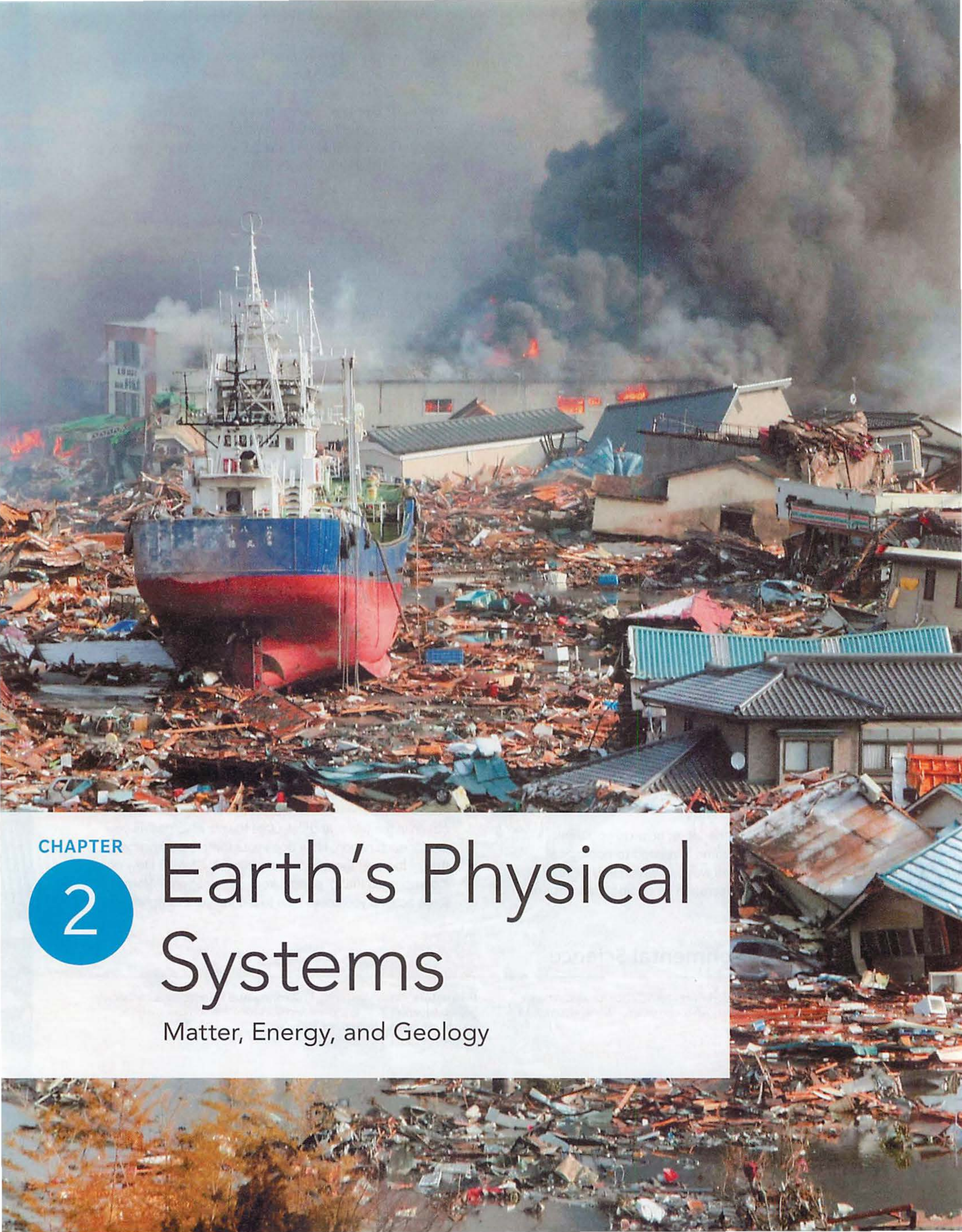


CHAPTER 2

Earth's Physical Systems

Matter, Energy, and Geology

CENTRAL
case study

What Is the Legacy of the Fukushima Daiichi Nuclear Tragedy?

> **This used to be one of the best places for a business. I'm amazed at how little is left.**
> Takahiro Chiba, surveying the devastated downtown area of Ishinomaki, Japan, where his family's sushi restaurant was located

> **Fukushima should not just contain lessons for Japan, but for all 31 countries with nuclear power.**
> Tatsujiro Suzuki, Vice-Chairman, Japan Atomic Energy Commission

At 2:46 p.m. on March 11, 2011, the land along the northeastern coast of the Japanese island of Honshu began to shake violently—and continued to shake for six minutes. These tremors were caused when a large section of the seafloor along a fault line 125 km (77 mi) offshore suddenly lurched, releasing huge amounts of energy through the earth's crust and generating an earthquake of magnitude 9.0 on the Richter scale (a scale used to measure the strength of earthquakes). The Tohuku earthquake, as it was later named, violently shook the ground in northeastern Japan. In Tokyo, 370 km (230 mi) from the quake's epicenter, commuter trains ground to a stop and skyscrapers swayed to and fro, but major damage to the city was avoided due to earthquake-resistant building codes for structures (see **SUCCESS STORY**, p. 26) and the immediate detection of the offshore earthquake. But even when the earth stopped shaking, the residents of northeastern Japan knew that further danger might still await them—from a tsunami.

A **tsunami** ("harbor wave" in English) is a powerful surge of seawater generated when an offshore earthquake displaces large volumes of rocks and sediment on the ocean bottom, suddenly pushing the overlying ocean water upward. This upward movement of water creates waves that speed outward from the earthquake site in all directions. These waves are hardly noticeable at sea, but can rear up to staggering heights when they enter the shallow waters near shore and can sweep inland with great force. The Japanese had built seawalls to protect against tsunamis, but the Tohoku quake caused the island of Honshu to sink perceptively, thereby lowering the height of the seawalls by up to 2 m (6.5 ft) in some locations. Waves reaching up to 15 m (49 ft) in height then overwhelmed these defenses (**FIGURE 2.1**, p. 24). The raging water swept up to 9.6 km (6 mi) inland; scoured buildings from their foundations; and inundated towns, villages, and productive agricultural land. As the water's energy faded, the water receded, carrying structural debris, vehicles, livestock, and human bodies out to sea.

When the tsunami overtopped the 5.7-m (19-ft) seawall protecting the Fukushima Daiichi nuclear power plant, it flooded the diesel-powered emergency generators responsible for circulating water to cool the plant's nuclear reactors. With the local electrical grid knocked

Upon completing this chapter, you will be able to:

- Explain the fundamentals of matter and chemistry and apply them to real-world situations
- Differentiate among forms of energy, and explain the first and second laws of thermodynamics
- Distinguish photosynthesis, cellular respiration, and chemosynthesis, and summarize their importance to living things
- Explain how plate tectonics and the rock cycle shape the landscape around us
- Identify major types of geologic hazards, and describe ways to minimize their impacts

◀ **Destruction in northeastern Japan from tsunami generated by the Tohoku earthquake**

▲ **One of the 300,000 people displaced by the Tohoku earthquake**

FIGURE 2.1 Tsunami waves overtop a seawall following the Tohoku earthquake in 2011. The tsunami caused a greater loss of life and property than the earthquake that generated it and led to a meltdown at the Fukushima Daiichi nuclear power plant.

out by the earthquake and the backup generators off-line, the nuclear fuel in the cores of the three active reactors at the plant began to overheat. The cooling water that normally kept the nuclear fuel submerged within the reactor cores boiled off, exposing the nuclear material to the air and further elevating temperatures inside the cores. As the overheated nuclear fuel melted its containment vessel (an event called a nuclear meltdown), chemical reactions within the reactors generated hydrogen gas. This hydrogen gas then set off explosions in each of the three active reactor buildings, and in an adjacent inactive reactor that was connected to an active reactor through ductwork, releasing radioactive material into the air (**FIGURE 2.2**). To prevent a full-blown catastrophe that could render large portions of their nation uninhabitable, Japanese authorities flooded the reactor cores with seawater pumped in from the ocean.

The 1–2–3 punch of the earthquake–tsunami–nuclear accident left 18,000 people dead and caused hundreds of billions of dollars in material damage. Around 340,000 people were displaced from their homes, and shortly after the accident the evacuation of a 20-km (12-mi) area around the Fukushima Daiichi plant was ordered due to unsafe levels of radioactive fallout in the soil. After the accident, public opposition to nuclear power in Japan ran high, and the government ordered the immediate shutdown and reinspection of its 54 nuclear reactors, which were, at the time, supplying 30% of Japan's electricity. The once productive fishing industry of the region was shut down over fears of people consuming seafood contaminated with high levels of radioactivity. The world watched and waited to see how the events in Japan would play out over the coming years and took a critical look at the

