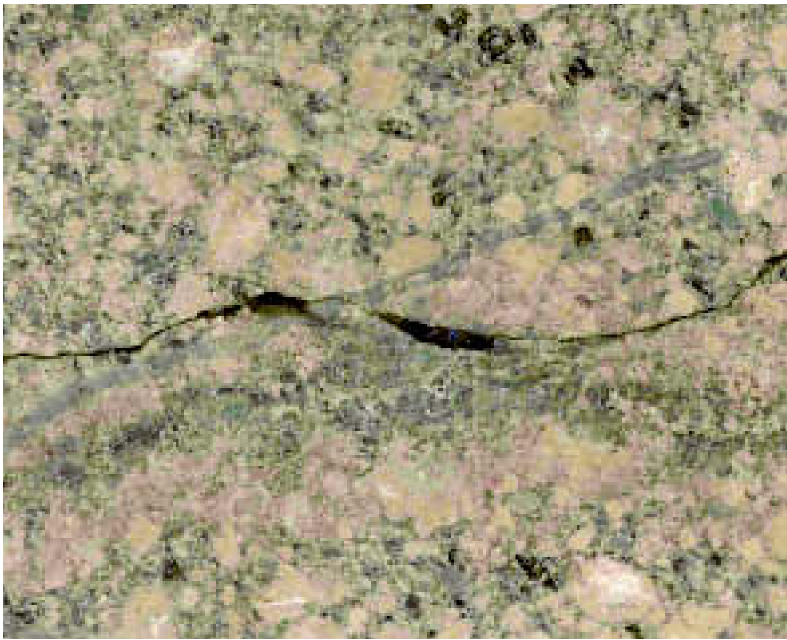
Porphyry deposits have a very low ore grade. For example porphyry copper deposits contain only 0.4 to 0.8 percent copper. However, the ore occurs in such large volumes and so close to the surface that they are well worth mining. Large deposits of porphyry copper and molybdenum figure prominently in the mining industry of British Columbia.

Volcanogenic Massive Sulphide Deposits Some hydrothermal deposits form pod-shaped bodies of *massive sulphides* that are almost entirely composed of interlocking sulphide minerals and are intimately associated with volcanic (usually basaltic) rock. These are called *volcanogenic massive sulphide* (VMS) *deposits*.

The hydrothermal systems associated with the black smokers we see in today's mid-ocean ridge settings are considered to be similar to those that produced VMS deposits in ancient rocks. As discussed earlier, the convective fluid flow that develops in centres of seafloor spreading, leaches metals from oceanic crust, transports them through fractures, and deposits them as sulphide minerals in mounds that surround volcanic vents (Figure 21.8). VMS deposits appear to represent these large sulphide bodies (Figure 21.12).

VMS deposits are extremely important worldwide as they commonly contain economically valuable concentrations of copper, zinc, lead, silver, and gold. VMS deposits occur in all provinces and terri-

◆ **Figure 21.11** Sample of a porphyry copper deposit from British Columbia. Mineralization has occurred in the dark groundmass of this andesitic igneous rock. (Photo by Bob Hodder)



◆ **Figure 21.12** Massive sulphide deposit at Noranda, Québec. This deposit contains mainly pyrite (light-coloured material), but thin, dark-coloured bands of galena are also visible. The rusty coloured patches are iron oxides produced by the weathering of the pyrite. (Photo by Bob Hodder)

tories of Canada, except Alberta and Prince Edward Island and most of them are hosted in Precambrian greenstone belts. Among the better-known VMS deposits in Canada are those of Kidd Creek, Ontario; Matagami and Noranda, Québec; Flin Flon, Manitoba; and Buchans, Newfoundland and Labrador.

Sediment-Associated Hydrothermal Deposits

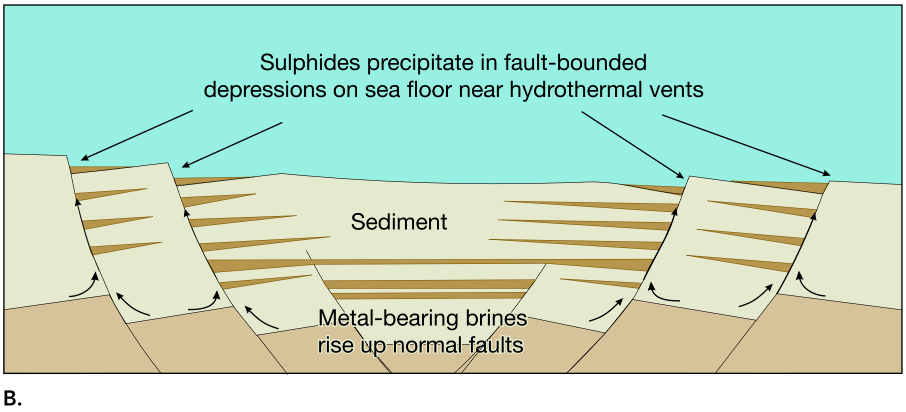
Some mineral deposits are intimately associated with sedimentary rocks and appear to have involved mineral precipitation from hydrothermal fluids at relatively low temperatures. For most of these deposits, the source of the metals is believed to be brine that was flushed from sediments buried deep within the sedimentary pile of a sedimentary basin, although deep-seated igneous activity (e.g., in rift basins) may be responsible for contributing heat to the hydrothermal system.

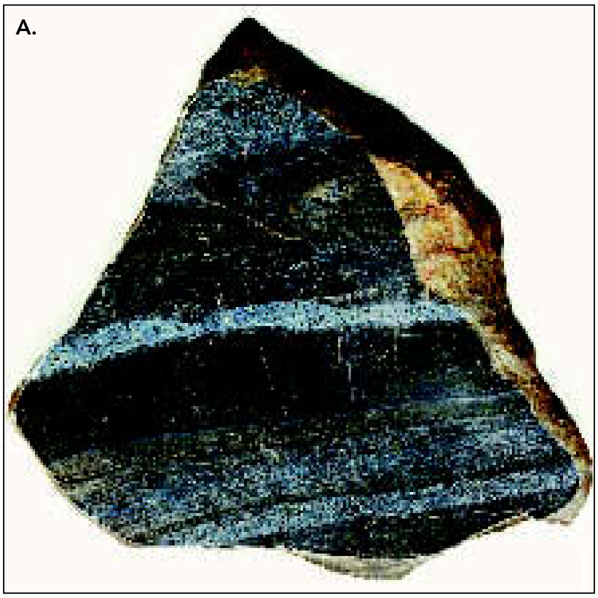
Sedimentary Exhalative (SEDEX) Deposits Some mineral deposits feature thin layers of massive sulphide that are interbedded with detrital or chemical sedimentary rocks (Figure 21.13A). These deposits are called *sedimentary exhalative* (SEDEX) *deposits*, as they are not only intimately related with sedimentary strata (most commonly mudrocks, chert, and fine-grained carbonates), but are also thought to be associated with the mineral precipitation from fluids that were "exhaled" from hydrothermal vents onto the seafloor. SEDEX deposits typically form sheet-to lens-like bodies that are vertically stacked within the sediment fill of failed continental rifts (Figure 21.13B) and fault-bounded basins of rifted continental margins. Hot brines, derived from deep areas within rift basins, are believed to have leached metallic ions from sediments and to have carried them in solution along fault, ultimately emerging at the seafloor from hydrothermal vents. It is further speculated that the brines formed dense pools in fault-bounded depressions on the seafloor, ultimately precipitating metals in the form of sulphide minerals. The role of normal faults in the migration of hydrothermal fluids is indicated by the preservation of subvertical vein networks, apparently representing feeder vents, associated with some SEDEX deposits. In addition, concentrations of lead, zinc, and silver decrease with distance away from these vein networks. The floor of the present-day Red Sea has been noted to bear pools of hydrothermal brines that are believed to be similar to those that formed ancient SEDEX deposits.

Canada's most famous SEDEX deposit of this type is an impressive lead-zinc deposit that was the foundation of the Sullivan mine in southwestern British Columbia (Figure 21.13A). This mine closed in 2001 after 92 years of production.

Sediment-Hosted Stratiform Deposits Highly enigmatic in terms of their origin are strata-like bodies of metallic minerals called *sediment-hosted stratiform deposits*, which occur within sedimentary units of some ancient rift basins. A key characteristic of these deposits, most of which are rich in copper sulphides, is that

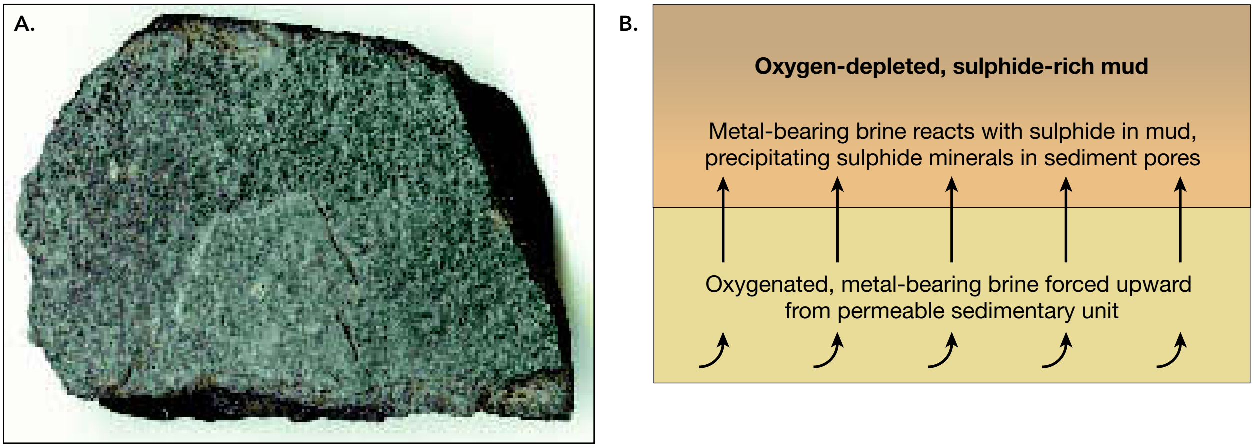
◆ **Figure 21.13** **A.** A sample of a SEDEX mineral deposit from the Sullivan Mine near Kimberley, British Columbia, showing distinct, highly reflective beds of lead/zinc sulphides and dark-coloured beds of mudstone. (Photo by C. Tsujita) **B.** Sedimentary-exhalative (SEDEX) deposits are interpreted to result from the precipitation of sulphide minerals from hydrothermal vents in fault-bounded depressions on the seafloor. SEDEX deposits typically occur in the sediment fills of rift basins.



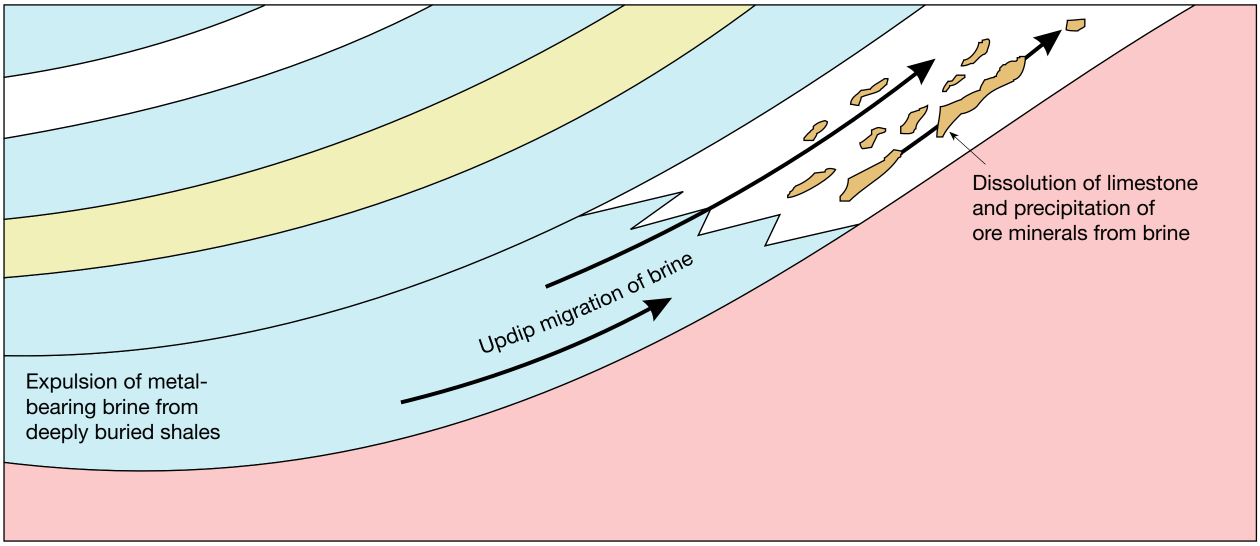


the ore minerals occur as pore-filling material of the host rock, rather than as the pure bands (Figure 21.14A). Also significant is the tendency of such deposits to occur in the basal portions of marine shales that abruptly overlie nearshore and nonmarine sandstones.

Some geologists believe that sediment-hosted stratiform deposits are produced because of mineral precipitation from submarine brine pools, as envisaged for SEDEX deposits. However, more recent interpretations favour a mechanism by which oxygenated, copper-bearing brines travelling through a coarse-grained sedimentary unit are forced upward into an overlying unit of oxygen-poor, sulphide-rich mud, thereby promoting the precipitation of copper sulphide minerals amongst the tiny particles of clay and other detrital grains (Figure 21.14B). The most commonly cited deposit of this type is the Kupferschiefer of Germany (Figure 21.14A), but similar deposits are known in the Coppermine District of the Northwest Territories of Canada.



◆ **Figure 21.14** **A.** Sample of the Kupferschiefer shale from Germany. Note the greenish tinge in this sample imparted by copper oxide that was produced by the weathering of the contained copper sulphide minerals. Scale bar: 1 cm. (Photo by C. Tsujita) **B.** Sediment-hosted stratiform copper deposits are formed by the interaction of oxygenated brine with overlying sulphide-rich sediment.



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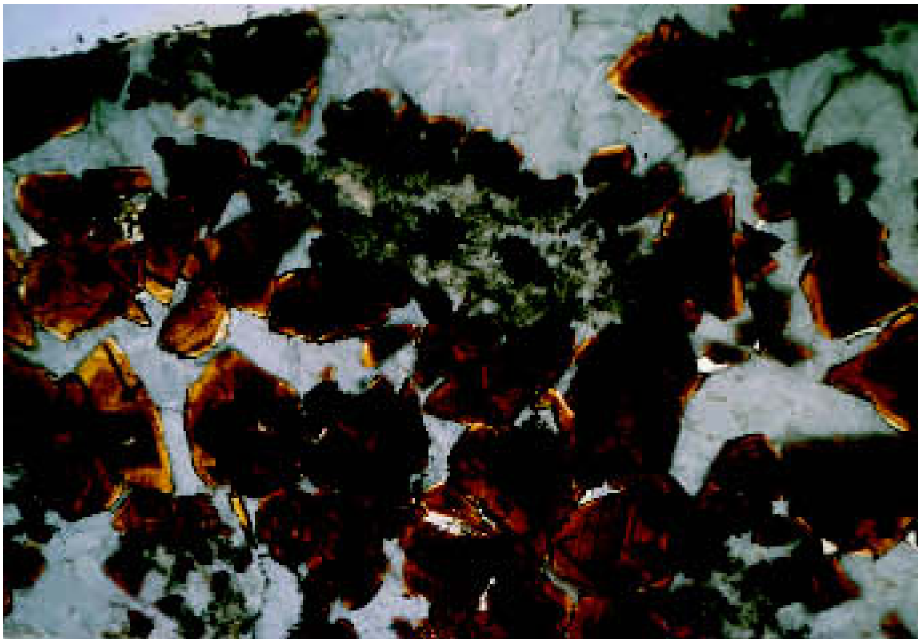


B.