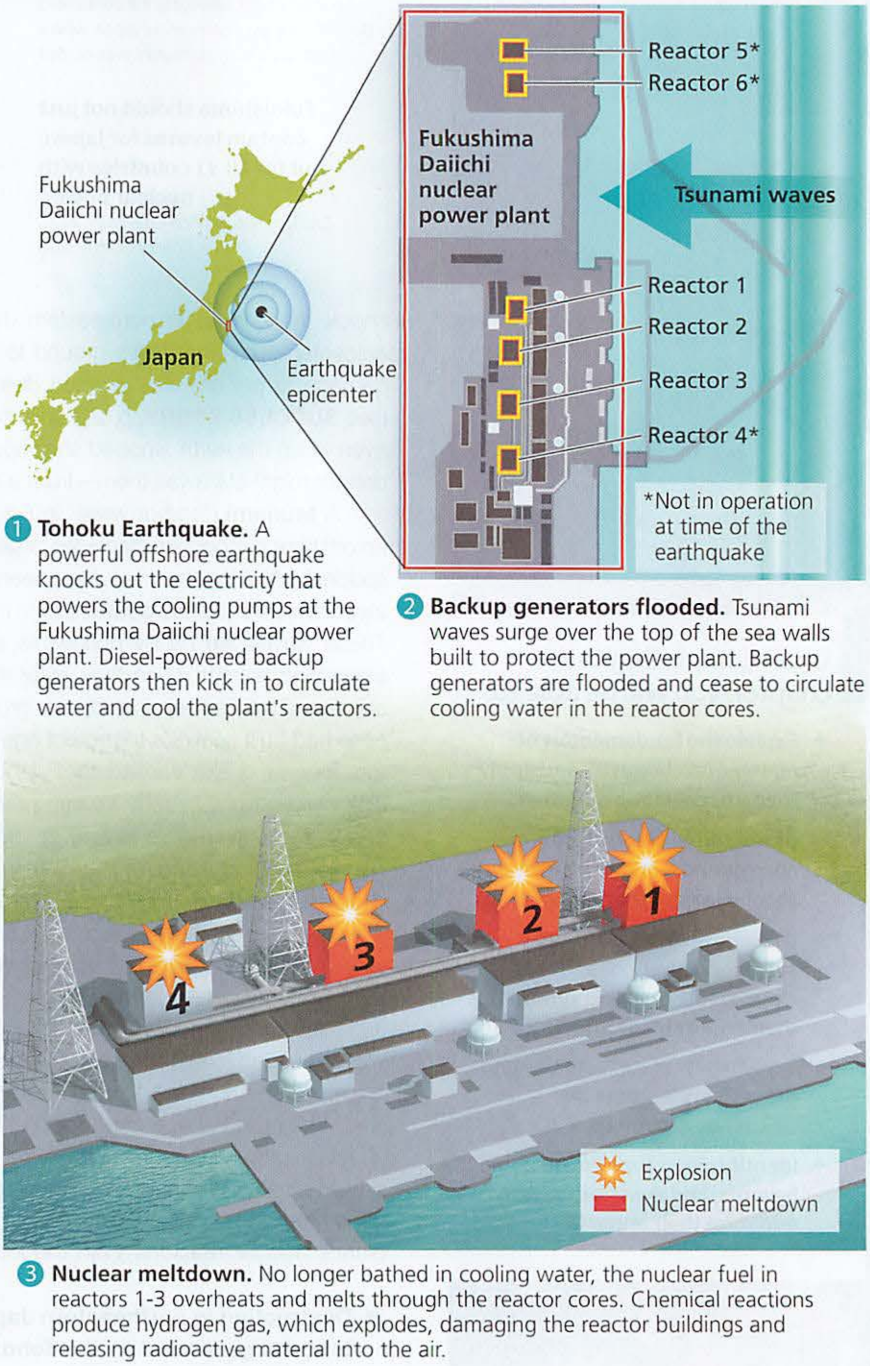


FIGURE 2.2 Timeline of events in the nuclear accident at the Fukushima Daiichi power plant.

future of nuclear power around the world. Whereas nuclear power does have an inherent danger for large-scale accidents and we have yet to find a safe, sustainable way to store the radioactive wastes it produces, it does have benefits over other methods of generating electricity in that it does not release significant amounts of air pollutants or greenhouse gases into the atmosphere when producing energy.

The destruction at Fukushima following the Tohoku earthquake was the product of natural forces—an earthquake and subsequent tsunami—coupled with an accident involving one of humanity's most advanced technologies: nuclear power. These events highlight why knowledge of matter, energy, and geologic forces is vital to understanding environmental impacts in our complex, modern world.

Matter, Chemistry, and the Environment

The tragic events in northeastern Japan in 2011 were the result of large-scale forces generated by the powerful geologic processes that shape the surface of our planet. Environmental scientists regularly study these types of processes to understand how our planet works. Because all large-scale processes are made up of small-scale components, however, environmental science—the broadest of scientific fields—must also study small-scale phenomena. At the smallest scale, an understanding of matter itself helps us to fully appreciate the processes of our world.

All material in the universe that has mass and occupies space—solid, liquid, and gas alike—is called **matter.** The study of types of matter and their interactions is called **chemistry.** Once you examine any environmental issue, from acid rain to toxic chemicals to climate change, you will likely discover chemistry playing a central role.

Matter is conserved

To appreciate the chemistry involved in environmental science, we must begin with the fundamentals. Matter may be transformed from one type of substance into others, but it cannot be created or destroyed, a principle referred to as the **law of conservation of matter.** In environmental science, this principle helps us understand that the amount of matter stays constant as it is recycled in ecosystems and nutrient cycles (p. 121). It also makes it clear that we cannot simply wish away "undesirable" matter, such as nuclear waste and toxic pollutants. Because harmful substances can't be destroyed, we must take steps to minimize their impacts on the environment.

Elements and atoms are chemical building blocks

The nuclear reactors at Fukushima Daiichi used the element **uranium** to power its reactors. An **element** is a fundamental type of matter, a chemical substance with a given set of properties that cannot be broken down into substances with other properties. Chemists currently recognize 118 elements. Most occur in nature, but more than 20 elements have been created solely in the lab. Elements especially abundant on our planet include **oxygen, hydrogen, silicon, nitrogen,** and **carbon** (**TABLE 2.1**). Elements that organisms need for survival, such as carbon, nitrogen, calcium, and phosphorus, are called **nutrients.** Each element is assigned an abbreviation, or chemical symbol (for instance, "H" for hydrogen and "O" for oxygen). The periodic table of the elements organizes the elements according to their chemical properties and behavior (see **APPENDIX C**).

An **atom** is the smallest unit that maintains the chemical properties of the element. Atoms of each element contain a specific number of **protons,** positively charged particles in the atom's nucleus (its dense center), and the number of

TABLE 2.1 Earth's Most Abundant Chemical Elements, by Mass

EARTH'S CRUST		OCEANS		AIR		ORGANISMS	
Oxygen (O)	49.5%	Oxygen (O)	88.3%	Nitrogen (N)	78.1%	Oxygen (O)	65.0%
Silicon (Si)	25.7%	Hydrogen (H)	11.0%	Oxygen (O)	21.0%	Carbon (C)	18.5%
Aluminum (Al)	7.4%	Chlorine (Cl)	1.9%	Argon (Ar)	0.9%	Hydrogen (H)	9.5%
Iron (Fe)	4.7%	Sodium (Na)	1.1%	Other	<0.1%	Nitrogen (N)	3.3%
Calcium (Ca)	3.6%	Magnesium (Mg)	0.1%			Calcium (Ca)	1.5%
Sodium (Na)	2.8%	Sulfur (S)	0.1%			Phosphorus (P)	1.0%
Potassium (K)	2.6%	Calcium (Ca)	<0.1%			Potassium (K)	0.4%
Magnesium (Mg)	2.1%	Potassium (K)	<0.1%			Sulfur (S)	0.3%
Other	1.6%	Bromine (Br)	<0.1%			Other	0.5%

SUCCESS **story**

Saving Lives with Building Codes

The Tohoku earthquake was not the first major earthquake to strike Japan. The city of Kobe experienced substantial damage from a quake in 1995 that claimed more than 5500 lives. And in 1923, an earthquake devastated the cities of Tokyo and Yokohama, resulting in more than 142,000 deaths. Losses of life and property from the Tohoku quake were far less extensive than the losses from these earlier events, thanks to new stringent building codes ensuring that the design and construction of structures are such that they resist crumbling and toppling over during earthquakes.

To minimize damage from earthquakes, engineers have developed ways to protect buildings from collapsing while shaking. They do this by strengthening structural components while also designing points at which a structure can move and sway harmlessly with ground motion. Just as a flexible tree trunk bends in a storm while a brittle one breaks, buildings with built-in flexibility are more likely to withstand an earthquake's violent shaking. Such designs continue to figure in the building codes used in California, Japan, and other quake-prone regions.

Such quake-resistant designs are more expensive to build than conventional designs, so many buildings in poorer nations do not have such protections. Consequently, earthquakes in these regions typically result in greater losses of life and property due to the greater numbers of buildings that collapse. For example, Haiti suffered a 7.0 magnitude earthquake in 2010 that devastated huge portions of the capital city of Port-au-Prince and claimed over 220,000 lives. Although the Tohoku earthquake released more than 950 times the energy than the earthquake that struck Haiti, mortality and property damage from the Tohoku quake (not including the damage and loss of life caused by the subsequent tsunami) were minimized because of Japan's earthquake-conscious building codes.

Collapsed buildings in Port-au-Prince, Haiti, following a 7.0 magnitude earthquake in 2010

→ **Explore the Data** at Mastering Environmental Science

protons is called the element's atomic number. (Elemental carbon, for instance, has six protons in its nucleus; thus, its atomic number is 6.) Most atoms also contain **neutrons,** particles in the nucleus that lack an electrical charge. An element's mass number denotes the combined number of protons and neutrons in the atom. An atom's nucleus is surrounded by negatively charged particles known as **electrons,** which are equal in number to the protons in the nucleus of an atom, balancing the positive charge of the protons (**FIGURE 2.3**).

Isotopes Although all atoms of a given element contain the same number of protons, they do not necessarily also contain the same number of neutrons. Atoms of the same element with differing numbers of neutrons are **isotopes** (**FIGURE 2.4a**). Isotopes are denoted by their elemental symbol preceded by the mass number, the combined number of protons and neutrons in the nucleus of the atom. For example, ^{14}C (carbon-14) is an isotope of carbon with eight neutrons (and six protons) in the nucleus rather than the six neutrons (and six protons) of ^{12}C (carbon-12), the most abundant carbon isotope.

Some isotopes, called **radioisotopes,** are **radioactive** because their chemical identity changes as they shed subatomic particles and emit high-energy radiation. The radiation released by radioisotopes harms organisms because it focuses a great deal of energy in a very small area, which

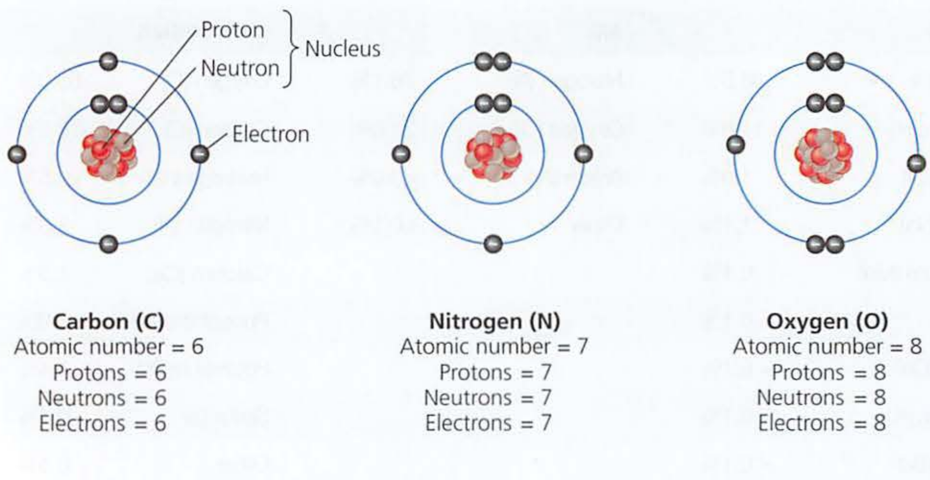


FIGURE 2.3 In an atom, protons and neutrons stay in the nucleus and electrons move about the nucleus. Each chemical element has its own particular number of protons. For example, carbon possesses six protons, nitrogen seven, and oxygen eight. These schematic diagrams are meant to clearly show and compare numbers of electrons for these three elements. In reality, however, electrons do *not* orbit the nucleus in rings as shown; they move through space in more complex ways.