◆ **Figure 21.15** **A.** Mississippi Valley-type deposits are believed to result from the precipitation of sulphide minerals from metal-bearing brines that migrated from deeply buried sediments of a sedimentary basin. **B.** Zinc ore from the Mississippi Valley-type Pine Point deposit in the Northwest Territories, as seen under a microscope. In this sample, cavities within a carbonate sedimentary rock have been filled with crystals of sphalerite (yellow) and dolomite (white). Scale bar: 1 mm. (Photo by Bob Hodder)

Mississippi Valley-Type Deposits *Mississippi Valley-Type* (MVT) *Deposits* are unusual hydrothermal deposits that, as their name implies, are well developed in southeastern North America. Similar deposits have, however, also been found on nearly all other continents. It is believed that the compaction of shales deep within a sedimentary basin can release metal-bearing brines that migrate toward the edges of the basin, where they react with limestones (Figure 21.15A). MVT deposits show evidence of significant calcite dissolution and replacement by other minerals, particularly sphalerite and galena (Figure 21.15B). Limestone breccias associated with MVT deposits in places like Tennessee suggest that dissolution was sufficiently great to cause the collapse of underground caverns. Cavities developed in limestones hosting MVTs can be sufficiently large to permit the growth of huge crystals of sulphide minerals. In Canada, MVTs are actively mined for lead and zinc in Nunavut and the Northwest Territories.

Sedimentary Deposits

Banded Iron Formations As already briefly mentioned in Chapter 6, a peculiar chemical sedimentary rock called **banded iron formation** was formed during the Archean and Proterozoic. The common *Superior type banded iron formation* is Proterozoic in

◆ **Figure 21.16** Banded iron formation has historically been an important source of iron in the Lake Superior area of Ontario and the northern U.S. This example is from a Proterozoic sequence in Arctic Canada. The purple bands are composed of magnetite and hematite and the red bands are iron-stained chert. (Photo by Grant Young)

age and typically consists of alternating bands of iron oxides, (magnetite and/or hematite) and chert (Figure 21.16). Due to the generally reducing conditions that prevailed through much of the Precambrian, a great deal of iron occurred in the soluble ferrous state and was dissolved in large quantities from weathered rocks and delivered to the sea. Large quantities of iron were probably also produced from hydrothermal vents.

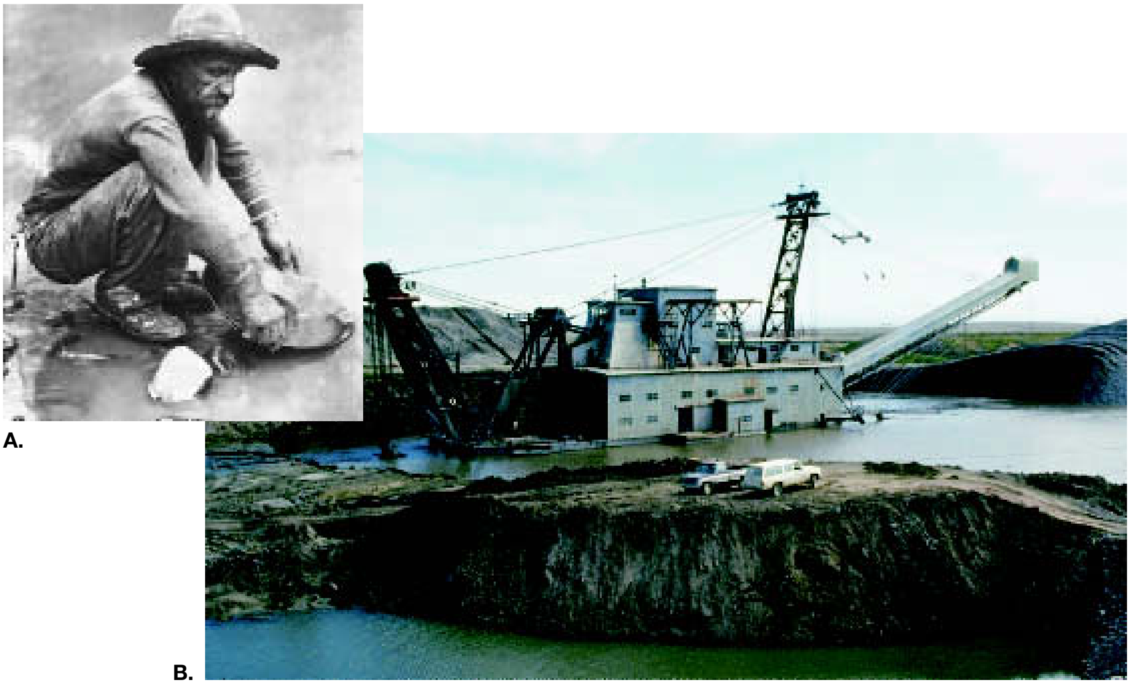
It is believed that the oxygen liberated from photosynthesizing bacteria eventually accumulated in sufficient quantities in the oceans to oxidize some of the iron, resulting in the deposition of insoluble iron oxide minerals. It appears that such oxygenation occurred in pulses, such that the iron oxides were deposited in more or less distinct bands. During intervening periods when iron oxide precipitation was low, silica was deposited as a gel that eventually lithified to form chert.

Despite the presence of oxygen in the oceans when banded iron formations were formed, oxygen had not yet reach sufficient quantities to occur in gaseous state in the atmosphere. Iron formations are not formed today because of our oxygen-rich atmosphere. In today's world, iron is immediately oxidized into the insoluble ferric state, and therefore does not accumulate in a dissolved form to the degree it did during the Precambrian. In addition, much of the dissolved silica in today's oceans is taken up by organisms (e.g., radiolarians, diatoms, and sponges) to make their skeletons, and therefore does not precipitate in large quantities to form chert.

In Canada and the northern United States, banded iron formations occur abundantly in the Lake Superior area of the Canadian Shield. They also reach ore grade in Newfoundland and Labrador. Banded iron formations presently comprise the main sources of iron in North America.

Placer Deposits The formation of **placer** deposits relates to the sorting action of running water. As you will recall from Chapter 6, large, heavy sediment grains tend to be deposited in more agitated water than smaller, lighter ones. In the same sense, mineral particles of high density can be concentrated due to the sorting out and washing away of mineral particles of lower density. The concentrations of heavy minerals that form in this manner are called placers and are associated with areas of high water agitation such as streams and beaches.

Placer deposits of gold were the foundation of the famous gold rushes in California and the Yukon, and continue to perpetuate images of old, haggard-looking prospectors panning river sediment along-



◆ **Figure 21.17** **A.** It was placer deposits that led to the 1848 California gold rush. Here, a prospector in 1850 swirls his gold pan, separating sand and mud from flecks of gold. (Photo courtesy of Seaver Center for Western History Research, Los Angeles County Museum of Natural History) **B.** Modern gold mining of a placer deposit near Nome, Alaska. The dredge scoops up thawed gravel. (Photo by Fred Bruemmer/DRK Photo)

side their mules. It is in placer deposits where the familiar *nuggets* of gold are found, their commonly rounded appearance attesting to the trials of sediment transport. It has traditionally been assumed that nuggets are sourced from hydrothermal veins as large sedimentary particles and become increasingly smaller as they are transported away from their host rocks by water action. More recently, however, some geologists have pondered the possibility that gold nuggets might actually grow due to bacterially-mediated gold precipitation from surface waters.

Panning is a simple, small-scale method of concentrating gold that takes advantage of the essentially same process responsible for concentrating heavy minerals in natural deposits. Water and a bit of sediment are scooped into a pan and swirled to suspend the light rock particles. When the pan is tipped, the suspended sediment is dumped out with the water, and the heavy minerals are left behind in the pan as a residue. Most other methods of extracting heavy minerals, including sluicing, are based on the same principle (Figure 21.17).

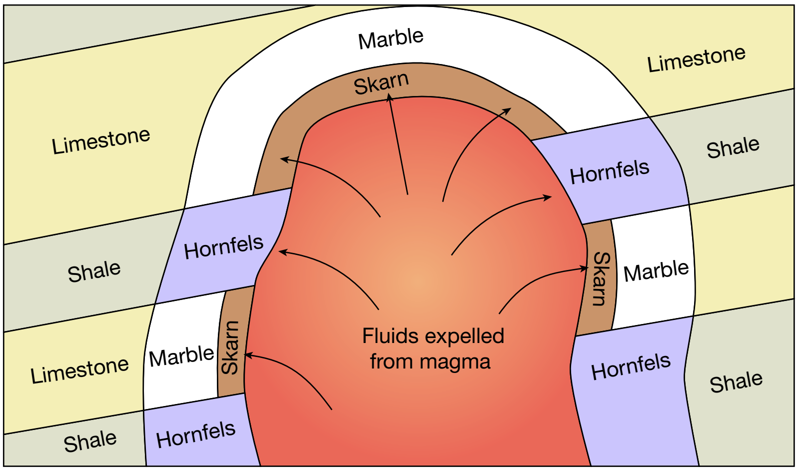
Additional minerals extracted from placer deposits include magnetite, rutile and ilmenite (titanium oxides), and diamonds. Ancient placer deposits, such as those in the Witwatersrand in South Africa are also mined for precious minerals.

Students Sometimes Ask …

How big was the largest gold nugget ever discovered?
The largest gold nugget ever discovered was the Welcome Stranger Nugget found in 1869 as a placer deposit in the gold-mining region of Victoria, Australia. It weighed a massive 2520 troy ounces (210 pounds, or 95 kilograms) and, at today's gold prices, was worth over $700,000. The largest gold nugget known to remain in existence today is the Hand of Faith Nugget, which was found in 1975 near Wedderburn, Victoria, Australia. It was found with a metal detector and weighs 875 troy ounces (73 pounds, or 33 kilograms). Sold in 1982, it is now on display in the Golden Nugget Casino in Las Vegas, Nevada.

Deposits Associated With Metamorphism

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



◆ **Figure 21.18** Skarns are associated with contact metamorphism. In this example, the intrusion of magma into sedimentary rock layers has metamorphosed limestone to marble and shale to hornfels. Infiltration of magmatic fluids into the zones of marble promotes the reaction of the fluids with minerals of the various intruded rocks, the dissolution of calcium carbonate, and the precipitation of metallic minerals.

The extent to which the host rock is altered depends on the nature of the intruding igneous mass as well as the nature of the host rock.

Some resistant materials, such as quartz sandstone, may show little alteration, whereas others, including limestone (readily metamorphosed to marble), might exhibit the effects of metamorphism for several kilometres from the igneous pluton. As hot, iron-rich fluids move through limestone, chemical reactions take place. These reactions release carbon dioxide, which greatly facilitates the mobilization of metal ions. These extensive aureoles of metal-rich deposits are called skarns and commonly surround igneous plutons that have invaded limestone strata (Figure 21.18).

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

As one might expect by their similar geologic setting, skarns can be closely associated with porphyry deposits. Two of Canada's best-known skarn deposits are the Copper Mountain deposit of British Columbia and Mines Gaspé copper deposits of Québec. A number of tungsten and gold skarns occur in British Columbia and the Yukon.

Deposits Associated With Weathering

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

Bauxite The metal most often cited in discussions on the relationships between weathering and ore deposit formation is aluminum. While aluminum is one of the most common metallic elements on Earth and a primary component of many silicates, it is generally so tightly bonded with other elements that the energy required to extract the aluminum outstrips the value of the metal. Fortunately, aluminum also occurs in oxide form. Aluminum oxides are generally produced by the weathering of aluminum-bearing silicates in warm, humid regions of the world. In such areas, soils tend have very deep profiles and are severely leached in their upper horizons. Infiltration of groundwater removes soluble ions such as calcium, sodium, and potassium from the upper soil profile, leaving a residue of less soluble iron and aluminum oxides and hydroxides. The resulting *residual deposit*, called *bauxite* (Figure 21.19), is an aluminum-rich laterite (see also Chapter 5). Similarly, the olivine of nickel-bearing ultramafic rocks may weather to form silicate minerals containing up to 5 percent nickel.

Great concern surrounds the mining of bauxite and other residual deposits because they tend to occur in the humid, environmentally sensitive areas of the tropics. Not only does the clear-cutting of forest, which necessarily precedes mining, destroy rainforest ecosystems, but the thin, moisture-retaining layer of organic matter that naturally covers the soil is also disturbed. When allowed to dry in the hot sun, the exposed soil becomes hard as brick, loses its moisture-retaining abilities, and can no longer sup-

◆ **Figure 21.19** Bauxite is the ore of aluminum and forms as a result of weathering processes under tropical conditions. Its color varies from red or brown to nearly white. (Photo by E. J. Tarbuck)

port vegetation for farming or forest growth. The long-term consequences of bauxite mining are obvious and continue to be points of concern for the many developing countries of the tropics.

Other Deposits Many copper and silver deposits result when weathering processes concentrate metals that are deposited through a low-grade primary ore. Usually such enrichment occurs in deposits containing pyrite (FeS_2), the most common and widespread sulphide mineral. Pyrite is important because when it chemically weathers, sulphuric acid forms, which enables percolating waters to dissolve the ore minerals. Once dissolved, the metals gradually migrate downward through the primary ore body until they are precipitated. Deposition takes place because of changes that occur in the chemistry of the solution when it reaches the groundwater zone (the zone beneath the surface where all pore spaces are filled with water). In this manner, the small percentage of dispersed metal can be removed from a large volume of rock and redeposited as a higher-grade ore in a smaller volume of rock. This enrichment process is responsible for the economic success of some metallic mineral deposits, particularly those containing copper.

Nonmetallic Resources

Earth materials that are not used as fuels or processed for metals are referred to as **nonmetallic mineral resources**. Realize the use of the world "mineral" is very broad in the economic context and is quite different from the geologist's strict definition of mineral found in Chapter 2. Nonmetallic mineral resources are extracted and processed either for the nonmetallic elements they contain or for their desirable physical or chemical properties.

People often do not realize the importance of nonmetallic minerals because they see only the products that result from their use, not the minerals themselves. That is, many nonmetallics are used up in the process of creating other products. Examples include the fluorite and limestone that are part of the steel-making process, the abrasives required to make a piece of machinery, and fertilizers needed to grow a food crop. Accordingly, the quantities of nonmetallics used in construction and other applications are huge.

Nonmetallic mineral resources are divided into two broad groups here—aggregate and stone, and industrial minerals. Because some substances have many uses, they can technically belong to either category. Limestone, for example, is used as crushed rock and building stone in its raw form, but its main mineral constituent, calcite, is important in its own right as the key ingredient for the manufacture of cement, and as a component of a score of other products including cosmetics and pharmaceuticals.

Aggregate and Stone

Because most building materials are widely distributed and present in almost unlimited quantities, they have little intrinsic value. Their economic worth comes only after the materials are removed from the ground and processed. Because their per-tonne value compared with metals and industrial minerals is low, mining and quarrying operations are usually undertaken to satisfy local needs. Except for special types of cut stone used for building and monuments, transportation costs greatly limit the distance most building materials can be moved. The aggregate and stone industry is very important in the lives of Canadians, as reflected in the thousands of sand and gravel pits and stone quarries that exist in our country.

Natural aggregate consists of crushed stone, sand, and gravel. From the standpoint of quantity and value, aggregate is a very important building material. It is produced in all provinces and territories in Canada and is used in nearly all road and building construction (Figure 21.20). Thanks to the large volume of sand and gravel in Canada deposited as glacial outwash during and at the end of the last ice age, every province and territory has an ample supply of aggregates for construction. Aggregate is used as-is in various construction applications, and is also important in the manufacture of concrete and road asphalt. To appreciate the importance of aggregate in our daily lives, one only needs to consider that just one kilometre of four-lane highway, such as Highway 401 in Ontario, requires more than 40 tonnes of aggregate.

◆ **Figure 21.20** Aggregate pits are located in all provinces and territories of Canada. This aggregate pit is located near Surrey, British Columbia. (Photo by Steve Hicock)

Attesting to diversity of Canada's geological makeup, many varieties of solid stone are quarried throughout the country, including rocks of igneous (e.g., granite), metamorphic (e.g., marble, gneiss and slate), and sedimentary (e.g., sandstone, limestone and dolostone) origin. Cut stone is largely used for aesthetic applications in construction, such as decorative facings, walkways, and countertops.

Industrial Minerals

Many nonmetallic resources are classified as industrial minerals. In some instances these materials are important because they contain specific chemical elements or compounds used in fertilizers or industrial chemicals. Some minerals possess useful physical properties. For example, garnet is both relatively hard and fairly common, making it a handy substance for the manufacture of abrasive products such as sandpaper. Other industrial minerals are used in the manufacture of products used in construction as fillers, coaters, and extenders in plastics, paints, and paper products and as heat-resistant materials, in addition to a host of other applications. Common industrial minerals and their uses are listed in Table 21.2. Some industrial minerals of particular importance in Canada, and their geologic occurrences, are indicated in Figure 21.21 and discussed below.

Diamonds Diamonds are familiar as gemstones, but diamond is also extremely valuable as an abrasive by virtue of being the hardest natural substance known. Only about one quarter of all diamonds mined are used as gemstones.

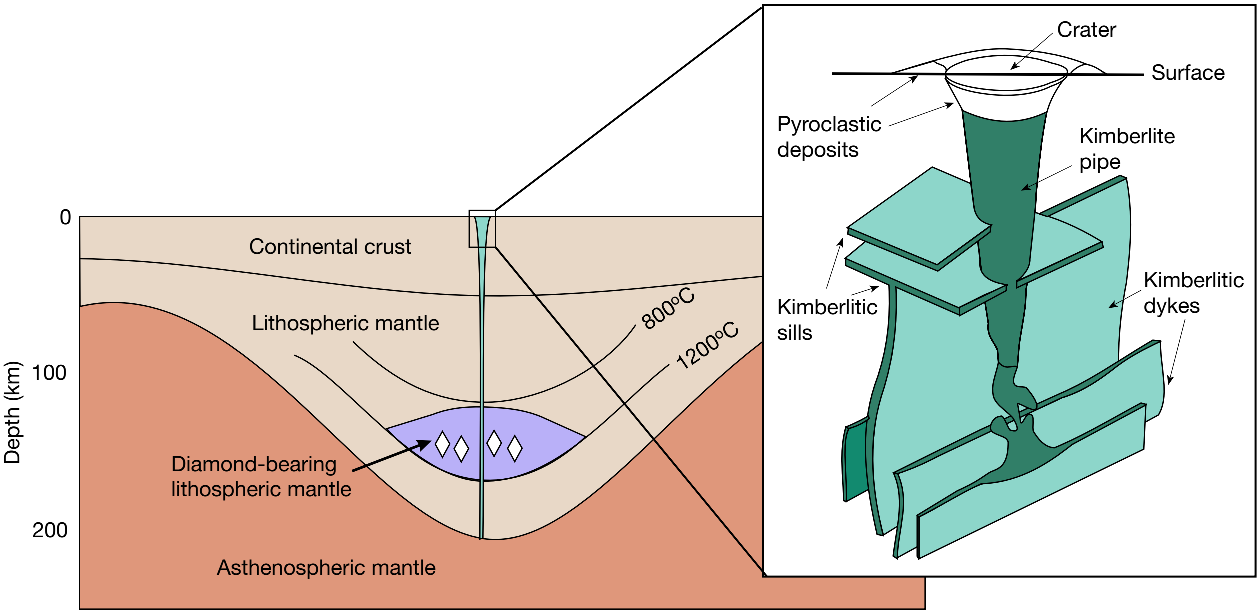
The vast majority of diamonds are found in a unique ultramafic igneous rock called **kimberlite**. Magmas that produce kimberlite are believed to be generated by a small amount partial melting in the asthenosphere at depths greater than 150 kilometres below Earth's surface. The diamonds themselves do not crystallize from kimberlitic magma. Rather, they are produced in the deep roots of the solid, lithospheric mantle beneath areas of old, stable, continental crust at depths of over 120 km (Figure 21.22). It is only here that high temperatures (between 900 and 1200°C) and pressures (over 40 kbar) remain stable for geologically long periods of time to allow the formation of diamonds.

Kimberlitic magma rapidly rises to the surface, acting as a sort of geological elevator that picks up chunks of lithospheric mantle material and crustal rock during its ascent. If kimberlitic magma passes through the deep areas of lithospheric mantle where diamonds reside, diamonds can be naturally sampled from this material as xenocrysts (individual mineral grains) and as crystal components of xenoliths (rock fragments) and be carried upward by the magma.

TABLE 21.2 Occurrences and Uses of Nonmetallic Minerals

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

◆ **Figure 21.21** Significant industrial mineral deposits in Canada. (Data courtesy of Natural Resources Canada)



◆ **Figure 21.22** Kimberlite pipes are carrot-shaped igneous bodies that are formed as mantle-sourced magma is violently extruded up to the Earth's surface. At the Ekati mine in the Northwest Territories, diamonds are mined from this rare type of igneous body.

During the last stage of magma ascent, and the rapid escape of carbon dioxide from the magma, together with the interaction of the hot kimberlitic magma with groundwater, produces an explosive volcanic eruption and a pipe-shaped vent (Figure 21.22). The fractures and cavities within the vent are ultimately filled with kimberlite and shattered fragments of the surrounding rock. Associated with the main, carrot-shaped kimberlite pipe are ultramafic dykes and sills at depth and pyroclastic volcanic deposits at the surface.

Major producers of diamonds include South Africa (the hub of the early diamond industry), Australia, Namibia, and Russia. Canada has recently entered into the diamond market through discoveries in the Northwest Territories. The Ekati mine, the first Canadian diamond mine, began production in 1998. It is projected that Canada may well supply 15 to 20 percent of the world's diamonds within the next decade.

Clays Clays, the fine-grained, platy minerals formed by the weathering and hydration of aluminosilicate minerals, are important industrial minerals. Certain clay minerals can form economically important deposits at the place of origin in masses of weathered material. However, much larger quantities of clay minerals occur in sedimentary deposits of seas and lakes, having been transported long distances by wind or water from their site of formation. Major Canadian producers of clay include Saskatchewan, Ontario, and British Columbia.

The diverse physical and chemical properties of clays make them extremely useful in many applications. For example, sediment dominated by the clay mineral kaolinite (but also generally containing minor amounts of other minerals) is extensively mined for the production of bricks, sewer pipes, and pottery. As an industrial mineral, kaolinite is also used in the production of wall and floor tiles, porcelain, insulation products, ion-exchange products, as a filler (and natural whitener) for paint, adhesives, sealants, pharmaceuticals, cosmetics and as a coater in paper. It might surprise you that the gloss finish on this very page is actually a thin layer of kaolinite.

Clay minerals such as montmorillonite (a weathering product of volcanic ash) readily absorb moisture and are therefore useful as absorbents in products such as cat litter. Montmorillonite is also an important ingredient of lubricating drill mud in the petroleum industry. In addition, due their high capacity for ion exchange, clays are used in oil refining and in waste treatment.

Carbonate Minerals As discussed in Chapter 6, calcium carbonate in the form of calcite (and to a lesser extent, aragonite) is an important component of many sedimentary rocks. Vast quantities of limestone, most representing accumulations of calcareous skeletal material secreted by organisms, are quarried worldwide. While some limestone is quarried raw in the form of building stone, a great deal of it is extracted for its calcium carbonate content.

Large volumes of limestone are quarried and processed for the manufacture of cement. The principal raw materials used in the making of common cements are calcite (from limestone), with smaller amounts of silica (from sand), clay (from shale), and iron oxide. These provide the necessary ingredients, calcium, silica, alumina, and iron that chemically interact to produce the desired qualities of cement. The raw materials are crushed into a powder and fed into the top of a tower containing a series of heating chambers. As the powdered substance drops through the series of chambers, it is heated to nearly 900°C, and then is fed through a kiln that heats the mixture further to about 1500–1600°C and converts the raw material into a substance called clinker. The key substance formed during this heating process is calcium silicate. The clinker is cooled, mixed with a small amount of gypsum (a regulator of cement setting time), and milled into a fine powder that is then ready for use as cement. When water is added to the cement powder, the calcium silicate crystals form an interlocking network that gives concrete its strength for construction purposes.

Calcium carbonate is also used in a great many other applications. It is used as a filler in asphalt, fertilizers, insecticides, paints, rubber and plastics, as a fluxing agent, as a mild abrasive in some toothpastes, as an acid neutralizer in a wide variety of cosmetic, medicinal, and paper products, and as a dietary supplement. In all likelihood, the very page you are reading in this text has a thin coat of calcium carbonate that has been added to the paper to provide a smooth, uniform surface for printing. Humans also use dolomite as a gentle abrasive and a dietary supplement.

Evaporite Salts Evaporite deposits are important sources of many industrial minerals, particularly chloride and sulphate salts, and some carbonate minerals. During many times in Earth's past, widespread evaporite deposits were deposited in shallow basins that were periodically flooded by seawater but dried up due to intense evaporation under arid conditions.

Normal seawater contains about 3.5 percent (by weight) dissolved matter that can be precipitated in mineral form when the water is evaporated. As observed in a glass of salty water left on the counter for several days, evaporation reduces the total volume of liquid, increasing the concentration of the dissolved matter to the point that salt can be precipitated. Partly due to differences in the relative concentrations of dissolved ions in seawater, minerals of different composition are precipitated sequentially as evaporation removes more and more water from the brine. In order of appearance, the principal minerals that form during progressive evaporation are: calcite, gypsum, halite, and finally sylvite. Few evaporite deposits contain sylvite, probably because of the dilution of brines by episodic influxes of normal seawater from the adjacent ocean. It should also be noted that thick evaporite deposits represent several cycles of seawater influx, evaporation, and mineral precipitation rather that a single "drying-up" event in a basin.

Gypsum is primarily used for the manufacture of plaster products used in construction and other applications. Gypsum ($CaSO_4 \cdot 2H_2O$) is heated to about 180ºC to drive off about three-quarters of its water (producing $CaSO_4 \cdot \frac{1}{2}H_2O$), milled to a fine powder, and sold as plaster. When water is added to the powder, it rehydrates the material to produce tiny, interlocking crystals of gypsum that give plaster products their strength for interior construction applications. A plaster product familiar to most people is drywall (also called wallboard or gyprock), which consists of a sheet of plaster sandwiched between two sheets of paper. Doctors also commonly use plaster to make casts for patients who require their limbs to be stabilized as their fractured bones heal. Gypsum is also widely used as a filler or additive in many products, including cosmetics, pharmaceuticals, fertilizers, paints, and plastics. Significant deposits of gypsum occur in British Columbia, Manitoba, Ontario, Nova Scotia, and Newfoundland and Labrador.

Halite, or salt, as it is more commonly known, is another important resource mined from evaporite deposits. The consumption of salt in Canada is very high, averaging about 360 kilograms of salt per person per year. This high figure is reflects not only our liberal use of salt in the de-icing of roads, but also the extensive use of halite in the manufacture of important substances used in the chemical industry such as chlorine and caustic soda. It is also used to "soften" water, and of course, to season and preserve foods. Salt is a common evaporite and thick deposits are exploited using conventional underground mining and brining, which involves dissolving salt underground and re-precipitating it at the surface. In Canada, extensive Paleozoic salt deposits occur in the sedimentary basins of the Prairie Provinces, southwestern Ontario, Québec, and the Maritime Provinces. Globally, salt is extracted directly from seawater in arid, coastal areas, using the natural evaporating abilities of the Sun's heat.

The mining of potash, an evaporite rock containing the potassium-bearing minerals sylvite (KCl) and carnallite ($KClMgCl_2 \cdot 6H_2O$) is a huge industry in Canada. Most of Canada's potash is mined from immense deposits in Saskatchewan, where it occurs in horizontal layers up to three metres thick (Figure 2.26). Potash deposits also occur in the Maritime Provinces and it is actively mined in New Brunswick. About 95 percent of all potash mined in Canada is exported to other countries, where it is primarily used in the production of fertilizers. It is also used in deicing products, in the manufacture of soaps and detergents and as an additive in glass and ceramic products.

Phosphate Phosphate, contained in the mineral apatite, is mined primarily for the production of phosphoric acid for fertilizers, additives for livestock feed, industrial chemicals, and some home products. Although generally scarce in nature, phosphate can reach high concentrations in sedimentary rocks. The manner in which these deposits form is somewhat enigmatic, but appears to require a combination of high primary productivity, low oxygen, and low input rates of detrital sediment in a marine environment. Such conditions appear to be fairly common in oceanic environments influenced by the upwelling cold, nutrient-rich seawater. North America's major phosphate mines are restricted to the states of Florida, North Carolina, Idaho, and Utah, although sedimentary phosphate deposits are also known to exist in British Columbia. Canada's only active phosphate mine is located in Kapuskasing, Ontario, where the weathering of an igneous intrusion has left a rich residue of apatite crystals.

Sulphur Because of its many uses, sulphur is an important nonmetallic resource. Sulphur is a major component of sulphuric acid and fertilizers: it is also featured in matches and gunpowder. Sources of sulphur include deposits of native sulphur associated with salt domes and volcanic areas and sulphides such as pyrite. In recent years, an increasingly important source has been the sulphur removed from coal, oil, and natural gas in order to reduce the sulphur dioxide emissions produced by their combustion.

Other Industrial Mineral Deposits In addition to igneous and sedimentary deposits of industrial minerals, deposits of metamorphic origin also occur. Recall that, at convergent plate boundaries, the oceanic crust and sediments that have accumulated at the continental margins are carried to great depths. In these high-temperature, high-pressure environments, the mineralogy and texture of the subducted material are altered, producing deposits of nonmetallic minerals such as talc (used widely in cosmetic products) and graphite (used in the manufacture of steel products, lubricants and pencils). Chrysotile asbestos is another product of metamorphism, resulting from the flushing of fluids through ultramafic rock. Concentrations of industrial minerals can also be produced in association with skarns during contact metamorphism. These minerals include garnet and corundum used in abrasive products.

Nonrenewable Energy Resources

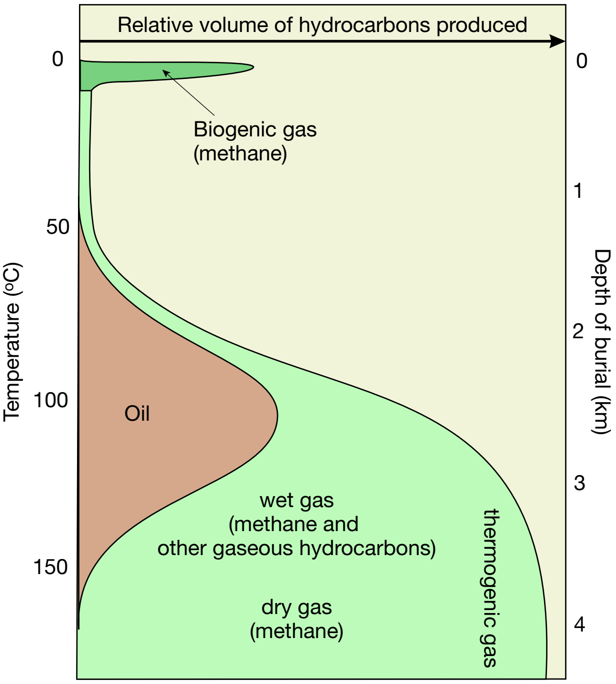
Petroleum

Petroleum is the group of hydrocarbons that includes oil and gas, and is presently a vital resource for the daily activities of humankind. It is mainly used as fuel, but it also comprises the main ingredients in plastics that find their way into synthetic fabrics, product packaging, casings, and a wide range of other products.

How Petroleum Is Formed The origin of petroleum ultimately lies in organic matter contained in the tissues of living things. The vast majority of petroleum is derived from the remains of simple, aquatic organisms (mostly planktonic algae) that constitute most of the plankton in the seas and other large bodies of water, although some land-derived organic matter may also contribute to petroleum generation. Organic matter has a rather low preservation potential in most aquatic environments, since scavenging organisms and aerobic microbes naturally recycle it. However, it often accumulates in quiet-water environments of shallow seas and lakes, where low-oxygen conditions prevail. Accordingly, organic rich-sediments are typically fine grained, and are represented in ancient deposits by shales and fine-grained carbonate rocks. Because they are the principal sources of organic matter from which petroleum is generated, these organic-rich rocks are called *source rocks*.

Although organic matter stands a better chance of survival under low-oxygen conditions, it is by no means immune to microbial attack. Organic-rich sediment can initially yield significant quantities of *biogenic gas* (principally methane) due to the breakdown of organic matter by anaerobic microbes (Figure 21.23). This microbial attack also removes much of the oxygen, nitrogen, phosphorus, and sulphur from the organic matter, leaving a residue that is enriched in hydrocarbons. With progressive burial, the production of biogenic gas ceases, the organic-rich sediment undergoes lithification, and heat becomes the main agent in the breakdown of the organic matter.