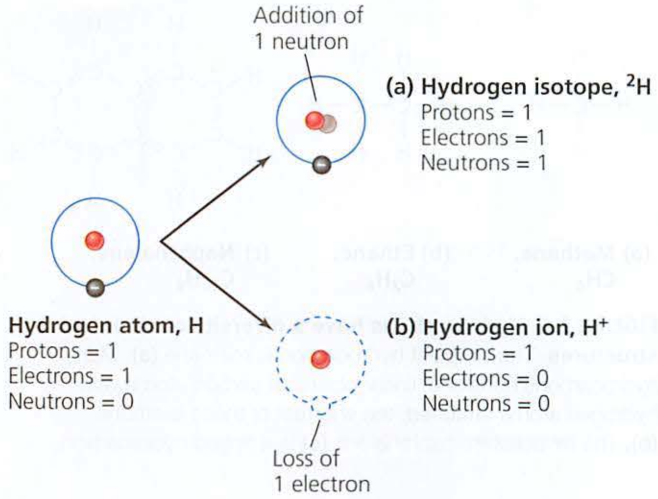


FIGURE 2.4 Hydrogen has a mass number of 1 because a typical atom of this element contains one proton and no neutrons. Deuterium (hydrogen-2, or ^{2}H), an isotope of hydrogen **(a),** contains a neutron, as well as a proton and thus has greater mass than a typical hydrogen atom; its mass number is 2. The hydrogen ion, H^{+} **(b),** occurs when an electron is lost; it therefore has a positive charge.

can be damaging to living cells. Intense radiation exposure can kill cells outright or cause changes to the cell's DNA that can increase the probability of the organism developing cancerous tumors.

The greatest danger from radioisotopes occurs when they enter the bodies of organisms through the lungs, skin, or digestive system. It is therefore important after nuclear accidents, like that at Fukushima, to regularly test food and water supplies for radioisotopes and to determine the eventual fate of radioactive particles released into the environment.

A radioisotope decays as it emits radiation, becoming lighter and lighter with the loss of subatomic particles, until it becomes a stable isotope (isotopes that are not radioactive). Each radioisotope decays at a rate determined by its **half-life,** the amount of time it takes for one-half of its atoms to decay. Different radioisotopes have very different half-lives, ranging from fractions of a second to billions of years. The radioisotope uranium-235 (^{235}U), used in commercial nuclear power plants like Fukushima Daiichi, decays into a series of daughter isotopes (atoms formed as radioisotopes that lose protons and neutrons during the process of radioactive decay), eventually forming lead-207 (^{207}Pb). Uranium-235 has a half-life of about 700 million years. Radioisotopes released into the environment from the Fukushima nuclear power plant accident included iodine-131 (half-life of 8 days), cesium-134 (half-life of 2 years), strontium-90 (half-life of 29 years), and cesium-137 (half-life of 30 years). Given these lengthy half-lives, finding ways to safely contain radioisotopes at nuclear waste storage sites and in areas, like Fukushima, that have experienced nuclear accidents is an area of active research (see **THE SCIENCE BEHIND THE STORY**, pp. 30–31).

Ions Atoms may also gain or lose electrons, thereby becoming **ions,** electrically charged atoms or combinations of atoms (**FIGURE 2.4b**). Ions are denoted by their elemental symbol followed by their ionic charge. For instance, a common ion used by mussels and clams to form shells is Ca^{2+}, a calcium atom that has lost two electrons and thus has a charge of positive 2. The damaging radiation emitted by radioisotopes is called **ionizing radiation** (see Figure 2.11, p. 33) because it generates ions when it strikes molecules. These ions affect the stability and functionality of biological important molecules such as enzymes (p. 28) and DNA (p. 28), and this can harm cells, cause them to die, or mutate their genetic code.

Atoms bond to form molecules and compounds

Atoms bond together and form **molecules,** combinations of two or more atoms. Common molecules containing only a single element include those of hydrogen (H_2) and oxygen (O_2), each of which exists as a gas at room temperature. A molecule composed of atoms of two or more elements is called a **compound.** One compound is **water;** it is composed of two hydrogen atoms bonded to one oxygen atom, and it is denoted by the chemical formula H_2O. Another compound is **carbon dioxide,** consisting of one carbon atom bonded to two oxygen atoms; its chemical formula is CO_2.

Atoms bond together because of an attraction for one another's electrons. Because the strength of this attraction varies among elements, atoms may be held together in different ways. When electrons are shared between atoms, a **covalent bond** forms. For example, two atoms of hydrogen will share electrons equally as they bind together to form

FAQ

When something is irradiated, does it become radioactive?

Thanks to comic books and movies, many people believe that when an organism is exposed to ionizing radiation from nuclear waste or a solar flare from the sun, the organism becomes a *source* of ionizing radiation—that is, it becomes "radioactive." In reality, this does not happen.

An irradiated organism suffers damage from radiation, but it does not absorb the ionizing radiation, store it, and then re-emit it to the environment. The radiation simply enters the organism's cells, causes damage, and passes through the organism. So even after experiencing substantial impacts from radiation poisoning, the organism is no more radioactive than it was before exposure. This occurs because the organism was only exposed to radiation (a form of energy) and was not contaminated with radioisotopes (a form of matter) that emit harmful radiation. It is for this reason that it is safe to expose raw meat to ionizing radiation in order to kill harmful microbes that may be lurking within it, such as *Salmonella* or disease-causing strains of *Escherichia coli (E. coli)*. The process, which is done to prevent foodborne illness in people with compromised immune systems and to prevent astronauts from becoming ill while in space, sterilizes the meat of microbes but does not cause the meat to become radioactive.

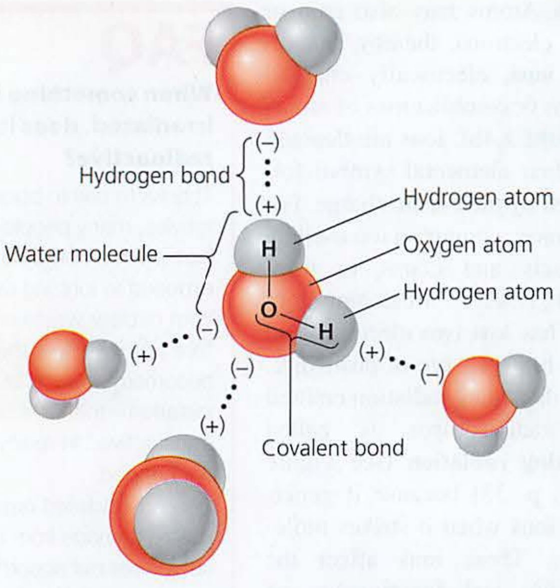


FIGURE 2.5 By enabling water molecules to adhere loosely to one another, hydrogen bonds give water several unique properties crucial for life.

hydrogen gas, H_2. However, in a water molecule, oxygen attracts shared electrons more strongly than does hydrogen. The result is that water has a partial negative charge at its oxygen end and partial positive charges at its hydrogen ends. This arrangement allows water molecules to adhere to one another in a type of weakly attractive interaction called a **hydrogen bond** (**FIGURE 2.5**). Hydrogen bonds allow water to dissolve (hold in solution) many other molecules. It is for this reason that water forms the majority of the mass of living cells, as it provides an ideal medium for the many biologically important molecules that exist within cells.

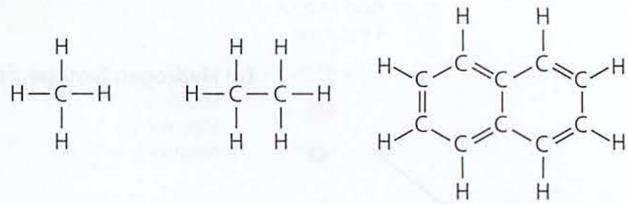
In compounds in which the strength of attraction is sufficiently unequal, an electron may be transferred from one atom to another. This creates oppositely charged ions that form **ionic bonds** due to their differing electrical charges. Such associations are called ionic compounds, or salts. Table salt (NaCl) contains ionic bonds between positively charged sodium ions (Na^+), each of which donates an electron, and negatively charged chloride ions (Cl^-), each of which receives an electron.

Elements, molecules, and compounds can also come together in mixtures without chemically bonding or reacting. Such mixtures are called solutions. Air in the atmosphere is a solution formed of constituents such as nitrogen, oxygen, and water vapor. Other solutions include ocean water, plant sap, petroleum, and metal alloys such as brass.

Matter is composed of organic and inorganic compounds

Beyond their need for water, living things also depend on organic compounds. **Organic compounds** consist of carbon atoms (and generally hydrogen atoms) joined by covalent bonds, and they may also include other elements, such as nitrogen, oxygen, sulfur, and phosphorus. Inorganic compounds, in contrast, lack carbon–carbon bonds.

Carbon's unusual ability to bond together in chains, rings, and other structures to build elaborate molecules has resulted in millions of different organic compounds. One class of such compounds that is important in environmental science is **hydrocarbons,** which consist solely of bonded atoms of carbon and hydrogen (although other elements may enter these compounds as impurities) (**FIGURE 2.6**). Fossil fuels and the many petroleum products we make from them (Chapter 19), such as plastics, consist largely of hydrocarbons.