As the hydrocarbon-rich organic matter of a source rock is subjected to higher and higher temperatures, they are transformed into a solid waxy substance called *kerogen*. At temperatures above about 50°C, carbon-carbon bonds within the kerogen break, producing the lighter, less complex hydrocarbon molecules. This process is called cracking. As the temperature rises, more carbon-carbon bonds are broken, both in the kerogen and in the hydrocarbon molecules that formed previously, generating oil (Figure 21.23). Oil generation peaks at a temperature of about 100°C, beyond which the kerogen is depleted of its hydrocarbon supply, and significant amounts of



◆ **Figure 21.23** The temperatures and corresponding depths of burial at which oil and gas are generated. Note that biogenic gas is only produced at low temperatures, whereas themogenic gas produced by the thermal cracking of organic molecules dominates at higher temperatures. Oil generation is restricted to a temperature window between approximately 50 and 150°C. Note also the large amounts of natural gas produced at the expense of oil as hydrocarbons are cracked to progressively simpler molecular forms.

themogenic natural gas are produced (Figure 21.23). The natural gas produced at temperatures just above that of peak oil generation is commonly called *wet gas* because, in addition to its primary constituent, methane, it contains gaseous components such as ethane, propane, and butane, which can be separated by condensation. At temperatures above about 150°C, only *dry gas*, consisting almost entirely of methane, is generated.

It should be noted that the specific proportions of oil and gas generated in any given source rock depend not only on burial depth and duration of cooking, but can also reflect the composition of the organic matter from which the hydrocarbons are derived. Whereas organic matter from marine sources is *oil-prone*, land-derived organic matter tends to be more *gas-prone*. Because land-derived organic matter can be transported into aquatic environments, some source rocks can be expected to be more gas prone than others.

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

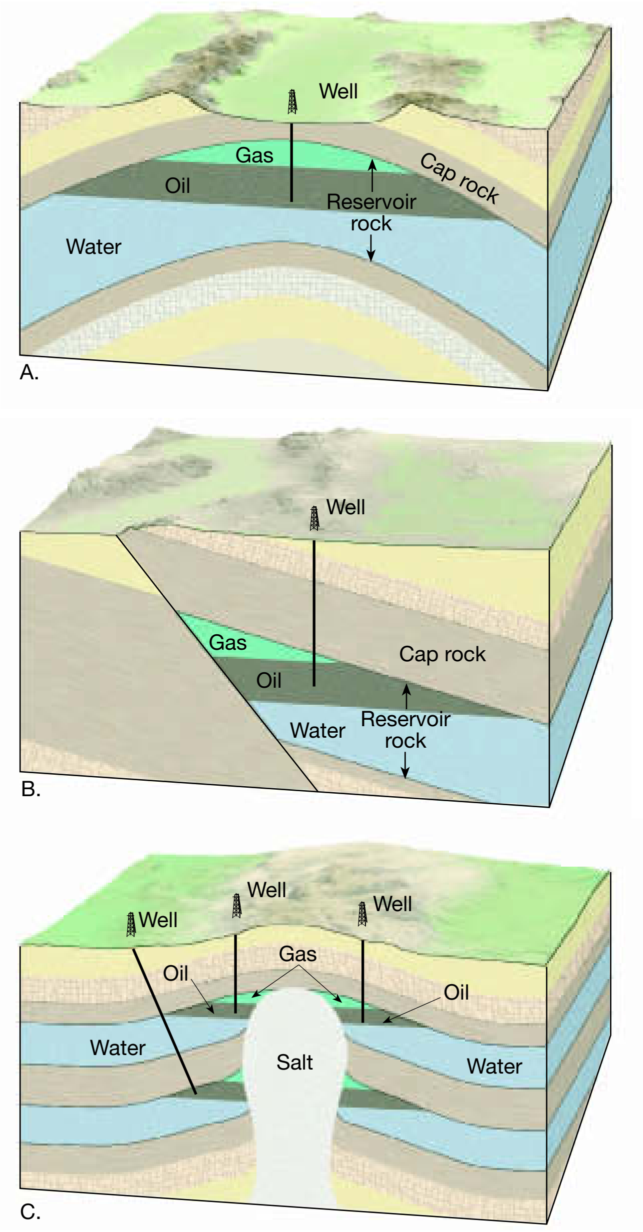
Petroleum Traps Sometimes the upward migration of oil and gas is halted. A geologic environment that allows for economically significant amounts of oil and gas to accumulate underground is called a **petroleum trap**. Several geologic structures may act as petroleum traps, but all have two basic conditions in common: a porous, permeable **reservoir rock** that will yield oil and natural gas in sufficient quantities to make drilling worthwhile; and a **cap rock**, such as shale, that is virtually impermeable to oil and gas. The cap rock halts the upwardly mobile oil and gas and keeps them from escaping to the surface. Petroleum traps can be produced in a number of ways, but they can be separated into two groups: structural traps and stratigraphic traps.

Structural Traps are petroleum traps that form due to the structural deformation of the rock layer that contains the hydrocarbons. One of the simplest structural traps is an anticline, an uparched succession of sedimentary strata (Figure 21.24A). As the strata are bent, the rising oil and gas collect at the apex (top) of the fold. Because of its lower density, the natural gas collects above the oil. In turn, the oil rests upon the denser water that saturates the reservoir rock. One of the world's largest oil fields, El Nala in Saudi Arabia, is the result of anticlinal traps, as is the famous Teapot Dome in Wyoming.

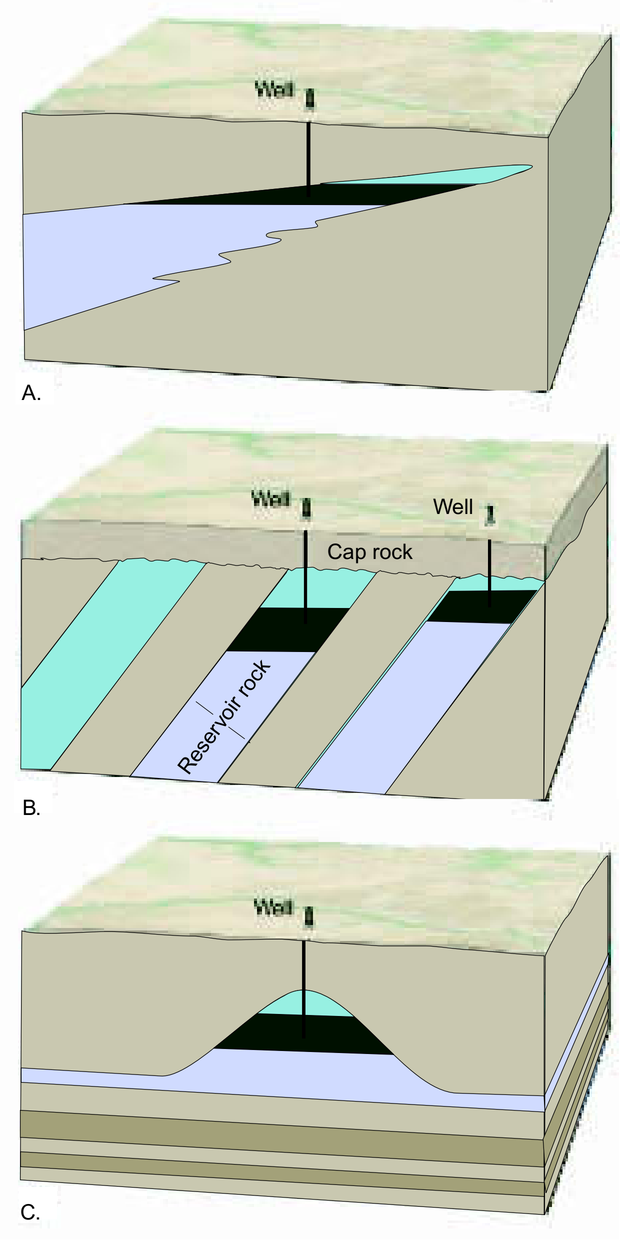
Fault traps form when strata are displaced in such a manner as to bring a dipping reservoir rock into position opposite an impermeable bed, as shown in Figure 21.24B. In this case the upward migration of the oil and gas is halted where it encounters the fault.

In the Gulf coastal plain region of the United States, important accumulations of oil occur in association with *salt domes*. Such areas have thick accumulations of sedimentary strata, including layers of rock salt. Salt, occurring at great depths has been forced to rise in columns by the pressure of overlying beds. These rising salt columns gradually deform the overlying strata. Because oil and gas accumulate in the upturned sandstone beds adjacent to the salt column (Figure 21.24C).

Stratigraphic Traps are petroleum traps that are formed due to lateral and vertical changes in



◆ **Figure 21.24** Common structural petroleum traps. **A.** Anticline. **B.** Fault trap. **C.** Salt dome.



◆ **Figure 21.25** Common stratigraphic petroleum traps. **A.** Pinch-out traps. **B.** Unconformity trap. **C.** Limestone reef.

rock type that reflect patterns of sediment deposition (Figure 21.25). A common type of stratigraphic trap is a pinch-out trap, characterized by the tapering off of a reservoir unit into a body impermeable rock. An unconformity trap results from the truncation of a reservoir unit by erosion, followed by the deposition of impermeable cap rock sediments. Reefs also form important stratigraphic traps, by virtue of representing lens-shaped bodies of porous, permeable limestone that are commonly encased by impermeable shales.

Coal

Whereas petroleum is generally sourced from organic matter provided by aquatic plankton, coal is largely derived from the fibrous and woody remains of land plants. Similar to petroleum, the organic remains that form coal can only accumulate in appreciable quantities in oxygen-poor environments. Accordingly, accumulations of coal-forming organic matter tend to be restricted to areas such as swamps. In a swamp, the decomposition of organic matter consumes so much oxygen from the water that much of the organic matter escapes decomposition. The organic matter that survives decomposition is buried to progressively greater depths, where it is gradually cooked and compressed to form coal. This is discussed in greater detail in Chapter 6.

Coal has been an important fuel for centuries. In the nineteenth and early twentieth centuries, cheap and plentiful coal powered the Industrial Revolution. Until the 1950s, coal was an important domestic fuel as well as a power source for industry. However, its direct use in the home has largely been replaced by oil, natural gas, and electricity. These fuels are preferred because they are more readily available (delivered via pipes, tanks or wiring) and cleaner to use. Nevertheless, coal remains the major fuel used by many nations.

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

Moreover, underground mining long ago ceased to be a pick-and-shovel operation and is today a highly mechanized and computerized process (Figure 21.26). However, the hazards of collapsing roofs, gas explosions, and working with heavy equipment remain.

Air pollution is a major problem associated with the burning of coal. Much coal contains significant quantities of sulphur. Despite efforts to remove sulphur before it is burned, the sulphur is converted into noxious sulphur oxide gases. Through a series of complex chemical reactions in the atmosphere, the sulphur oxides are converted to sulphuric acid, which then falls to the Earth's surface as rain or snow. This acid precipitation can have adverse ecological effects over widespread areas (see Box 5.1, p. xxx).

As none of the problems just mentioned are likely to prevent the increased used of this important and abundant fuel, stronger efforts must be made to correct the problems associated with the mining and use of coal. Disposal of fly ash produced by coal burning also poses problems. However, as indicated in Box 21.1, this material may well prove to be a resource in itself in the future.

Fossil Fuel in Canada

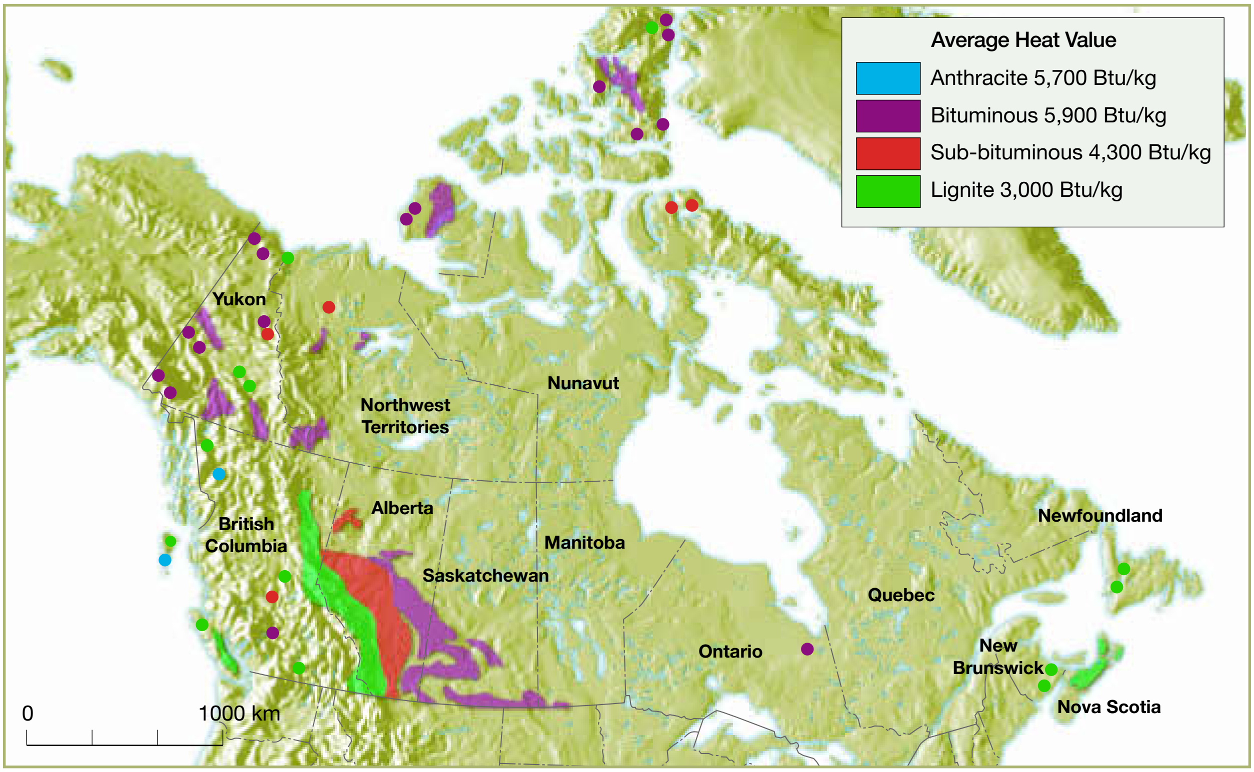
Canada is fortunate to host large quantities of coal and petroleum—so much so that most of it is exported. The overwhelming majority of Canada's petroleum is produced in the southern areas of the Prairie Provinces and British Columbia that overlie strata of the Western Canada Sedimentary Basin (Figure 21.27). Through much of Paleozoic and Mesozoic time, warm, shallow seas, within which organic-rich sediments were deposited, occupied this area of Canada. Hydrocarbons were squeezed out of the organic-rich sediments and migrated to the permeable, low-pressure areas of the rock column such as Paleozoic reefs and units of Mesozoic sandstone. Similar circumstances allowed oil to be produced and trapped in basins and continental shelf areas of Newfoundland and Labrador (Hibernia project), Yukon, Northwest Territories,

◆ **Figure 21.26** Modern underground coal mining is highly mechanized and relatively safe. (Photo by Melvin Grubb/Grubb Photo Services, Inc.) Strip mining (inset) of coal at Black Mesa, Arizona. Surface mining is common when coal seams are near the surface. (Photo by Richard W. Brooks/Photo Researchers, Inc.)

◆ **Figure 21.27** Distribution of important oil and gas-bearing areas of North America. (Source: Natural Resources Canada)

Nunavut, and to a lesser degree, British Columbia and Nova Scotia. Modest quantities of oil and gas are also extracted from Paleozoic sedimentary rocks of the Michigan Basin in Ontario (Figure 21.27). As discussed in Box 21.3, Canadians have played major roles in the development of the North American oil industry.

In the Prairie Provinces, the shallow seas that supplied marine organic matter to form oil were rimmed with coastal lowlands where land plants thrived and supplied their fibrous remains to form coal. About 98 percent of Canada's coal is produced in British Columbia, Alberta, and Saskatchewan and is of Mesozoic age (Figure 21.28). The famous coal of Nova Scotia is somewhat older, dating to the Late Paleozoic, and contributed greatly to the Canadian coal output for over 100 years. In 2001, Canada's coal production is reported to have been worth 1.5 billion dollars. Canada supplies over 20 countries (but mainly Japan and Korea) with coal and ranks as one of the world's leading coal exporters. A large proportion of coal that remains in Canada supplies energy required for steel production.