(a) Methane, CH_4 **(b) Ethane,** C_2H_6 **(c) Naphthalene,** $C_{10}H_8$

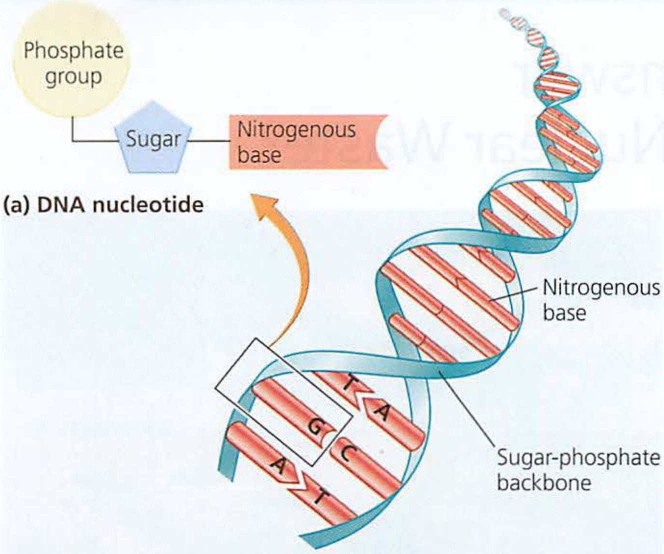
FIGURE 2.6 Hydrocarbons have a diversity of chemical structures. The simplest hydrocarbon is methane **(a).** Many hydrocarbons consist of linear chains of carbon atoms with hydrogen atoms attached; the shortest of these is ethane **(b).** The air pollutant naphthalene **(c)** is a ringed hydrocarbon.

Macromolecules are building blocks of life

Just as carbon atoms in hydrocarbons may be strung together in chains, organic compounds sometimes combine to form long chains of repeated molecules. These chains are called **polymers.** There are three types of polymers that are essential to life: proteins, nucleic acids, and carbohydrates. Along with lipids (which are not polymers), these types of molecules are referred to as **macromolecules** because of their large sizes.

Proteins consist of long chains of organic molecules called amino acids. The many types of proteins serve various functions. Some help produce tissues and provide structural support. For example, animals use proteins to generate skin, hair, muscles, and tendons. Some proteins help store energy, whereas others transport substances. Some act in the immune system to defend the organism against foreign attackers, such as bacteria and viruses that cause disease. Still others are hormones, molecules that act as chemical messengers within an organism. Proteins can also serve as enzymes, molecules that catalyze, or promote, certain chemical reactions.

Nucleic acids direct the production of proteins. The two nucleic acids—**deoxyribonucleic acid (DNA)** and **ribonucleic acid (RNA)**—carry the hereditary information for



(a) DNA nucleotide

(b) DNA double helix

FIGURE 2.7 Nucleic acids encode genetic information in the sequence of nucleotides, small molecules that pair together like rungs of a ladder. DNA includes four types of nucleotides **(a),** each with a different nitrogenous base: adenine (A), guanine (G), cytosine (C), and thymine (T). Adenine (A) pairs with thymine (T), and cytosine (C) pairs with guanine (G). In RNA, thymine is replaced by uracil (U). DNA **(b)** twists into the shape of a double helix.

organisms and are responsible for passing traits from parents to offspring. Nucleic acids are composed of a series of nucleotides, each of which contains a sugar molecule, a phosphate group, and a nitrogenous base. DNA contains four types of nucleotides and can be pictured as a ladder twisted into a spiral, giving the molecule a shape called a double helix (**FIGURE 2.7**). Regions of DNA coding for particular proteins that perform particular functions are called **genes.**

Carbohydrates include simple sugars that are three to seven carbon atoms long. Glucose ($C_6H_{12}O_6$) fuels living cells and serves as a building block for complex carbohydrates, such as starch. Plants use starch to store energy, and animals eat plants to acquire starch. Plants and animals also use complex carbohydrates to build structure. Insects and crustaceans form hard shells from the carbohydrate chitin. Cellulose, the most abundant organic compound on Earth, is a complex carbohydrate found in the cell walls of leaves, bark, stems, and roots.

Lipids include fats and oils (for energy storage), phospholipids (for cell membranes), waxes (for structure), and steroids (for hormone production). Although chemically diverse, the compounds that are categorized as lipids are so grouped because they do not dissolve in water.

Hydrogen ions determine acidity

The functioning of proteins and other biologically important molecules in cells can be influenced by the level of acids and bases in the liquid medium in which they reside. In any aqueous solution, a small number of water molecules split apart, each forming a hydrogen ion (H^+) and a hydroxide ion (OH^-). The product of hydrogen and hydroxide ion concentrations is always the same; as one increases, the other decreases. Pure water contains equal numbers of these ions. Solutions in which the H^+ concentration is greater than the OH^- concentration are **acidic,** whereas solutions in which the OH^- concentration exceeds the H^+ concentration are **basic,** or alkaline.

The **pH** (potential of hydrogen) scale quantifies the acidity or alkalinity of solutions from 0 to 14, according to hydrogen ion concentration (**FIGURE 2.8**). Pure water has a hydrogen ion concentration of 10^{-7} and thus a pH of 7. Solutions with a pH less than 7 are acidic, and those with a pH greater than 7 are basic. The pH scale is logarithmic, so each step on the scale represents a 10-fold difference in hydrogen ion concentration. A substance with a pH of 6, for example, contains 10 times as many hydrogen ions as a substance with a pH of 7 and 100 times as many hydrogen ions as a substance with a pH of 8.

Most biological systems have a pH between 6 and 8, and substances that are strongly acidic (battery acid) or strongly basic (sodium hydroxide) are harmful to living things. Human activities can change the pH of water or soils and make conditions less amenable to life. Examples include the acidification of soils and water from acid rain (pp. 474–477) and from acidic mine drainage (p. 650).

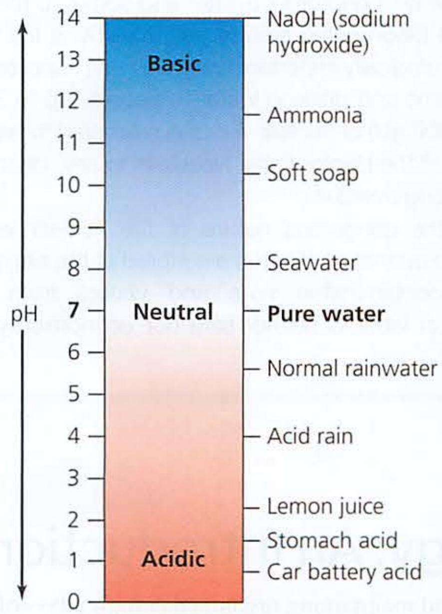


FIGURE 2.8 The pH scale measures how acidic or basic (alkaline) a solution is. The pH of pure water is 7, the midpoint of the scale. Acidic solutions have a pH less than 7, whereas basic solutions have a pH greater than 7.

THE SCIENCE **behind** the **story**

Are Yeast the Answer to Cleaning up Nuclear Waste?

Radiation warning signs outside the Hanford Nuclear Reservation

During the Cold War era from 1945 to 1986, the United States generated massive amounts of radioactive waste while producing 46,000 nuclear weapons. A mixture of harmful substances, the radioactive waste includes radioisotopes (such as uranium and plutonium), toxic chemicals, and heavy metals (such as mercury and cadmium) in a highly acidic solution (due to the processing of weapons-grade uranium involving nitric acid). The radioactive waste is stored in underground tanks at 120 locations across the United States, sites administered by the Department of Energy.

As far back as 1959, a leak was detected at the Hanford Nuclear Reservation in Washington, one of the largest nuclear waste storage sites in the country, which houses 60% of the United States' radioactive waste from weapons production since 1943 (**FIGURE 1**). Today, over a third of the 177 tanks on-site are leaking radioactive waste, contaminating an estimated 3 trillion liters (790 billion gal) of surface waters and groundwater and some 70 million cubic meters (2.4 billion cubic feet) of soil. Nearby is the Columbia River, an ecologically important waterway that supplies irrigation water to farms and drinking water to people. Up to 3.7 million liters (977,000 gal) of nuclear waste is estimated to have leaked from tanks at the Hanford site. Needless to say, cleanup of the leakage is long overdue.

Given the dangerous nature of the nuclear waste and the massive quantities of it that are stored at the site, physically removing contaminated soils and waters from the site using human labor is neither safe nor economically feasible.

FIGURE 1 Leaks from some of the 177 underground storage tanks at the Hanford Nuclear Reservation in Washington State are threatening to dangerously contaminate the nearby Columbia River.

A potential alternative that scientists are considering is the use of **bioremediation,** whereby microorganisms clean up toxic waste. Certain microorganisms metabolize toxic chemicals and convert toxic heavy metals into less dangerous forms. Some can also produce biofilms, a weblike matrix of proteins and carbohydrates that surround the cell and to which radioisotope metals and other toxic substances adhere. Biofilm traps these harmful substances, minimizing their movements in the environment.

In 2000, researchers led by Michael Daly of the Uniformed Services University of the Health Sciences sampled the sediments at the Hanford site beneath a tank leaking highly radioactive waste. They were looking for a microorganism to be used in bioremediation of the site and isolated 110 different species of

Energy: An Introduction

Creating and maintaining organized complexity—of a cell, an organism, an ecological system, or a planet—require energy. Energy is needed to organize matter into complex forms, to build and maintain cellular structure, to govern species' interactions, and to drive the geologic forces that shape our planet. Energy is involved in nearly every chemical, biological, and physical phenomenon.

But what is energy? **Energy** is the capacity to change the position, physical composition, or temperature of matter—in other words, a force that can accomplish **work** (when a force acts on an object, causing it to move). As we saw with Japan's 2011 earthquake and tsunami, geologic events involve some of the most dramatic releases of energy in nature. Energy is omnipresent in living things as well. A sparrow in flight expends energy to propel its body through the air (change of position). When the sparrow lays an egg, its body uses energy bacteria. From these bacteria, they selected *Deinococcus radiodurans,* a microbe known for its high tolerance to radioactivity and its ability to neutralize toxic metals, for further research. After six years, the team produced a genetically engineered strain of the bacterium that neutralized toxic metals and metabolized toxic chemicals, all while being exposed to high temperatures and high levels of radioactivity. However, this strain of *D. radiodurans,* nicknamed "Conan the Bacterium" for its heartiness, had a few shortcomings. Although it could tolerate the heat and radioactivity present in contaminated sediments at Hanford, its activity levels dropped off when conditions became moderately acidic. As the nuclear waste stored at Hanford and elsewhere was leaking wastes that were strongly acidic, the bacterium's usefulness was limited, as it was largely ineffective at treating nuclear wastes at locations nearest the tanks, where pH levels were the lowest (the most toxic). *D. radiodurans* also did not produce biofilms under the harshest conditions, which somewhat hindered its effectiveness in trapping contaminants.

To locate other candidates for use in bioremediation at the Hanford sites, Daly and his team looked elsewhere for microorganisms adapted to harsh conditions, sampling 60 different and extreme environments, from arctic ice to underground mines to hot springs. But instead of focusing on the bacteria in their samples, they turned their attention to another kind of microorganism—yeast. Yeast are fungi, not bacteria, and the team found 27 different types of yeast in the samples. Very little research had been conducted on the effectiveness of yeast in bioremediation, but as yeast are generally tolerant of acidic conditions, the team believed these microorganisms had the potential to contain nuclear waste.

As reported in a 2018 paper in the journal *Frontiers in Microbiology*, the researchers screened the 27 types of yeast for their tolerance to ionizing radiation, acidity, and temperature, as well as their resistance to toxic heavy metals. From the screening, a red-pigmented strain of the yeast *Rhodotorula taiwanensis,* which had been collected from an abandoned acid mine drainage (p. 650) facility in Maryland, stood out as an ideal candidate for bioremediation at the Hanford site. Not only did the species tolerate high levels of radioactivity and elevated concentrations of toxic metals, but *R. taiwanesis* did so under highly acidic conditions. It also formed biofilms under the harshest conditions (**FIGURE 2**). Whereas the study of *R. taiwanesis* showed the promise of fungi in nuclear waste containment, the organism was not the *perfect* fit for cleanup projects like that at Hanford. For example, radioisotopes in nuclear waste generate heat, and *R. taiwanensis* growth slows considerably as temperature increases. In the high-temperature environment beneath a leaking nuclear waste tank, the yeast is therefore not as effective as it is further away from the tank where conditions are cooler.

The pioneering research on bioremediation using *D. radiodurans* and *R. taiwanesis* opens up the possibility of employing a mixture, or "cocktail," of organisms for containment of nuclear waste at the Hanford Nuclear Reservation and similar radioactive sites. By combining a diversity of bacteria and fungi, each with specific tolerances to radioactivity, pH, and temperature—and differing abilities to detoxify harmful chemicals and trap contaminants in biofilms—we may one day be able to effectively contain the nuclear waste leaking at storage sites around the United States and in other nations around the world.

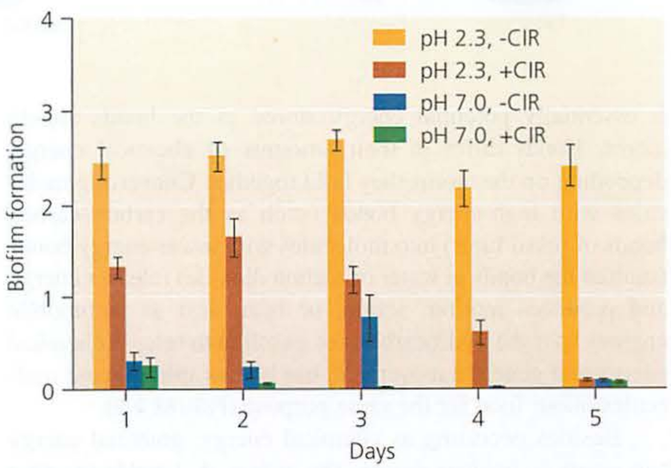


FIGURE 2 The yeast *Rhodotorula taiwanensis* form biofilms, which aid in the containment of radioactive and toxic wastes, under challenging environmental conditions. The species form biofilms even when growing on very low pH substrates (pH 2.3) with steady exposure to harmful ionizing radiation (+CIR). *Data from Tkavc, R., et al., 2018. Prospects for fungal bioremediation of acidic radioactive waste sites: Characterization and genome sequence of* Rhodotorula taiwanensis *MD1149.* Front. Microbiol. *8: 2528.* doi: 10.3389/fmicb.2017.02528.

to create the calcium-based eggshell and color it with pigment (change in composition). The sparrow sitting on its nest transfers energy from its body to heat the developing chicks inside its eggs (change of temperature).

Energy comes in different forms

Energy manifests itself in different ways and can be converted from one form to another. Two major forms of energy that scientists commonly distinguish are **potential energy,** energy of position or composition, and **kinetic energy,** energy of motion. Consider river water held behind a dam. By preventing water from moving downstream, the dam causes the water to accumulate potential energy. When the dam gates are opened, the potential energy is converted to kinetic energy as the water rushes downstream.

Energy conversions take place at the atomic level every time a chemical bond is broken or formed. Chemical energy

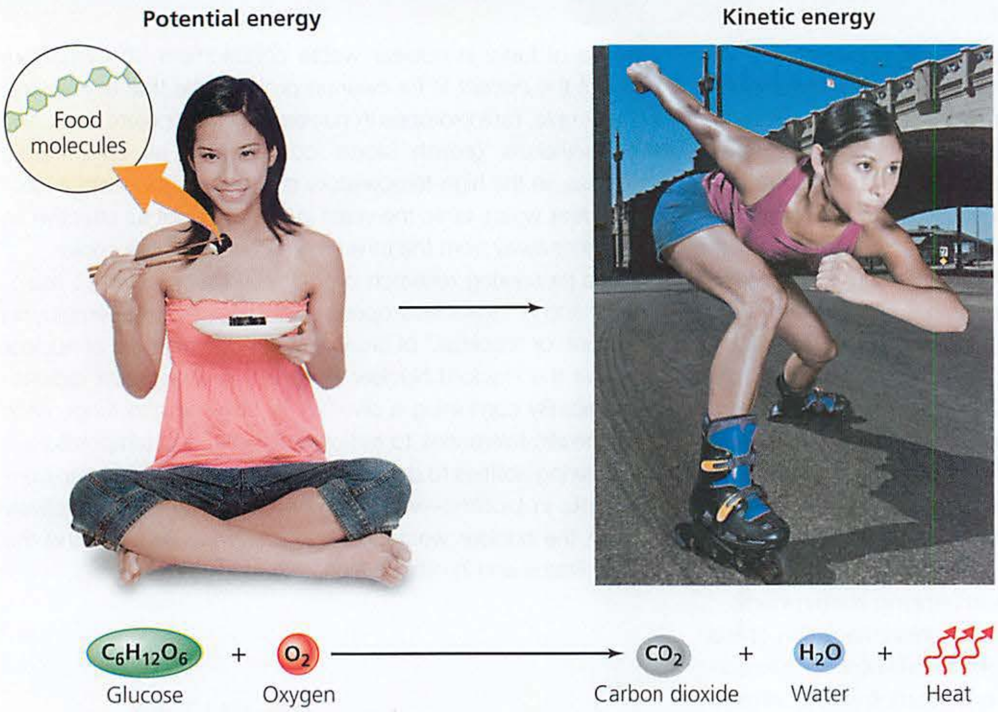


FIGURE 2.9 Energy is released when potential energy is converted to kinetic energy. Potential energy stored in sugars (such as glucose) in the food we eat, combined with oxygen, becomes kinetic energy when we exercise, releasing carbon dioxide, water, and heat as by-products.

is essentially potential energy stored in the bonds among atoms. Bonds differ in their amounts of chemical energy, depending on the atoms they hold together. Converting molecules with high-energy bonds (such as the carbon–carbon bonds of fossil fuels) into molecules with lower-energy bonds (such as the bonds in water or carbon dioxide) releases energy and produces motion, action, or heat. Just as automobile engines split the hydrocarbons of gasoline to release chemical energy and generate movement, our bodies split glucose molecules in our food for the same purpose (**FIGURE 2.9**).

Besides occurring as chemical energy, potential energy can occur as nuclear energy, the energy that holds together atomic nuclei. Nuclear power plants use this energy when they break apart the nuclei of large uranium atoms within their reactors. Mechanical energy, such as the energy stored in a compressed spring, is yet another type of potential energy. Kinetic energy can also express itself in different forms, including thermal energy, light energy, sound energy, and electrical energy—all of which involve the movement of atoms, subatomic particles, molecules, or objects.

A nuclear power plant, such as Fukushima Daiichi, illustrates the many ways energy can be used to change the position, physical composition, or temperature of matter and how energy can change form (see Figure 20.5, p. 565, for an illustration of the operation of a commercial nuclear power plant). In the plant's reactor, the potential energy in uranium is released by nuclear fission reactions (the splitting of atom nuclei), producing heat energy. This heat changes water from liquid to steam, and the kinetic energy of steam molecules is harnessed to generate mechanical energy in turbines. This mechanical energy is then sent to an electrical generator, where the spinning of wires within a magnetic field generates electrical energy. Similarly, complex energetic interactions occur in other human uses of energy, as well as in the natural world.

Energy is always conserved, but it changes in quality

The study of the relationships between different forms of energy is termed **thermodynamics,** and the theories that explain energetic interactions are called the *laws of thermodynamics*. The **first law of thermodynamics** states that energy can change from one form to another, but it cannot be created or destroyed. Just as matter is conserved (p. 25), the total energy in the universe remains constant and thus is said to be conserved. The potential energy of the water behind a dam will equal the kinetic energy of its eventual movement downstream. Likewise, we obtain energy from the food we eat and then expend it in exercise, apply it toward maintaining our body and all its functions, or store it in fat. We do not somehow create additional energy or end up with less energy than the food gives us. Any particular system in nature can temporarily increase or decrease in energy, but the total amount in the universe always remains constant.