◆ **Figure 21.28** Distribution of coal deposits in North America

BOX 21.3

Canadian Profile

The Hard Oilers of Enniskillen Township and Canada's Petroleum Industry

In the early 1850s, the industrial revolution was well underway in both Europe and the New World. As in ancient times, asphalt was needed for ship construction and for paving streets and sidewalks, and fuel was required for illumination. Although the Victorians had been using whale oil for their lamps, the great whales had been hunted almost to extinction. The world was desperate for a cheap source of petroleum. It was in the swampy hinterland of Lambton County's Enniskillen Township, that the North American oil industry was born.

In response, the enterprising Tripp Brothers, Henry and Charles, following their noses as well as reports from the Geological Survey of Canada, found their way to the site of the Lambton County oil seeps. In 1852 they started digging and manufacturing asphalt, which they sold for ships and roads. "The International Mining & Manufacturing Company", chartered in 1854, was the first oil company in North America.

Initially the Tripps were immensely successful. Only a year after incorporation their asphalt was displayed at the Paris Universal Exhibition and received an honourable mention from the Emperor Napoleon III. More importantly, they received an order for asphalt to pave the streets of Paris. That winter the Enniskillen gum was transported overland by sled to Port Sarnia, and then by ship across the Atlantic Ocean to France. In 1854, another enterprising Canadian and government geologist, Abraham Gesner, was experimenting with oil seeps in the colony of Nova Scotia. He had just invented and patented a method of extracting kerosene lamp fuel from the liquid oil component of natural seeps. When he set up a factory in New York the world suddenly lit up, and the search for crude oil was on.

Others, driven by dreams of profitable lighting, quickly followed the Tripps to Enniskillen Township and in 1858 James Miller Williams produced oil from sandy lenses at the base of the Tripp's gum bed. Initially pumped by hand and later by steam, his well yielded about 50 whiskey barrels a day. It was the first producing oil well in North America. By early winter, using a simple iron kettle distiller, he was refining kerosene. Although the resulting product was not very clean (it was called "skunk juice"), his was also the first oil refinery in North America. On the other side of Lake Erie near Titusville in Pennsylvania, the Americans were exploiting gum beds as well, and a year later "Colonel" Edwin Drake, drilling all the way through into bedrock, encountered oil.

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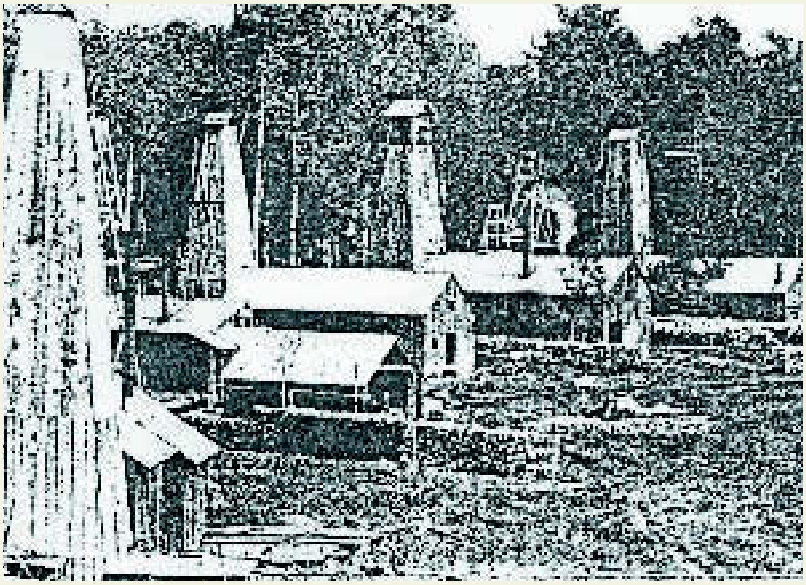
BOX 21.3

Canadian Profile (continued)

The Hard Oilers of Enniskillen Township and Canada's Petroleum Industry



◆ **Figure 21.C** A photo taken in the late 1800s of drilling rigs in the Petrolia oilfield of southern Ontario, the birthplace of the Canadian oil industry. (Photo courtesy of Charles Fairbank)

By 1860 word got out in both countries and the twin oil rush was on. In Enniskillen Township workers flocked to the new village of Oil Springs, and within a year there were 400 wells in the field; some of them also drilled into bedrock, each producing 50–500 barrels a day. In 1862 one of these wells brought in a gusher, reputed to produce 2000 barrels a day, and the rush compounded. Oil Springs boomed and soon 1000 wells covered a square mile around Black Creek (Figure 21.C). A forest of shifting ash-pole service-derricks replaced the native woodland. The oil flowed freely and there was often no need to pump. Indeed sometimes it flowed too freely, running into Black Creek and into Lake St. Clair where it produced an oil slick several centimetres thick. Oil Springs and Titusville have often produced conflicting claims for the position of "first in North America"; but neither has cared to take credit for the continent's first petroleum-related environmental debacle!

One of the more successful drillers, John Henry Fairbank, devised an ingenious method of pumping numerous wells efficiently and economically. The well pumps were linked each to another, and thereby all were connected up to a central power source by a series of parallel wooden rods. Known as the "jerker rod system", it could pump more than two hundred wells from one large central steam engine. Fairbank eventually expanded his operation over a large part of the Oil Springs field that is still operated by his descendants today. The Oil Springs boom was short-lived—less than eight years. The gushers "watered-out" and oil was discovered in Petrolia and further afield in Texas. Production went up, the oil prices went down as the market became saturated, and Oil Springs became a ghost town.

But for Enniskillen Township, the story was not finished. The producers and the party simply moved a few miles north to Petrolia, which produced its first gusher in 1866. This time, with a better infrastructure already in place, the boom was sustained for four glorious decades and Petrolia thrived as the oil capital of Canada. The only intrusion on this refined lifestyle was the indelicate smell of sour crude that wafted over the town when the wind was blowing in the wrong direction—the townspeople referred to it as "the smell of money".

It was in Petrolia that the energetic drillers came to call themselves "hard oilers". Although the exact origin of the label is obscure, it has been said that a team of resolute Petrolia oil workers were threatened by their opponents at a ball game with a "hard oil finish" and that the term was born upon their victory. Many of the Petrolia Hard Oilers went on to open new oil fields abroad—in North Africa, Asia and South America. Dubbed "the foreign drillers" they returned to Petrolia, full of exotic stories and souvenirs from strange lands. In all, they eventually went to 87 countries and were present in the 1920s and 1930s when giant oil fields were found in Iraq and other parts of the Middle East.

Price fluctuations were one of the greatest banes of the oil producers' lives. In an attempt to control supply, Jacob Englehart bought up several refineries in Petrolia and the nearby city of London, where he and several other Ontarian financiers established the Imperial Oil Company in 1880. Three years later, after a major fire in London, all of the operations were moved to Petrolia.

By 1893 Imperial Oil, still operating out of Petrolia, was a great refining success with twenty-three branches all over Canada. But as demand outstripped supply, Imperial needed capital for expansion. As Canada was in a recession, the Directors initially approached British investors, but were unsuccessful in securing funds. The only option left was to sell to the Americans. Standard Oil had already bought many small refineries in the United States, including Abraham Gesner's New York kerosene factory, and had been casting a covetous eye on the Canada's flagship firm for several years. The conditions of the takeover, effected in 1898, were unequivocal:

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BOX 21.3

Canadian Profile (continued)

The Hard Oilers of Enniskillen Township and Canada's Petroleum Industry

the Imperial name was kept; Canadian headquarters and refineries were moved from Petrolia to Sarnia; and Imperial Oil went on to participate in developing the industry in other parts of Canada over the next century.

One of the new frontiers of petroleum exploration was western Canada. The first exploration well in Alberta was drilled in 1902 at the site of an oil seep near Cameron Brook, which is now part of the Waterton Lakes National Park. It produced a brief boomtown of Oil Springs that suffered the same fate as its namesake in Ontario. But the nearby Turner Valley field, discovered in 1914 and drilled with the assistance of Petrolia Hard Oilers, established that Alberta was indeed a fertile ground for petroleum production.

After 20 years and 133 dry holes, Imperial Oil more than encountered Canada's first giant oil field at Leduc, Alberta in 1947. Pipelines to Sarnia, Vancouver, and the U.S. were quickly built and Canada became a world-class oil-producing nation. But oil is not the only economically important hydrocarbon. In fact, natural gas is cleaner and requires no refining. Commercial natural gas production was pioneered in Alberta, and Ontario. In 1883 CPR workers, drilling for water for their steam engines at Langevin in Southern Alberta, hit an unexpected flow of natural gas that ignited and destroyed their derrick. George Dawson of the Geological Survey of Canada, observing that the strata that contained the gas were continuous over much of Western Canada, predicted large volumes of gas from the Territory. Indeed, George Dawson's prediction was well-fulfilled in that the reserves of the Western Interior Basin are 80 percent gas prone.

Looking further afield for oil, Imperial pioneered exploration in the north with Canada's first Arctic discovery at Norman Wells in the Northwest Territories in 1920. The first well was drilled in the vicinity of yet another oil seep that had been originally noted by the intrepid explorer, Alexander Mackenzie. The field was produced only intermittently over the years until it was connected to the Canadian pipeline system in 1985.

The East Coast of Canada was also considered to be prime exploration territory and, at about the same time as the Leduc discovery, drillers were exploring underwater in the Atlantic Ocean near Prince Edward Island. This first effort at offshore drilling in Canada was not economically encouraging, but the technology was off to a good start. Half a century later, in 1997, the Hibernia Field was discovered 315 kilometres off the coast of Newfoundland.

With the dawn of the 21st century, Canada and its neighbours are encountering new petroleum challenges. Conventional sources of crude oil and natural gas are being depleted, and other more technologically sophisticated methods of extraction will be required for the future. The Canadian oil sands, North Atlantic offshore drilling, and Arctic reserves are all potential sources of hydrocarbon energy. However, their exploitation will require not only more advanced and expensive technology, but also recognition of environmental hazards and social concerns. In the Kyoto Accord, which was ratified by Ottawa in 2002, Canada pledged to reduce the emissions of greenhouse gases over the next 10 years. As well, Canada's First Nations are asserting their right to a share of the wealth, and long-ignored land claims must ultimately be negotiated. Therefore the future of the petroleum industry in Canada and elsewhere will depend not only upon rampant technological growth, as in the past, but upon the development of sober and responsible social and ecological policies as well.

At the start of the 21st century, the fourth generation of Fairbank Oil celebrated its 140th anniversary in tiny Oil Springs, Ontario (population 800). North America's first oil discovery field remains a commercially viable operation as the fourteenth largest oil producer in Ontario. Victorian technology is still largely utilized, and remarkably, the original jerker rod system, designed by J.H. Fairbank early in the 1860s, remains in place. This is the oldest continuously operated oil company in the world.

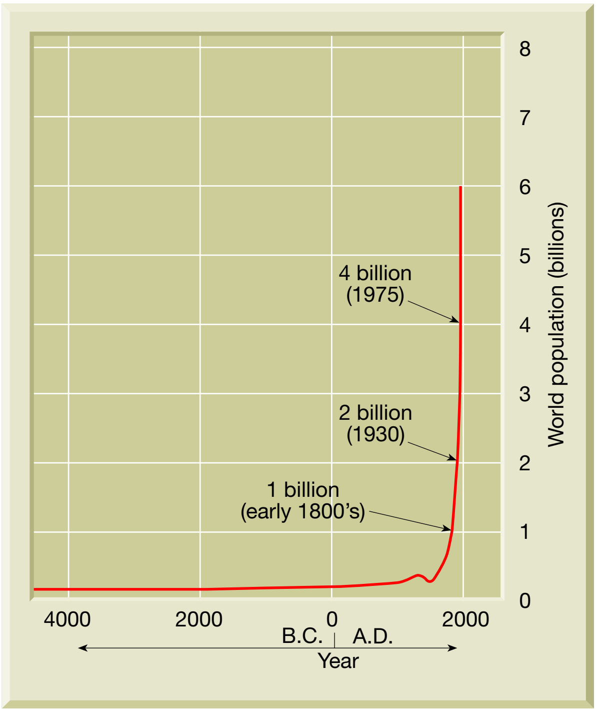
Contributing writer: Claudia Cochrane, Cairnlins Resources

Environmental Effects of Fossil Fuel Use

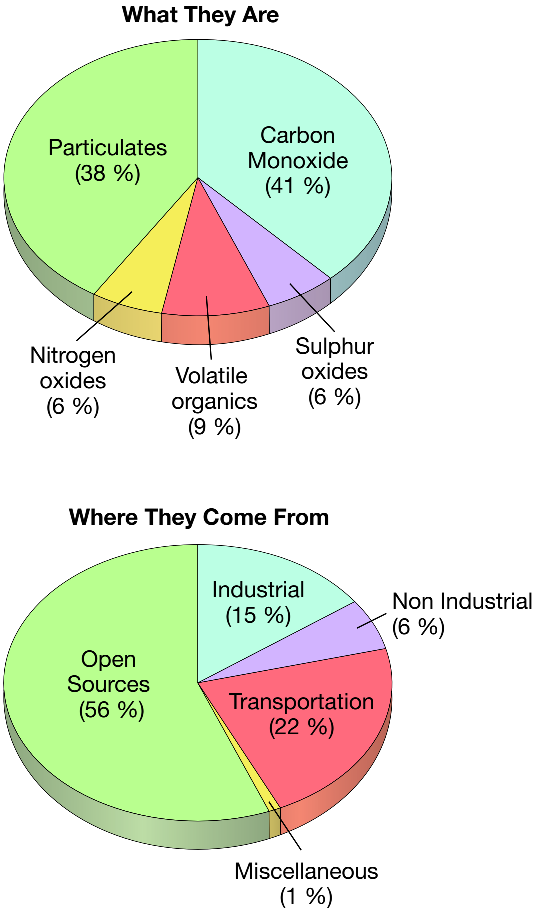
Humanity faces a broad array of human-caused environmental problems. Among the most serious are the impacts on the atmosphere that occur because of **fossil fuel** combustion. As human population continues its explosive growth (Figure 21.29), environmental problems associated with fossil fuel emissions will continue to grow unless drastic measures are taken to decrease them. Rural and urban air pollution, acid rain, and global greenhouse warming are all closely linked to the use of these basic energy resources.

Air pollution *Air pollutants* are airborne particles and gases that occur in concentrations that endanger the health of organisms or disrupt the orderly function of the environment.

The human population constitutes a giant chemical factory producing a remarkable variety of undesirable products. Figure 21.30 shows the major primary pollutants and their sources. *Primary pollutants* are emitted directly from identifiable sources. They pollute the air immediately upon their emission. Much of the air pollution in Canada is particulate matter,



◆ **Figure 21.29** Growth of world population. It took until 1800 for the number to reach 1 billion. By the year 2010, nearly 7 billion people may inhabit the planet. The demand for basic resources is growing faster than the rate of population increase. (Data from the Population Reference Bureau)



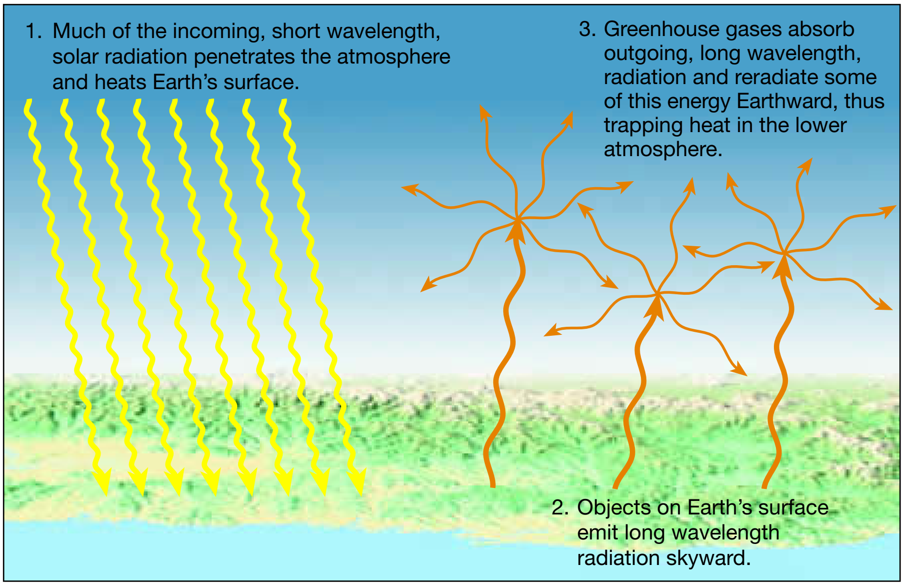
◆ **Figure 21.30** Principal types and sources of air pollution in Canada per unit mass. While particulates from nonindustrial sources such as fields and roads comprise a large proportion of pollutants, the remaining pollutants can be linked largely to industrial and transportation-related emissions. (Data courtesy of Statistics Canada)

most of which comes simply from dust blown from open sources such as roads and fields. For the remainder of pollution sources, the significance of the industrial and transportation categories are obvious. Industry (including fuel generating plants) and the hundreds of millions of vehicles on the roads are the greatest contributors in this category.