Although the overall amount of energy is conserved in any conversion of energy, the **second law of thermodynamics** states that the nature of energy will change from a more-ordered state to a less-ordered state as long as no force counteracts this tendency. That is, systems tend to move toward increasing disorder, or entropy. For instance, a log of firewood—the highly organized and structurally complex product of many years of tree growth—transforms in a campfire to a residue of carbon ash, smoke, and gases such as carbon dioxide and water vapor, as well as the light and the heat of the flame (**FIGURE 2.10**). With the help of oxygen, the complex biological polymers that make up the wood are converted into a disorganized assortment of rudimentary molecules and heat and light energy. When energy transforms from a more-ordered state to a less-ordered state, it cannot accomplish tasks as efficiently. For example, the

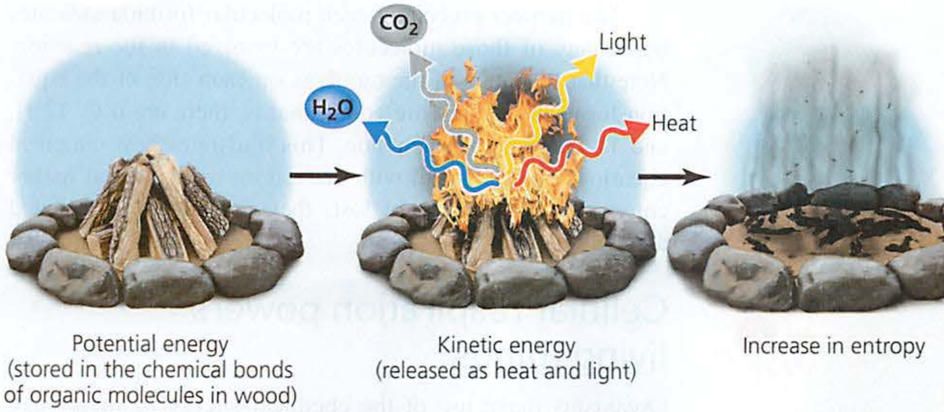


FIGURE 2.10 The burning of firewood demonstrates energy conversion from a more-ordered to a less-ordered state. This increase in entropy reflects the second law of thermodynamics.

potential energy available in ash (a less-ordered state of wood) is far lower than that available in a log of firewood (the more-ordered state of wood).

The second law of thermodynamics specifies that systems tend to move toward disorder. How, then, does any system maintain its order? The order of an object or system can be increased by the input of energy from outside the system. Living organisms, for example, maintain their highly ordered structure by regularly consuming energy. But when organisms die and these inputs of energy cease, they undergo decomposition and revert to a less-ordered state.

Light energy from the sun powers our planet

The energy that powers Earth's biological systems comes primarily from the sun. The sun releases radiation across large portions of the electromagnetic spectrum, although our atmosphere filters out much of this and we see only some of this radiation as visible light (**FIGURE 2.11**). Most of the sun's energy is reflected, or else absorbed and re-emitted, by the atmosphere, land, or water (p. 487). Solar energy drives winds, ocean currents, weather, and climate patterns. A small amount (less than 1% of the total) powers plant growth, and a still smaller amount flows from plants into the organisms that eat them and the organisms that decompose dead organic matter. A minuscule percentage of this energy is eventually deposited belowground in the chemical bonds in fossil fuels (which are derived from ancient plants; pp. 529–531).

Photosynthesis converts solar energy to chemical energy

Some organisms use the sun's radiation directly to produce their own food. Such organisms, called **autotrophs** or **primary producers,** include green plants, algae, and cyanobacteria. Through the process of **photosynthesis,** autotrophs use sunlight to power a series of chemical reactions that transform molecules with lower-energy bonds—water and carbon dioxide—into sugar molecules with many high-energy bonds. Photosynthesis is an example of a process that moves toward a state of lower entropy, so it requires a substantial input of outside energy, in this case from sunlight.

Photosynthesis occurs within cellular organelles called chloroplasts, where the light-absorbing pigment chlorophyll (the substance that makes plants green) uses solar energy to

FAQ

What part of the universe is offsetting all the complexity on Earth?

The second law of thermodynamics tells us that systems, such as our universe, tend to move toward entropy. But Earth is a highly ordered planet populated by huge numbers of highly ordered organisms. What part of the universe is offsetting this localized decrease in entropy to satisfy the second law?

It's our local star, the sun. The decrease in entropy in the universe that occurs on Earth is being offset by a larger *increase in entropy* in the sun. The sun provides our planet with energy inputs that resist entropy and maintain order. But in doing so, it consumes its nuclear fuel and becomes increasingly disordered over time. In several billion years, once the sun has exhausted its supplies of nuclear fuel, it will no longer be able to resist entropy. It will then burn out and attain a highly disordered state that will no longer be able to produce substantial amounts of energy.

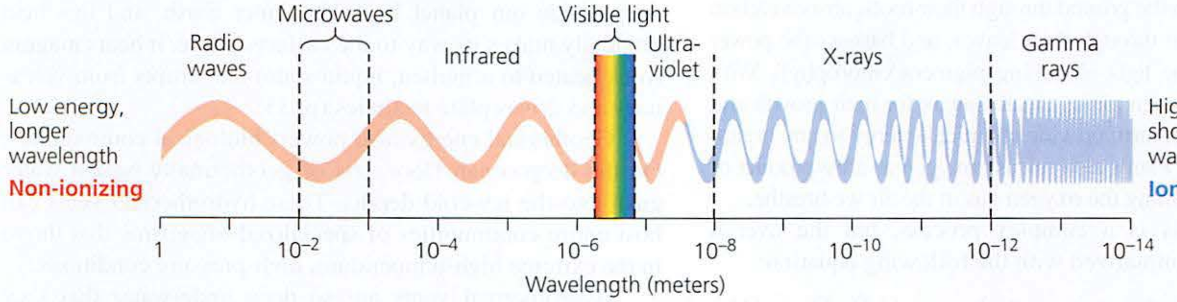


FIGURE 2.11 The sun emits radiation from many portions of the electromagnetic spectrum. Visible light makes up only a small proportion of this energy.

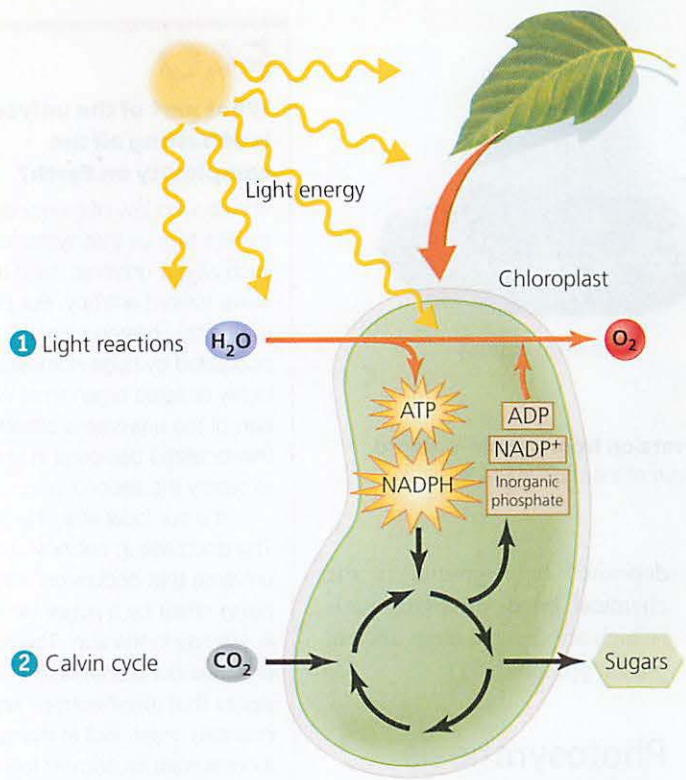


FIGURE 2.12 In photosynthesis, autotrophs such as plants, algae, and cyanobacteria use sunlight to convert water and carbon dioxide into oxygen and sugar. In the light reactions, water is converted to oxygen in the presence of sunlight, creating high-energy molecules (ATP and NADPH). These molecules help drive reactions in the Calvin cycle, in which carbon dioxide is used to produce sugars. Molecules of ADP, $NADP^+$, and inorganic phosphate formed in the Calvin cycle, in turn, help power the light reactions, creating an endless loop.

initiate a series of chemical reactions called the light reactions (**FIGURE 2.12**). During these reactions, 1 water molecules split, releasing electrons whose energy is used to produce high-energy molecules. A phosphate is added to the lower-energy molecule adenosine diphosphate (ADP) to form the higher-energy molecule adenosine triphosphate (ATP). A hydrogen ion and a pair of electrons convert the lower-energy molecule nicotinamide dinucleotide phosphate ($NADP^+$) into the higher-energy NADPH. ATP and NADPH are then used to fuel reactions in the Calvin cycle. During 2 the Calvin cycle, carbon atoms—from the carbon dioxide in air that enters the plant through its leaves—are linked together to produce sugars. In photosynthesis, plants draw up water from the ground through their roots, absorb carbon dioxide from the air through their leaves, and harness the power of sunlight with the light-absorbing pigment chlorophyll. With these ingredients, green plants create sugars for their growth and maintenance and, in turn, provide chemical energy to any organism that eats them. Plants also release oxygen as a by-product of photosynthesis, forming the oxygen gas in the air we breathe.

Photosynthesis is a complex process, but the overall reaction can be summarized with the following equation:

$$\underset{\text{(carbon dioxide)}}{6CO_2} + \underset{\text{(water)}}{6H_2O} + \text{the sun's energy} \longrightarrow \underset{\text{(sugar)}}{C_6H_{12}O_6} + \underset{\text{(oxygen)}}{6O_2}$$

The number preceding each molecular formula indicates how many of those molecules are involved in the reaction. Note that the sums of the numbers on each side of the equation for each element are equal; that is, there are 6 C, 12 H, and 18 O atoms on each side. This illustrates how chemical equations are balanced, with each atom recycled and matter conserved. No atoms are lost; they are simply rearranged among molecules.

Cellular respiration powers living things

Organisms make use of the chemical energy in sugars that they create by photosynthesis in a process called **cellular respiration,** which is vital to life. To release the chemical energy of glucose, cells use oxygen to convert glucose back into its original starting materials, water and carbon dioxide. The energy released during this process is used to power all the biochemical reactions that sustain life. The net equation for cellular respiration is the exact opposite of that for photosynthesis:

$$\underset{\text{(sugar)}}{C_6H_{12}O_6} + \underset{\text{(oxygen)}}{6O_2} \longrightarrow \underset{\text{(carbon dioxide)}}{6CO_2} + \underset{\text{(water)}}{6H_2O} + \text{energy}$$

However, the energy released per glucose molecule in respiration is only two-thirds of the energy input per glucose molecule in photosynthesis—a prime example of the second law of thermodynamics. Cellular respiration is a continuous process occurring in all living things and is essential to life. Thus, it occurs in the autotrophs that create glucose and also in **heterotrophs (consumers),** organisms that gain their energy by feeding on other organisms. Heterotrophs include most animals, as well as the fungi and microbes that decompose organic matter.

Geothermal energy also powers Earth's systems

Although the sun is life's primary energy source, it is not the only source of energy for our planet. An additional, although minor, energy source is the gravitational pull of the moon, which in conjunction with the sun's gravitational pull causes ocean tides (p. 429). Another significant energy source is geothermal heating emanating from inside Earth, powered primarily by radioactivity (p. 26). Radiation from radioisotopes deep inside our planet heats the inner Earth, and this heat gradually makes its way to the surface. There, it heats **magma** (rock heated to a molten, liquid state) that erupts from volcanoes and drives plate tectonics (p. 35).

Geothermal energy also powers biological communities. On the deep ocean floor, jets of geothermally heated water gush into the icy-cold depths. These hydrothermal vents can host entire communities of specialized organisms that thrive in the extreme high-temperature, high-pressure conditions.

Hydrothermal vents are so deep underwater that they completely lack sunlight, so the energy flow of these communities cannot be fueled through photosynthesis. Instead, bacteria in deep-sea vents use the chemical-bond energy of hydrogen sulfide (H_2S) to transform inorganic carbon into organic carbon compounds in a process called **chemosynthesis.** Chemosynthesis occurs in various ways, and one way is defined by the following equation:

$$\underset{\text{(carbon dioxide)}}{6CO_2} + \underset{\text{(water)}}{6H_2O} + \underset{\text{(hydrogen sulfide)}}{3H_2S} \longrightarrow \underset{\text{(sugar)}}{C_6H_{12}O_6} + \underset{\text{(sulfuric acid)}}{3H_2SO_4}$$

Energy from chemosynthesis passes through the deep-sea-vent animal community as consumers such as tubeworms, mussels, fish, shrimp, and gigantic clams gain nutrition from chemoautotrophic bacteria and one another.

Geology: The Physical Basis for Environmental Science

A good way to understand how our planet functions is to examine the rocks, soil, and sediments beneath our feet. The physical processes that take place at and below Earth's surface shape the landscape and lay the foundation for most environmental systems and for life.

The physical nature of our planet also benefits our society, because without the study of Earth's rocks and the processes that shape them, we would have no metals for consumer products, no energy from fossil fuels, and no uranium for nuclear power plants. Our planet is dynamic, and this dynamism is what motivates **geology,** the study of Earth's physical features, processes, and history. A human lifetime is just a blink of an eye in the long course of geologic time, and the Earth we experience is merely a snapshot in our changing planet's long history. We can begin to grasp this long-term dynamism as we consider two processes of fundamental importance—plate tectonics and the rock cycle.

Earth consists of layers

Our planet consists of multiple layers (**FIGURE 2.13**). At Earth's center is a dense **core** consisting mostly of iron, solid in the inner core and molten in the outer core. Surrounding the core is a thick layer of less dense, elastic rock called the **mantle.** A portion of the upper mantle called the **asthenosphere** contains especially soft rock, melted in some areas. The harder rock above the asthenosphere is the **lithosphere.** The lithosphere includes both the uppermost mantle and the entirety of Earth's third major layer, the **crust,** the thin, brittle, low-density layer of rock that covers Earth's surface. The intense heat in the inner Earth rises from core to mantle to crust, and it eventually dissipates at the surface.

The heat from the inner layers of Earth also drives convection currents that flow in loops in the mantle, pushing the mantle's soft rock cyclically upward (as it warms) and downward (as it cools), like a gigantic conveyor belt system. As the mantle material moves, it drags large plates of lithosphere along its surface. This movement is known as **plate tectonics,** a process of extraordinary importance to our planet.

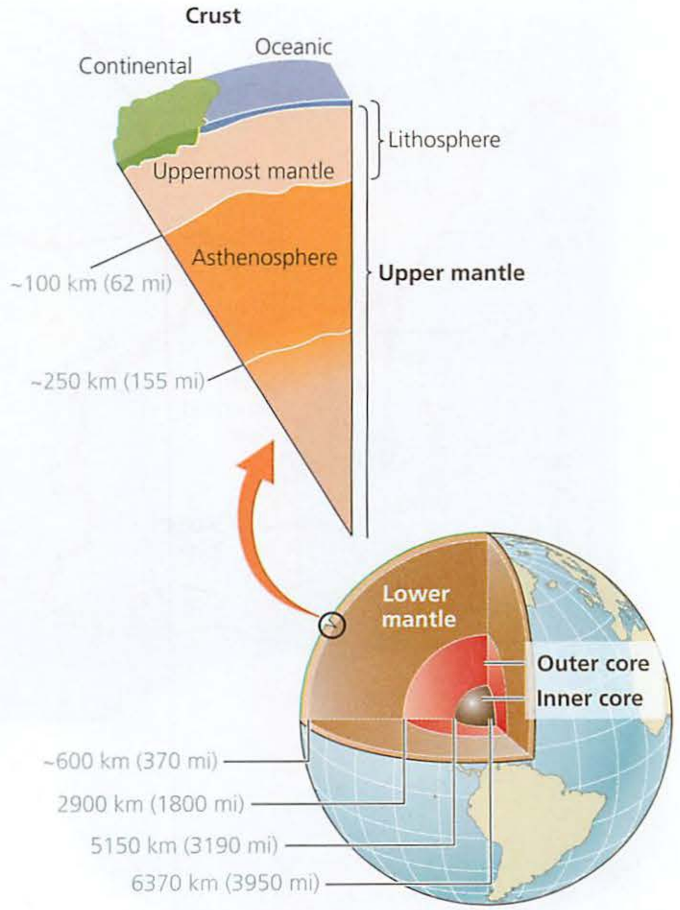


FIGURE 2.13 Earth's three primary layers—core, mantle, and crust—are themselves layered. The inner core of solid iron is surrounded by an outer core of molten iron, and the rocky mantle includes the molten asthenosphere near its upper edge. At Earth's surface, dense and thin oceanic crust abuts lighter, thicker continental crust. The lithosphere consists of the crust and uppermost mantle above the asthenosphere.

Plate tectonics shapes Earth's geography

Our planet's surface consists of about 15 major tectonic plates, which fit together like pieces of a jigsaw puzzle (**FIGURE 2.14**, p. 36). Imagine peeling an orange and then placing the pieces back onto the fruit; the ragged pieces of peel are like the lithospheric plates riding atop Earth's surface. However, the plates are thinner relative to the planet's size, more like the skin of an apple. These plates move at rates of roughly 2–15 cm (1–6 in.) per year. This slow movement has influenced Earth's climate and life's evolution throughout our planet's history as the continents combined, separated, and recombined in various configurations. By studying ancient rock formations throughout the world, geologists have determined that at least twice, all landmasses were joined together in a "supercontinent." Scientists have dubbed the landmass that resulted about 225 million years ago Pangaea (see the inset in Figure 2.14).