When chemical reactions take place among primary pollutants, *secondary pollutants* are formed. The noxious mixture of gases and particles that make up urban smog is an important example that is created when volatile organic compounds and sulphur and nitrogen oxides react in the presence of sunlight. The burning of fossil fuels by industry and various modes of transportation are the greatest contributors of these compounds.

Carbon Dioxide and Global Warming Warming of the lower atmosphere is global in scale. Unlike acid rain and urban air pollution, this issue is not associated with any of the primary pollutants in Figure 21.30. Rather, the connection between global warming and burning of fossil fuels relates to a basic product of combustion: carbon dioxide.

Carbon dioxide (CO_2) is a gas that occurs naturally in the atmosphere and is augmented by fuel combustion. Although CO_2 represents only about 0.036 percent of clean, dry air, it is nevertheless meteorologically significant. The importance of carbon dioxide lies in the fact that it is transparent to incoming, short-wave solar radiation, but is not transparent to some of the longer wavelength, outgoing radiation emitted by Earth. A portion of the energy leaving the ground is absorbed by carbon dioxide and subsequently re-emitted, part of it toward the surface, thereby keeping the air near the ground warmer than it would be without carbon dioxide. Thus, carbon dioxide is one of the gases responsible for warming the atmosphere. This process is called the greenhouse effect (Figure 21.31). Because carbon dioxide is an important heat absorber, any change in the air's carbon dioxide content could alter temperatures in the lower atmosphere.



◆ **Figure 21.31** The heating of the atmosphere. Most of the short-wavelength radiation from the Sun that is not reflected back to space passes through the atmosphere and is absorbed by Earth's land-sea surface. This energy is then emitted from the surface as longer-wavelength radiation, much of which is absorbed by certain gases in the atmosphere. Some of the energy absorbed by the atmosphere will be radiated Earthward. This so-called greenhouse effect is responsible for keeping Earth's surface much warmer than it would be otherwise.

Students Sometimes Ask …

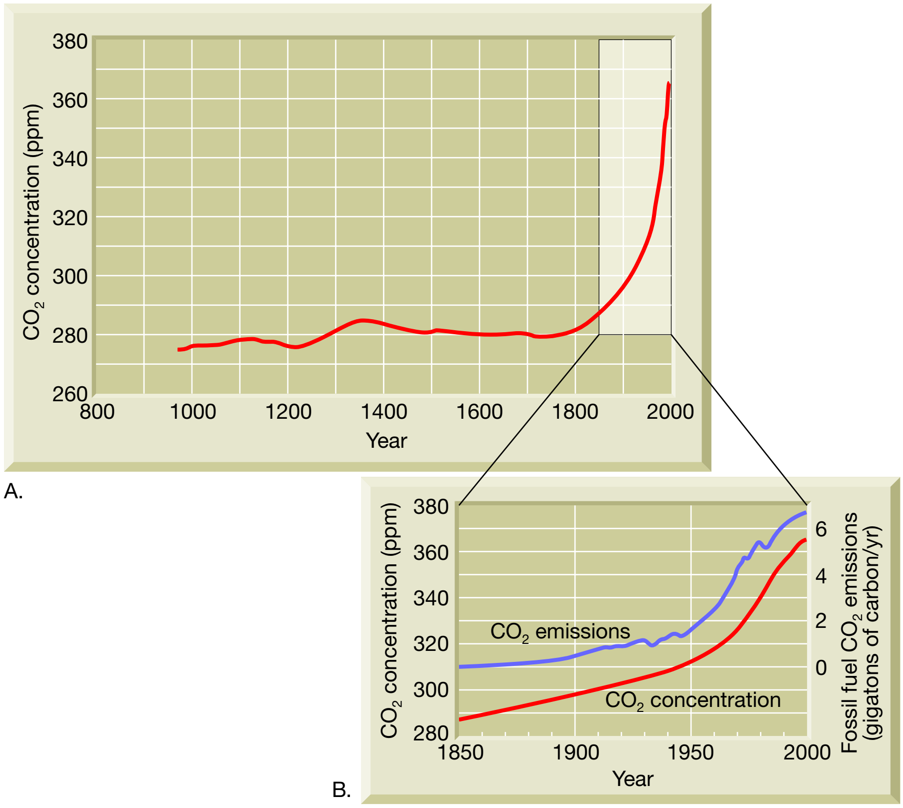
Is carbon dioxide the only gas that's responsible for global warming?

No. Although carbon dioxide is the most important, other gases also play a role. In recent years scientists have come to realize that the industrial and agricultural activities of people are causing a buildup of several trace gases that may also play a significant role. The substances are called *trace gases* because their concentrations are so much smaller than that of carbon dioxide. The trace gases that appear to be most important are methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs). These gases absorb wavelengths of outgoing radiation from Earth that would otherwise escape into space. Although individually their impact is modest, taken together the effects of these trace gases may be nearly as great as (CO_2) in warming the lower atmosphere.

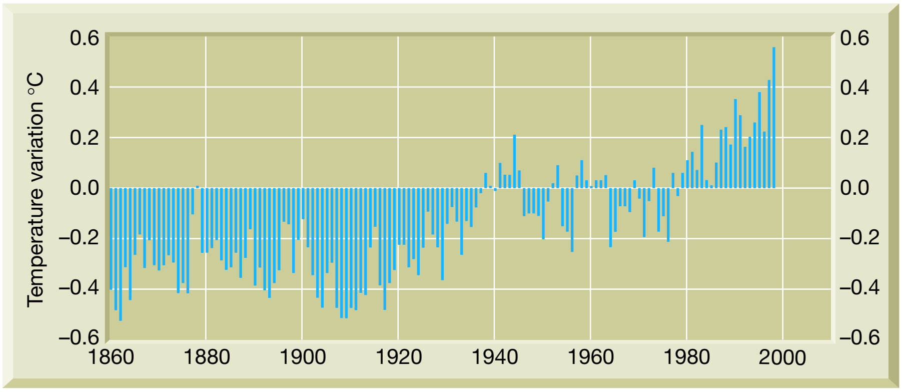
Although the proportion of carbon dioxide in the air is relatively uniform at any given time, its percentage has been rising steadily for more than a century (Figure 21.32). Much of this rise is the result of burning ever-increasing quantities of fossil fuels. From the mid-19th century until 2000, there was an increase of more than 25 percent in the carbon dioxide content of the air.

Have global temperatures already increased as a result of the atmosphere's growing carbon dioxide level? This appears to be the case, according to the Intergovernmental Panel on Climate Change (IPCC). During the 20th century the increase was about 0.6°C. Moreover, recent years have been among the warmest on record. Globally, the 1990s was the warmest decade and 1998 the warmest year since 1861, when reliable instrument records began (Figure 21.33). Other studies indicate that the increase in temperature in the 20th century is likely to have been the largest of any century during the past millennium. Are these temperatures caused by human activities or would they have occurred anyway? In January the IPCC declared that most of the observed warming over the last 50 years is likely to have been due to the increase in carbon dioxide and other greenhouse gases that humans contribute to the atmosphere.

If fossil fuel use continues to increase at projected rates, the present carbon dioxide content of 260 parts per million (ppm) will climb to between 540 and 970 ppm by 2100. With such an increase, the greenhouse effect would be much more dramatic and measurable than in the past. The predicted result would be an average global surface temperature increase of 1.4 to 5.8°C. The warming of the lower atmosphere will not be the same everywhere. Rather, the temperature response in the polar regions could be much greater than the global average while some low-latitude regions would experience much smaller fluctuations. According to the IPCC, the projected rate of warming during the 21st century will be much larger than the observed changes in the 20th century and is very likely without precedent during the last 10,000 years. However, the possible effects of aerosol emissions from fossil fuel combustion complicate this outlook considerably.



◆ **Figure 21.32** **A.** Carbon dioxide (CO_2) concentrations over the past 1000 years. Most of the record is based on data obtained from Antarctic ice cores. Bubbles of air trapped in the glacial ice provide samples of past atmospheres. The record since 1958 comes from direct measurements of atmospheric CO_2 taken at Mauna Loa Observatory, Hawaii. **B.** The rapid increase in CO_2 concentration since the onset of industrialization in the late 1700s is clear and has followed closely the rise in CO_2 emissions from fossil fuels.



◆ **Figure 21.33** Annual average global temperature variations for the period 1860–1998. The basis for comparison is the average for the 1961–90 period (the 0.0 line on the graph). Each narrow bar on the graph represents the departure of the global mean temperature from the 1961–1990 average for one year. For example, the global mean temperature for 1862 was more than 0.5°C (1°F) *below* the 1961–90 average, whereas the global mean for 1998 was more than 0.5°C above. (Specifically, 1998 was 0.56°C warmer.) The bar graph clearly indicates that there can be *significant variations from year to year*. But the graph also shows a trend. Estimated global mean temperatures have been above the 1961–90 average every year since 1978. Also, the three warmest years in the 138-year record shown here were 1995, 1997, and 1998. *(After G. Bell, et al. "Climate Assessment for 1998," Bulletin of the American Meteorological Society, Vol. 80, No. 5, May 1999, p. 54.)*

In December 1997, Canada and more than 160 other countries met in Kyoto, Japan, and agreed on targets to reduce greenhouse gas emissions. The Kyoto Protocol includes the ratification of these targets and the proposed methods of achieving them. Canada's target is to reduce its greenhouse gas emissions to 6 percent below 1990 levels by 2012. In December 2002, the federal government of Canada officially ratified Canada's commitment to the Kyoto Protocol.

BOX 21.4

People and the Environment

Aerosols from the "Human Volcano"

◆ **Figure 21.D** One source of human-generated aerosols are power plants. (Photo by Bruce Forster/Tony Stone Images)

Increasing the levels of carbon dioxide and other greenhouse gases in the atmosphere is the most direct human influence on global climate. But it is not the only impact. Global climate is also affected by human activities that contribute to the atmosphere's aerosol content. *Aerosols* are the tiny, often microscopic, liquid and solid particles that are suspended in the air. Atmospheric aerosols are composed of many different materials, including soil, smoke, sea salt, and sulphuric acid. Natural sources are numerous and include such phenomena as dust storms and volcanoes. In Chapter 4 you learned that some explosive volcanoes (such as Mount Pinatubo) emit large quantities of sulphur dioxide gas high into the atmosphere. This gas combines with water vapour to produce clouds of tiny sulphuric acid aerosols that can lower air temperatures near the surface by reflecting solar energy back to space. So it is with sulphuric acid aerosols produced by human activities.

Presently the human contribution of aerosols to the atmosphere *equals* the quantity emitted by natural sources. Most human-generated aerosols come from the sulphur dioxide emitted during the combustion of fossil fuels and as a consequence of burning vegetation to clear agricultural land (Figure 21.A). Chemical reactions in the atmosphere convert the sulphur dioxide into aerosols, the same material that produces acid precipitation (see Box 5.1, p. xxx).

The aerosols produced by human activity act directly by reflecting sunlight back to space and indirectly by making clouds "brighter" reflectors. The second effect relates to the fact that sulphuric acid aerosols attract water and thus are especially effective as cloud condensation nuclei (tiny particles upon which water vapour condenses). The large quantity of aerosols produced by human activities (especially industrial emissions) trigger an increase in the number of cloud droplets that form within a cloud. A greater number of small droplets increases the cloud's brightness—that is, more sunlight is reflected back to space.

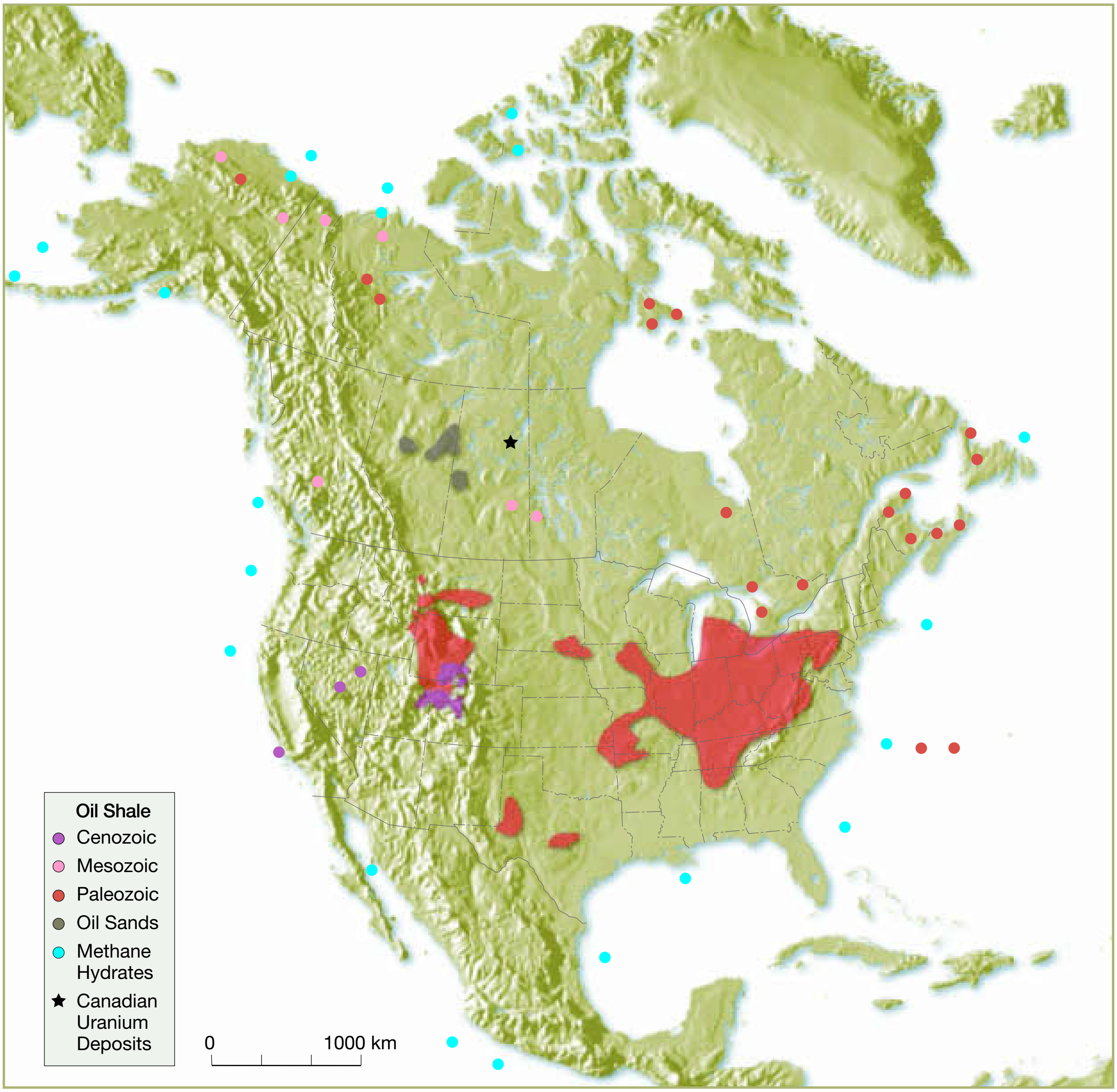
By reducing the amount of solar energy available to the climate system, aerosols have a net cooling effect. Studies indicate that the cooling effect of human-generated aerosols could offset a portion of the global warming caused by the growing quantities of greenhouse gases in the atmosphere. Unfortunately, the magnitude and extent of the cooling effect of aerosols is highly uncertain. This uncertainty is a significant hurdle in advancing our understanding of how humans alter Earth's climate.

It is important to point out some significant differences between global warming by greenhouse gases and aerosol cooling. After being emitted, greenhouse gases such as carbon dioxide remain in the atmosphere for many decades. By contrast, aerosols released into the lower atmosphere remain there for only a few days or, at most, a few weeks before they are "washed out" by precipitation. Because of their short lifetime in the atmosphere, human-generated aerosols are distributed unevenly over the globe. As expected, they are concentrated near the areas that produce them, namely industrialized regions that burn fossil fuels and land areas where vegetation is burned.

Because the lifetime of human-generated aerosols in the atmosphere is short, the effect of the "human volcano" on today's climate is determined by the quantity of material emitted during the preceding couple of weeks. By contrast, the carbon dioxide released into the atmosphere remains for much longer spans and thus influences climate for many decades.

Unconventional Fossil Fuel Deposits

As supplies of petroleum and coal that can be extracted by conventional methods dwindle, we can expect that an increasing volume of fossil fuel will be produced from lower-grade deposits that require innovative, unconventional methods (Figure 21.34). Two main types of deposits that are being seriously considered as candidates for future hydrocarbon extraction are oil shales and heavy oil sands.



◆ **Figure 21.34** Unconventional fossil fuel resources (oil sands, oil shales and methane hydrates) in North America and uranium deposits of northern Saskatchewan (compiled from various sources).

Heavy Oil Sands *Heavy oil sands*, also commonly called tar sands, are mixtures of sediment, water, and abundant, black, tar-like bitumen. It is thought that such deposits result from a very high level of interaction between regular crude oil and groundwater linked to long-distance and near-surface oil migration. A popular explanation for the origin of the tarry oil is that cool, oxygen-rich, groundwater provided optimal conditions for certain bacteria to preferentially consume light components of the oil, thus leaving behind a heavy residue. Exposure of petroleum to air at the surface of the Earth also allows its light components to evaporate and could also contribute to enrichment of the heavier components of the petroleum. In any case, the hydrocarbons of the tar sands appear to represent degraded oil. Heavy oil sands occur in abundance in Alberta (Figure 21.34), the most famous of which are the Athabasca Tar Sands located northeast of Edmonton.

Due to their high viscosity, hydrocarbons that occur in heavy oil sands cannot be pumped from a well like conventional oil. The tar sand is effectively mined at the surface, heated to mobilize the hydrocarbons, and upgraded to a synthetic crude with the

◆ **Figure 21.35** Outcrop of thinly bedded, kerogen-rich, Ordovician limestones ("oil shales") of the Collingwood Formation on the southern shore of Georgian Bay, Ontario. (Photo by C. Tsujita)

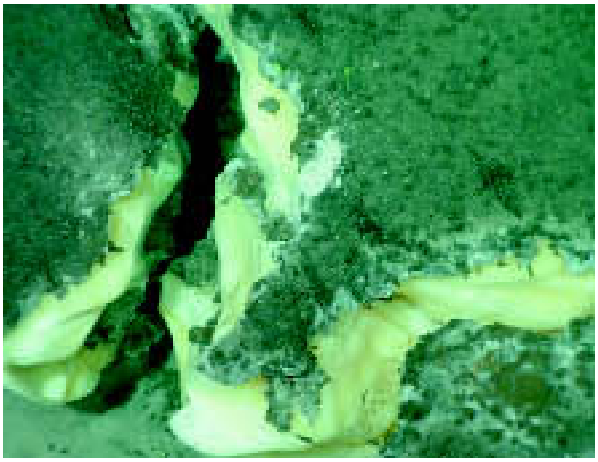
addition of hydrogen and removal of impurities. Projects have also been designed to bypass the mining process, whereby stream is injected directly into the tar sand deposit to mobilize the hydrocarbons, which are then recovered from pipes much like conventional crude oil. Much energy must be expended in the recovery process—about half as much as the end product yields. Relative to conventional petroleum resources, therefore, tar sands presently have a rather low profit margin per unit of liquid petroleum produced. Nonetheless, tar sands will undoubtedly play a major role in fossil fuel production as global supplies inevitably decrease.

Oil Shale In some cases, fine-grained, organic-rich sedimentary rocks are not subjected to sufficiently high temperatures and pressures to liberate liquid and gas hydrocarbons, and they instead retain organic matter in the form of kerogen. A fine-grained sedimentary rock containing an abundance of kerogen is called an *oil shale*. Although widely used, this term is somewhat misleading since most oil shales are not shales at all, but fine-grained limestones (Figure 21.35). In any case, oil shales contain enormous amounts of hydrocarbons and can be artificially heated to crack their kerogen into liquid petroleum. Huge deposits of Cenozoic-age oil shale comprising the Green River Formation occur in Colorado, Utah, and Wyoming, and represent fine-grained, lake sediments deposited during the Eocene Epoch. Paleozoic oil shales occur in a number of places in Canada, including New Brunswick, Nova Scotia and southern Ontario and a few Mesozoic deposits have also been identified (Figure 21.34). Oil extraction from Canadian oil shales has been attempted, but is not yet profitable. Similar to the case of heavy oil sands, the extraction of a liquid product from oil shale involves a high input of energy, both because it must be mined, and also because it must be heated to liberate oil. Accordingly, a considerable increase in the price of oil will be necessary for a profitable industry to be built around this resource.

Methane Hydrate *Methane hydrate* is a solid substance formed when water molecules form cages that surround single molecules of methane. Methane hydrates, once thought to be oddities in the natural world, are now known to be common in permafrost areas associated with methane seeps. Even more significant are vast methane hydrate deposits found in deep areas of continental shelves of nearly every continent on Earth, including North America (Figure 21.36). In those places, the methane-ice complexes are kept stable due to high pressures and cold temperatures at the seafloor. At least some of these deposits are associated with communities of microbes that produce methane as part of their normal metabolic activities. Methane hydrates are sufficiently high in methane content to produce a flame when ignited with a match.

While the thought of exploiting this large reservoir of methane is appealing, many concerns surround the use of this potential energy source. As with all unconventional hydrocarbon resources, the feasibility and cost of extraction is questionable at the present time. More serious, however, are the environmental impacts of extraction, both in terms of disturbing the seafloor, and the potential leakage of methane into the atmosphere during extraction. The warming effect of methane in the atmosphere is at least 20 times higher than carbon dioxide, and thus methane leakage from seafloor hydrates is a legitimate concern.

Coal Bed Methane The slow heating of fibrous organic matter derived from land plants not only produces solid coal, but also liberates methane. This *coal bed methane* is trapped in the pore spaces of coal seams and associated detrital sediments. Because it is confined in the pores of sedimentary rocks, it is difficult to extract by conventional means and is therefore not currently exploited on a large scale. It has been found that coal bed methane can be released by pumping large quantities of water from a coal seam through several wells. The merits of this practice have, however, been recently questioned due to concerns about surface- and ground-water water contamination, groundwater depletion, and the possible



◆ **Figure 21.36** A body of methane hydrate (yellowish-white) photographed on the seafloor some 850 metres below sea level, off the western coast of Vancouver Island, British Columbia. (Photo courtesy of Ross Chapman)

escape of the methane into the atmosphere. Still, coal bed methane is attractive as a clean-burning alternative to conventional fossil fuels such as oil and coal. As more efficient extraction technologies are developed, coal bed methane is likely to become more important as a fuel source in the future.

Nuclear Energy

Nuclear power plants generate roughly 14 percent of Canada's electricity supply. The fuel for these facilities comes from radioactive materials that release energy by the process of **nuclear fission**. Fission is accomplished by bombarding the nuclei of heavy atoms, commonly uranium-235, with neutrons. This causes the uranium nuclei to split into smaller nuclei and to emit neutrons and heat energy. The ejected neutrons, in turn, bombard the nuclei of adjacent uranium atoms, producing a chain reaction. If the supply of fissionable material is sufficient and if the reaction is allowed to proceed in an uncontrolled manner, an enormous amount of energy is released in the form of an atomic explosion. In most nuclear reactors, the chain reaction is regulated through the use of materials called *moderators*, which slow neutrons down to allow them to react with the uranium atoms in a controlled manner. Most reactors also use neutron-absorbing materials in control rods to prevent the participation of too many neutrons in the reaction at any one time.

◆ **Figure 21.37** A significant amount of electricity in Canada is produced by nuclear fission. Canadian nuclear reactors, such as those at the Pickering Nuclear Power Plant are of CANDU (Canadian Deuterium) design. (Photo courtesy of Robert J. Graniere)

CANDU Reactors The production of nuclear power in Canada is centred on the CANDU (Canadian Deuterium-Uranium) design, which uses natural uranium-235 as fuel and deuterium oxide as a moderator and heat transport medium (Figure 21.37). Deuterium is a stable isotope of hydrogen containing a proton and a neutron. Due to the higher mass of deuterium, relative to the more common "light" hydrogen that contains a single proton and no neutrons, deuterium oxide is heavier than regular hydrogen oxide (water). Deuterium oxide is therefore commonly called *heavy water*. The CANDU design allows on-power refuelling, does not require fuel reprocessing, and can potentially use spent fuel from other reactors. The versatility of CANDU reactors is a major factor that has contributed to their use in a number of countries outside North America, including Argentina, India, Korea, Pakistan, and Romania.

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

In addition to being scarce, the size of the uranium atom generally prevents it from being incorporated into the crystal lattice of most rock-forming minerals. In addition, uranium is highly soluble in oxidizing environments and therefore requires unusual conditions to be precipitated in minerals at the Earth's surface. Uranium ores are extremely diverse in their geological settings, but it appears that a critical factor controlling the precipitation of uranium-bearing minerals is the absence of oxygen.

Uranium can be enriched in residual fluids of felsic magmas, reaching concentrations over a hundred parts per million and incorporated as a trace element in minerals such as zircon and apatite. In sufficient concentrations, however, uranium forms an oxide mineral (UO_2) called uraninite (pitchblende if very fine-grained), which can occur in veins associated with felsic igneous intrusions. Ores of uranium-bearing minerals also occur as placers in Precambrian rocks, reflecting the oxygen-free atmosphere of those times. The Uranium ores of Elliot Lake, Ontario that formerly supplied a significant proportion of Canada's uranium represent such uranium placers.

The fact that uranium is soluble in oxidizing environments and insoluble in reducing environments can also contribute to the formation of uranium ores. For example, the rich uranium deposits of northern Saskatchewan's Athabasca Basin (Figure 21.34), which currently account for Canada's entire uranium production, appear to have been formed by the interaction of deep-sourced, oxygen-free fluid with shallow-sourced oxygenated fluid that carried dissolved uranium. In this case, this fluid interaction was focused in small areas where fault breccias intersect a nonconformity separating highly deformed metamorphic rocks from overlying sedimentary rocks. Lastly, uranium can be dissolved near the Earth's surface by oxygenated groundwater and carried through permeable, coarse-grained sedimentary rocks (e.g., sandstone). The uranium-charged fluid precipitates uranium in the mineral carnotite when it mixes with oxygen-poor water. Most of the uranium mined in Arizona, New Mexico, and Utah are contained in this type of ore. The close association of uranium and organic matter is also apparent in the slightly elevated concentration of uranium in organic-rich shales and phosphate deposits, relative to other sedimentary rock types.

Obstacles to Development At one time, nuclear power was heralded as the clean, cheap source of energy to replace fossil fuels. However, several obstacles have emerged to hinder the development of nuclear power as a major energy source, not the least of which is the enormous cost of building the facilities that contain numerous safety features. More important, perhaps, is the concern over the possibility of a serious accident at one of the nearly 200 nuclear plants that exist worldwide. The Three Mile Island (Harrisburg, Pennsylvania) accident in 1979 brought this point home. Here, a malfunction led the plant operators to believe there was too much water in the primary system rather than too little and allowed the reactor core to lie uncovered for several hours. Although the reactor sustained considerable damage, the public was fortunately spared great harm.

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

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

Renewable Fuel Sources

Organic-Based Sources

Landfill Methane Methane produced by the microbial decomposition of organic matter in landfills is a significant contributor of greenhouse gases to the atmosphere although it usually escapes attention from the media. Thus, with the continued rise in global population, methane production from landfills can only increase in total volume and production rate. One way to deal with both the volume of methane released to the atmosphere and the demand for energy is to use this methane as fuel. About one quarter of all landfill methane is presently being collected in Canada, about 70 percent of which is used for energy production. While the use of landfill methane does significantly decrease total greenhouse emissions, it does not eliminate them since carbon dioxide, although less potent than methane as a greenhouse gas, is produced from its combustion.

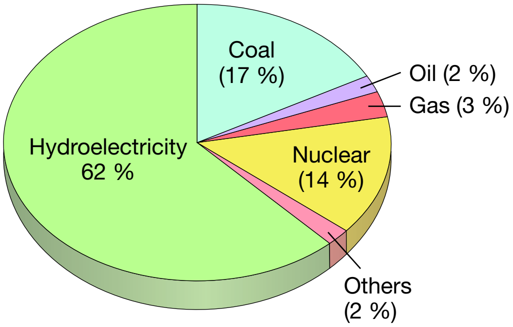
Biomass Energy Biomass energy is derived from the tissues of organisms, specifically plants, and provided the first organic fuel used by humans. Plants, through photosynthesis, produce their structural tissues and sugars using solar energy, and this stored energy can later be released through combustion. You release this kind of biomass energy every time you burn wood in a campfire.

Biomass fuel is a primary source of energy in Third World countries in the form of wood and dung, but has been largely replaced in developed countries by fossil fuels. Recently, however, the use of biomass fuel has been seriously considered as a clean, renewable energy source.

One very important biomass fuel is ethanol, which is a product of anaerobic (oxygen-free) fermentation. In Canada, industries such as forestry generate lots of waste material that could support large ethanol-producing operations. Although not used as fuel in its pure form, ethanol can be used as an additive to gasoline and has been found to reduce carbon monoxide and carbon dioxide emissions. A form of biodiesel has been developed from vegetable oils and could also be used as an additive to conventional fuel. Although biomass fuels are far from replacing conventional fossil fuels, they are, at the very least, renewable and can reduce the total volume of greenhouse gas emissions.

Hydroelectric Power

Falling water has been an energy source for centuries. Through most of history, the mechanical energy produced by waterwheels was used to power mills and other machinery. Today, the power generated by falling water drives turbines that produce electricity, hence the term **hydroelectric power**. Canada is a world leader in the production of hydroelectricity, as it contributes to the production of over 60 percent of Canada's total electricity generation (Figure 21.38). Most of this energy is produced at large dams, which allow for controlled flow of water (Figure 21.39). The water impounded in a reservoir is a form of stored (potential) energy that can be released at any time to produce electricity.



◆ **Figure 21.38** Electricity generation sources in Canada, 1997. Note the extremely high contribution of electricity from hydroelectric sources compared to fossil fuels and nuclear power generation.
(Source: Natural Resources Canada)

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

The availability of appropriate sites is an important limiting factor in the development of large hydroelectric power plants. A good site provides a significant height for the water to fall and a high rate of flow. Most of the best U.S. sites have already been developed, limiting the future expansion of hydroelectric power. Canada still has many rivers that have not been dammed for hydroelectric power, but many of these are in remote areas that are particularly sensitive to environmental disturbance.

Solar Energy

The direct use of *solar energy* has gained much appeal as an alternative resource on a small scale. Many people use south-facing windows in their homes as *passive solar collectors* that allow objects in a room to absorb energy of the Sun's rays and to re-emit the energy as heat. Together with more efficient insulation, south-facing windows are featured in many modern homes as a measure of heat conservation. More elaborate systems used in homes feature an active solar collector that utilizes large, glass-covered boxes to collect energy. This energy heats air or water that is, in turn, circulated through the house in pipes to supply heat where it is needed.

The use of solar energy on a large scale is becoming more practical as technology advances, but is still relatively insignificant compared to the energy used

◆ **Figure 21.39** Daniel Johnson Manic-5 hydroelectric dam in Québec.
(Photo by Walter Muma)

Students Sometimes Ask …

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

from conventional fuel resources. So if solar energy is free, why isn't it used more? The reason lies in economics; while solar energy is free, the equipment required for its exploitation is expensive. As supplies of nonrenewable fuels decrease, and as solar collecting technology becomes more advanced, solar energy will surely increase in popularity and might even become cost effective in the near future. Another major impetus for the conversion to solar energy will be the continued quest for nonpolluting energy sources.

Research is currently underway to improve sunlight-collecting technologies and experimental installations are becoming increasingly common throughout North America. One method currently under investigation in Barstow, California, involves the use of some 2000 sun-tracking mirrors that continually focus reflected light on a central receiving tower. The light energy collected by the receiver heats water in pressurized panels. This water is then transferred to turbines that generate electrical power. Another type of collector uses photovoltaic cells that collect sunlight and convert it directly into electricity. Examples of large experimental photovoltaic installation in Canada are the roof arrays of the Hugh MacMillan Rehabilitation Centre in Toronto, the CANMET Energy Technology Centre in Varennes, Québec, and the EPCOR office building in Edmonton (Figure 21.40).

Small rooftop photovoltaic systems have begun to be used in Third World countries such as the Dominican Republic, Sri Lanka, and Zimbabwe. The units are about as small as an open briefcase and use a battery to store electricity that is generated from sunlight during the day. These small photovoltaic systems can run a television or radio, plus a few lightbulbs for up to four hours. Although much cheaper than the construction of conventional electric generators, the units are still too expensive for poor families. Consequently, an estimated 2 billion people in developing countries still lack electricity.

◆ **Figure 21.40** Solar photovoltaic panel array installed on the EPCOR office building in Edmonton, Alberta.

Wind Energy

Approximately 0.25 percent of the solar energy that reaches the lower atmosphere is transformed into wind. Despite this deceptively miniscule figure, the total amount of energy that can be collected from the wind is enormous.

Wind has, of course, been used for centuries as an almost free and nonpolluting source of energy. Sailboats and windmills are two common forms of wind-powered devices used long ago. In addition, settlers of rural North America relied heavily on wind power for the pumping of water and other applications.

As technology has improved, efficiency has increased and the costs of wind-generated electricity have become more competitive. Between 1983 and 2000 technological advances cut the cost of wind power by about 85 percent. One area for the expansion of wind energy will likely be islands and other regions that are far from electrical grids and that presently must import fuel for power generation.

Wind turbines are becoming commonplace in Canada, with wind farms now well established in Alberta (Figure 21.41), Saskatchewan, Québec, and Prince Edward Island. At the time of writing, the largest

◆ **Figure 21.41** Castle River wind farm near Pincher Creek, Alberta.
(Photo courtesy of Vision Quest Windelectric Inc.)

modern wind turbine in North America is located next to Pickering Nuclear plant in Ontario. Although wind generation is still modest in Canada, the amount of energy produced in 2002 was equivalent to that used by 50,000 Canadian homes in a year.

Although the future for wind power is promising, it is not without difficulties. In addition to technical advances that must continue to be made, noise pollution and costs of large tracts of land in populated areas present significant obstacles to development.

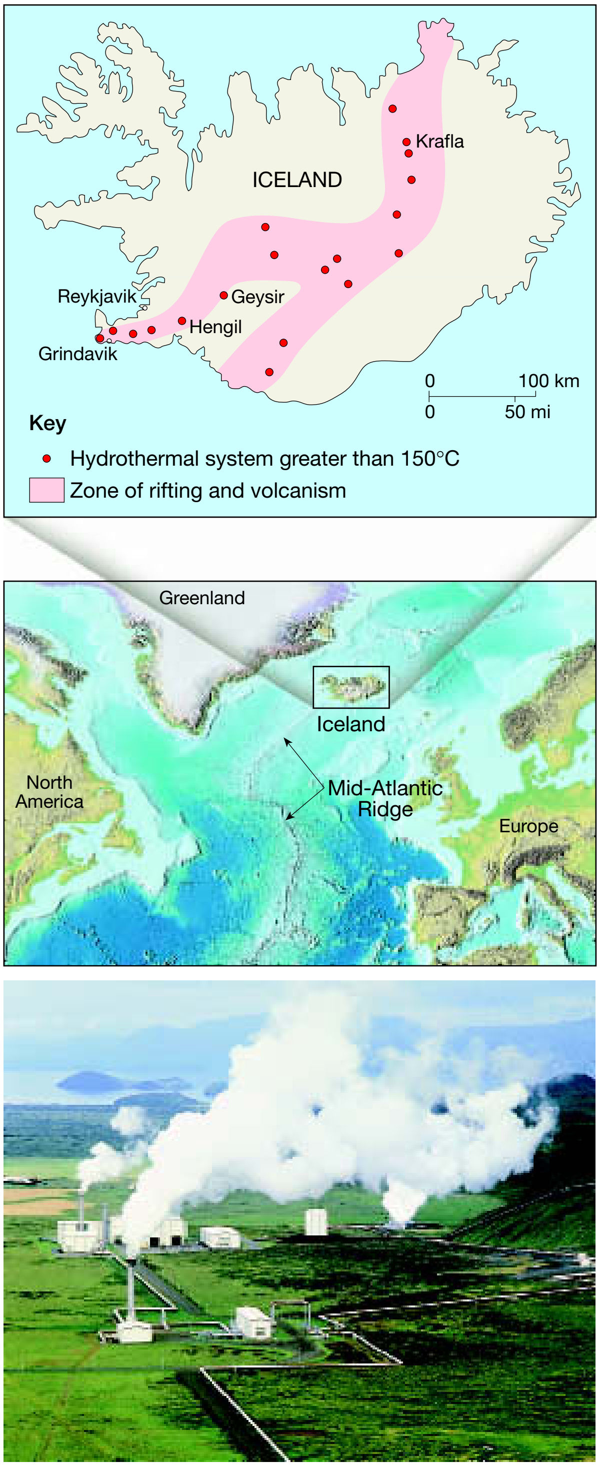
Geothermal Energy

Humans have taken advantage of water that has been heated by the Earth for centuries. In the modern age, such **geothermal energy** is now becoming popular for home and commercial heating, and is also being used in innovative applications such as the heating of greenhouses that can to grow fruit and vegetable crops year-round. Another novel use of geothermal heat can be found in Springhill, Nova Scotia, where water that has been slightly warmed by the natural geothermal gradient in abandoned shafts of coalmines is pumped to provide space heating for an industrial development.

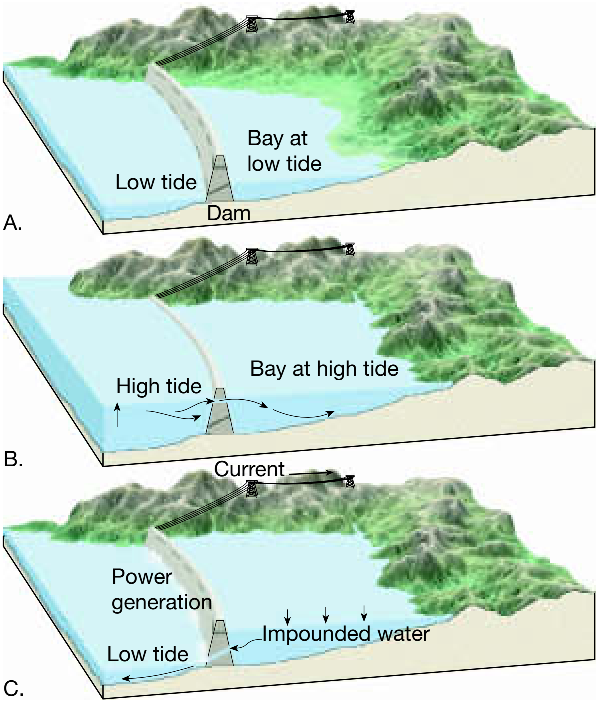
The use of geothermal energy for the generation of electricity is a relatively new development, and is focused areas where groundwater is heated by near-surface volcanic activity. Geothermal power plants are presently well established in Iceland (Figure 21.42), Italy, New Zealand, and the United States. In these facilities, the steam and superheated water generated by hot springs is tapped and piped to turbines that generate electric power.

Tidal Power

The ocean contains a huge amount of physical energy in the form of tides. Although harnessing this energy presently involves sophisticated technology, the principle of electricity generation from tidal energy is fairly simple. The most common method involves trapping ocean water in reservoirs at high tide, and later releasing it through hydroelectric turbines as the tide goes down (Figure 21.43). The largest tidal energy plant is located on the La Rance River in France, which generates 240 megawatts of power. The Annapolis Tidal Power Generation Station in the Bay of Fundy, Nova Scotia, is the only tidal plant in North America and generates about 20 megawatts. While tidal power is a good nonpolluting form of energy, its use is limited to areas where the tidal range is high and water turbidity is low. Thus, the focus of its further development will probably be focused on supplementing other forms of energy rather than replacing them.



◆ **Figure 21.42** Iceland straddles the Mid-Atlantic Ridge. This divergent plate boundary is the site of numerous active volcanoes and geothermal systems. Because the entire country consists of geologically young volcanic rocks, warm water can be encountered in holes drilled almost anywhere. More than 45 percent of Iceland's energy comes from geothermal sources. The photo shows a power station in southwestern Iceland. The steam is used to generate electricity. Hot (83°C) water from the plant is sent via an insulated pipeline to Reykjvik for space heating. (Photo by Simon Fraser/Science Photo Library)



◆ **Figure 21.43** Simplified diagram showing the principle of the tidal dam.

Students Sometimes Ask …

Is power from ocean waves a practical alternative energy source?

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

Chapter Summary

- *Mineral resources* are the endowment of useful minerals ultimately available commercially. Resources include already identified deposits from which minerals can be extracted profitably, called *reserves*, as well as known deposits that are not yet economically or technologically recoverable. Deposits inferred to exist but not yet discovered are also considered mineral resources. The term *ore* is used to denote those useful metallic minerals that can be mined for a profit, as well as some nonmetallic minerals, such as fluorite and sulphur, that contain useful substances.
- Some of the most important accumulations of metals, such as gold, silver, lead, and copper, are associated with igneous processes. The best-known and most important ore deposits are generated from *hydrothermal* (hot-water) *solutions*. Hydrothermal deposits can originate from hot, metal-rich fluids that are remnants of late-stage magmatic processes. These ion-rich solutions move along fractures or bedding planes, cool, and precipitate the metallic ions to produce *vein deposits*. In a *disseminated deposit* (e.g., much of the world's copper deposits) the ores from hydrothermal solutions are distributed as minute masses throughout the entire rock mass. Hydrothermal deposits can also be produced by mineral precipitation from fluids that picked up metals from volcanic or sedimentary rocks.
- Many of the most important metamorphic ore deposits are produced by contact metamorphism. Extensive aureoles of metal-rich deposits commonly surround igneous bodies where ions have invaded limestone strata. The most common metallic minerals associated with contact metamorphism are sphalerite (zinc), galena (lead), chalcopyrite (copper), magnetite (iron), and bornite (copper). Of equal economic importance are the metamorphic rocks themselves. In many regions, slate, marble, and quartzite are quarried for a variety of construction purposes.
- Weathering creates ore deposits by concentrating minor amounts of metals into economically valuable deposits. The process, often called *secondary enrichment*, is accomplished by either (1) removing undesirable materials and leaving the desired elements enriched in the upper zones of the soil, or (2) removing and carrying the desirable elements

to lower zones where they are redeposited and become more concentrated. *Bauxite*, the principal ore of aluminum, is one important ore created as a result of enrichment by weathering processes. In addition, many copper deposits result when weathering processes concentrate metals that were formerly dispersed through low-grade primary ore.

- Earth materials that are not used as fuels or processed for the metals they contain are referred to as *nonmetallic resources*. Many are sediments or sedimentary rocks. The two broad groups of nonmetallic resources are *aggregate and stone* and *industrial minerals*. Limestone, perhaps the most versatile and widely used rock of all, is found in both groups.
- *Renewable resources* can be replenished over relatively short time spans. Examples include natural fibers for clothing, and trees for lumber. *Nonrenewable resources* form so slowly that, from a human standpoint, Earth contains fixed supplies. Examples include fuels such as oil and coal, and metals such as copper and gold. A rapidly growing world population and the desire for an improved living standard cause nonrenewable resources to become depleted at an increasing rate.
- *Coal*, *petroleum*, and *natural gas*, the *fossil fuels* of our modern economy, are all associated with sedimentary rocks. Coal originates from large quantities of plant remains that accumulate in an oxygen-deficient environment, such as a swamp. More than 70 percent of present-day coal usage is for the generation of electricity. Air pollution produced by the sulphur oxide gases that form from burning most types of coal is a significant environmental problem.
- Oil and natural gas, which commonly occur together in the pore spaces of some sedimentary rocks, consist of various *hydrocarbon compounds* (compounds made of hydrogen and carbon) mixed together. Petroleum formation is associated with the accumulation of sediment in ocean areas that are rich in plant and animal remains that become buried and isolated in an oxygen-deficient environment. As the mobile petroleum and natural gas form, they migrate and accumulate in adjacent permeable beds such as sandstone. If the upward migration is halted by an impermeable rock layer, referred to as a *cap rock*, a geologic environment that allows for economically significant amounts of oil and gas to accumulate underground, called an *oil trap*, develops. The two basic conditions common to all oil traps are (1) a porous, permeable *reservoir rock* that will yield petroleum and/or natural gas in sufficient quantities, and (2) a cap rock.
- Environmental problems associated with burning fossil fuels include urban air pollution and global warming. The *primary pollutants* emitted by sources such as motor vehicles can react in the atmosphere to produce the *secondary pollutants* that make up urban smog. Combustion of fossil fuels is one of the ways that humans are increasing the atmosphere's carbon dioxide content. Greater quantities of this heat-absorbing gas contribute to global warming.
- When conventional petroleum resources are no longer adequate, fuels derived from *tar sands* and *oil shale* may become substitutes. Presently, tar sands from the province of Alberta are the source of about 15 percent of Canada's oil production. Oil from oil shale is presently uneconomical to produce. Oil production from both tar sands and oil shale has significant environmental drawbacks.
- Much of our energy is derived from fossil fuels. *Hydroelectric power* provides over 60 percent of Canada's electricity. Another important alternative energy source is *nuclear energy*. Other alternative energy sources are locally important but collectively provide little of the demand. These include *solar power*, *geothermal energy*, *wind energy*, and *tidal power*.

Review Questions

1. Contrast renewable and nonrenewable resources. Give one or more examples of each.
2. What is the estimated world population for the year 2010? How does this compare to the figures for 1930 and 1975? Is demand for resources growing as rapidly as world population?
3. Most coal in Canada is used for what purpose?
4. Describe two impacts on the atmospheric environment of burning fossil fuels.
5. What is an oil trap? List two conditions common to all oil traps.
6. List two drawbacks associated with the processing of tar sands recovered by surface mining.
7. North America has huge oil shale deposits but does not produce oil shale commercially. Explain.
8. What is the main fuel for nuclear fission reactors?
9. List two obstacles that have hindered the development of nuclear power as a major energy source.

10. Briefly describe two methods by which solar energy might be used to produce electricity.

11. Explain why dams built to provide hydroelectricity do not last indefinitely.

12. Is geothermal power considered an inexhaustible energy source? Explain.

13. What advantages does tidal power production offer? Is it likely that tides will ever provide a significant proportion of the world's electrical energy requirements?

14. Contrast *resource* and *reserve*.

15. What might cause a mineral deposit that had not been considered an ore to be reclassified as an ore?

16. List two general types of hydrothermal deposits.

17. Metamorphic ore deposits are often related to igneous processes. Provide an example.

18. Name the primary ore of aluminum and describe its formation.

19. Briefly describe the way in which minerals accumulate in placers. List four minerals that are mined from such deposits.

20. Describe the effects of metal mining in Canada or the natural environment.

21. Nonmetallic resources are commonly divided into two broad groups. List the two groups and some examples of materials that belong to each. Which group is most widely distributed?

Key Terms

banded iron formation (p. 597)
cap rock (p. 607)
disseminated deposit (p. 591)
fossil fuel (p. 613)
geothermal energy (p. 624)
hydroelectric power (p. 622)
hydrothermal solution (p. 591)
industrial minterals (p. 587)
kimberlite (p. 602)
mineral resource (p. 584)
nonmetallic mineral resource (p. 601)
nonrenewable resource (p. 585)
nuclear fission (p. 620)
ore (p. 587)
pegmatite (p. 590)
petroleum trap (p. 607)
placer (p. 598)
renewable resource (p. 585)
reserve (p. 587)
reservoir rock (p. 607)
resources (p. 585)
secondary enrichment (p. 600)
vein deposit (p. 591)

Web Resources

The *Earth* Web site uses the resources and flexibility of the Internet to aid in your study of the topics in this chapter. Written and developed by geology instructors, this site will help improve your understanding of geology. Visit **http://www.prenhall.com/tarbuck** and click on the cover of *Earth* 7e to find:

- Online review quizzes.
- Web-based critical thinking and writing exercises.
- Links to chapter-specific Web resources.
- Internet-wide key-term searches.

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