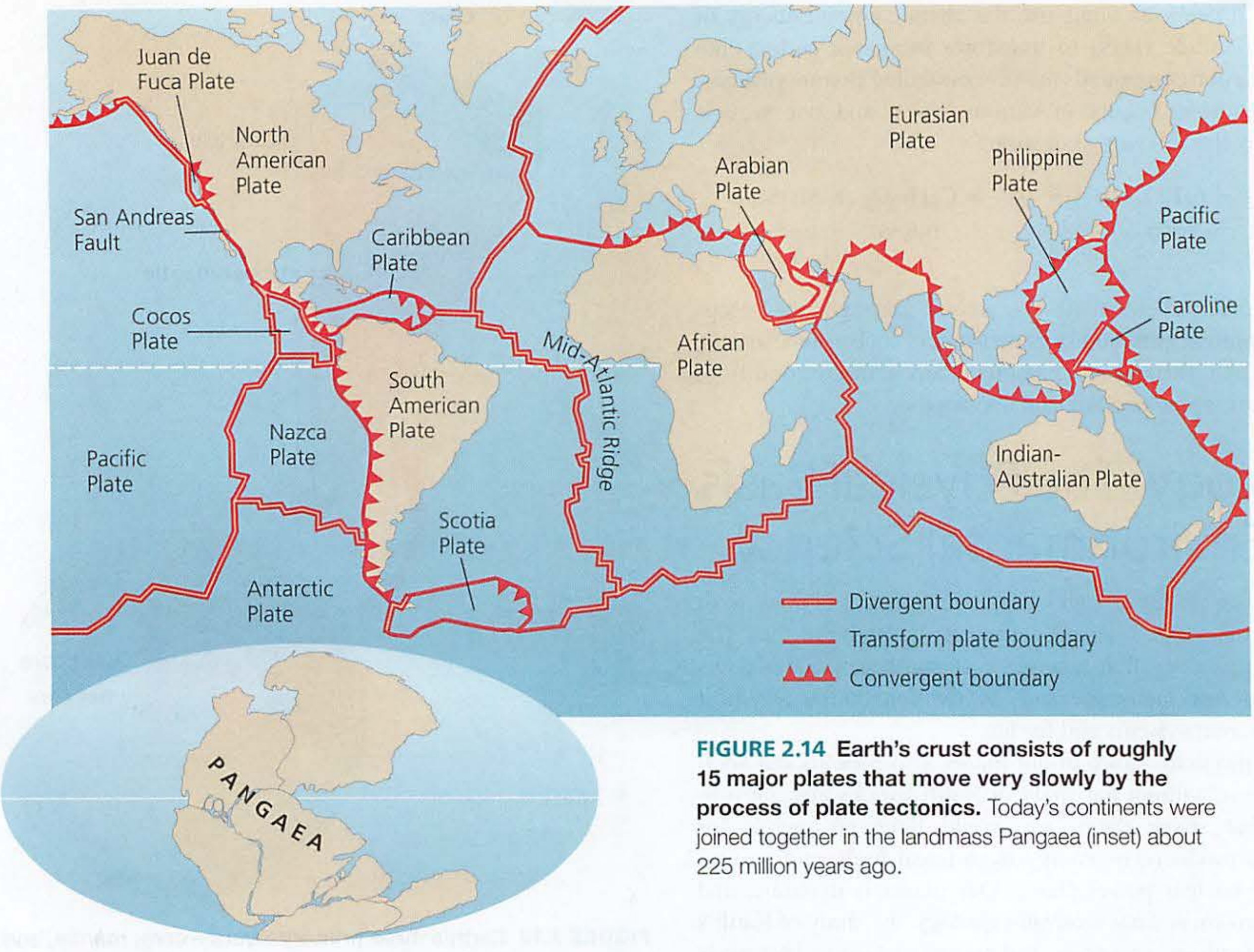


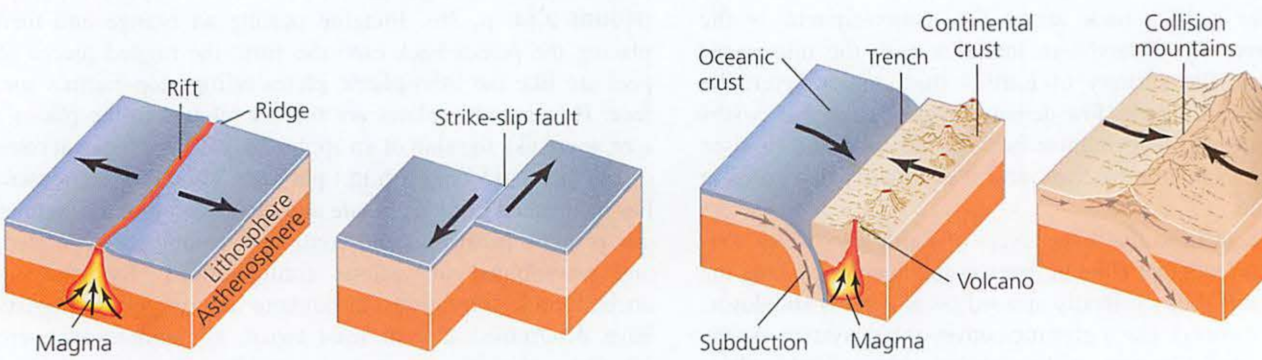
FIGURE 2.14 Earth's crust consists of roughly 15 major plates that move very slowly by the process of plate tectonics. Today's continents were joined together in the landmass Pangaea (inset) about 225 million years ago.

There are three types of plate boundaries

The processes that occur at each type of plate boundary all have major consequences.

At **divergent plate boundaries,** tectonic plates push apart from one another as magma rises upward to the surface, creating new lithosphere as it cools (**FIGURE 2.15a**). An example is the Mid-Atlantic Ridge, part of a 74,000-km (46,000-mi) system of divergent plate boundaries slicing across the floors of the world's oceans.

Where two plates meet, they may slip and grind alongside one another, forming a **transform plate boundary** (**FIGURE 2.15b**). This movement creates friction that generates earthquakes (p. 40) along strike-slip faults. The Tohuku earthquake, for example, occurred at such a fault off the eastern coast of Japan. Faults are fractures in Earth's crust, and at strike-slip faults, each landmass moves horizontally in opposite directions. The Pacific Plate and the North American Plate, for example, slide past one another along California's San Andreas Fault. Southern California is slowly inching its way northward along this fault, so the site of Los Angeles will



(a) Divergent plate boundary **(b) Transform plate boundary** **(c) Convergent plate boundaries**

FIGURE 2.15 There are three types of boundaries between tectonic plates, generating different geologic processes.

eventually—in about 15 million years or so—reach that of modern-day San Francisco.

Convergent plate boundaries, where two plates come together, can give rise to different outcomes (**FIGURE 2.15c**). As plates of newly formed lithosphere push outward from divergent plate boundaries, this oceanic lithosphere gradually cools, becoming denser. After millions of years, it becomes denser than the asthenosphere beneath it and dives downward into the asthenosphere in a process called **subduction.** As the lithospheric plate descends, it slides beneath a neighboring plate that is less dense, forming a convergent plate boundary. The subducted plate is heated and pressurized as it sinks, and water vapor escapes, helping to melt rock (by lowering its melting temperature). The molten rock rises, and this magma may erupt through the surface via volcanoes (p. 40).

When one plate of oceanic lithosphere is subducted beneath another plate of oceanic lithosphere, the resulting volcanism may form arcs of islands, such as Japan and the Aleutian Islands of Alaska. Subduction zones may also create deep trenches, such as the Mariana Trench, our planet's deepest abyss, located in the western Pacific Ocean. When oceanic lithosphere slides beneath continental lithosphere, volcanic mountain ranges form that parallel coastlines (Figure 2.15c, left). An example is South America's Andes Mountains, where the Nazca Plate slides beneath the South American Plate.

When two plates of continental lithosphere meet, the continental crust on both sides resists subduction and instead crushes together, bending, buckling, and deforming layers of rock from both plates in a **continental collision** (Figure 2.15c, right). Portions of the accumulating masses of buckled crust are forced upward as they are pressed together, and mountain ranges result. The Himalayas, the world's highest mountains, resulted from the Indian-Australian Plate's collision with the Eurasian Plate beginning 40–50 million years ago, and these mountains are still rising today as these plates converge.

Tectonics produces Earth's landforms

The processes of plate tectonics build mountains, shape the geography of oceans, islands, and continents, and give rise to earthquakes and volcanoes. The topography created by plate tectonic processes, in turn, shapes climate by altering patterns of rainfall, wind, ocean currents, heating, and cooling—all of which affect rates of weathering and erosion and the ability of plants and animals to inhabit different regions. Thus, the locations of biomes (pp. 94–101) are influenced by plate tectonics. Moreover, plate tectonics has affected the history of life's evolution; the convergence of landmasses into supercontinents such as Pangaea is thought to have contributed to widespread extinctions by reducing the area of species-rich coastal regions and by creating an arid continental interior with extreme temperature swings.

The rock cycle produces a diversity of rock types

Just as plate tectonics shows geology's dynamism on a large scale, the rock cycle shows it on a smaller one. We tend to think of rock as fairly solid stuff. Yet over geologic time, rocks and the minerals that make them up are heated, melted, cooled, broken down, and reassembled in a very slow process called the **rock cycle** (**FIGURE 2.16**).

A **rock** is any solid aggregation of minerals. A **mineral**, in turn, is any naturally occurring solid element or inorganic compound with a crystal structure, a specific chemical composition, and distinct physical properties. Understanding the rock cycle enables us to better appreciate the formation and conservation of soils, mineral resources, fossil fuels, groundwater sources, and other natural resources (all of which will be discussed in later chapters).

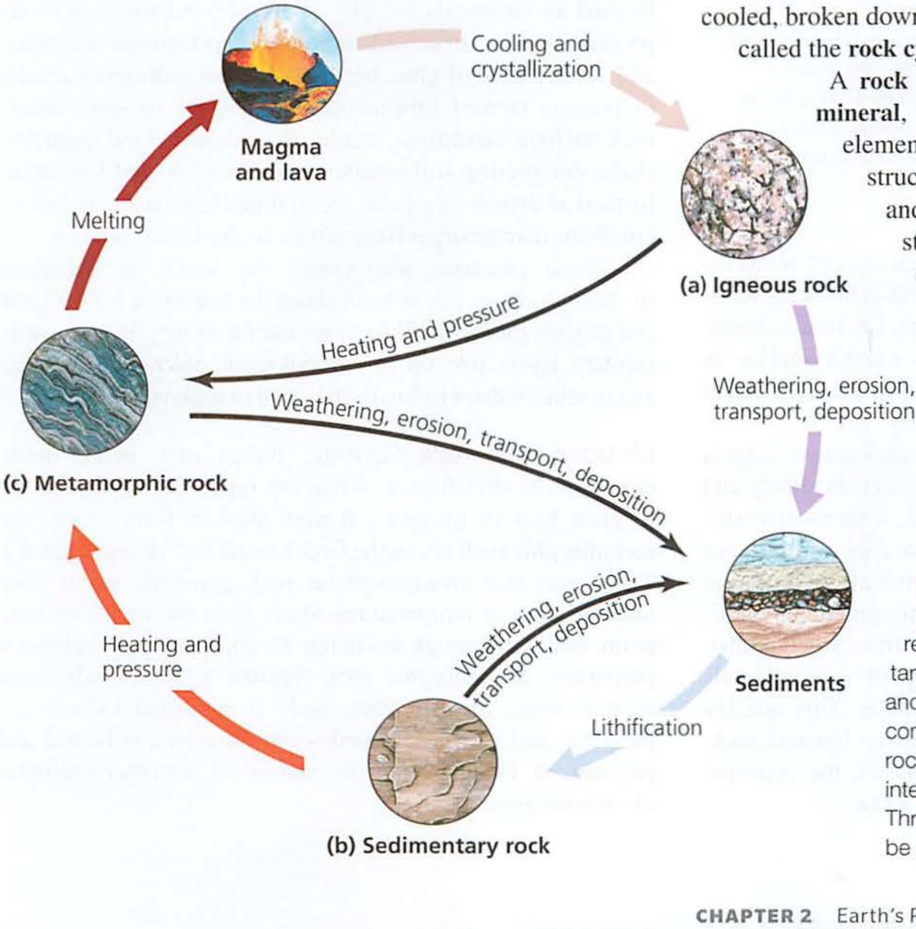
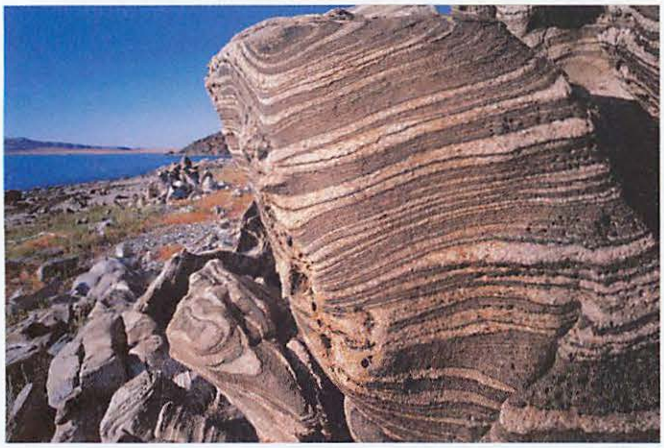


FIGURE 2.16 The rock cycle. Igneous rock **(a)** is formed when rock melts and the resulting magma or lava then cools. Sedimentary rock **(b)** is formed when rock is weathered and eroded, and the resulting sediments are compressed to form new rock. Metamorphic rock **(c)** is formed when rock is subjected to intense heat and pressure underground. Through these processes, each type of rock can be converted into either of the other two types.

(a) Extrusive igneous rock: Basalt in Japan

(b) Sedimentary rock: Sandstone in Arizona



(c) Metamorphic rock: Gneiss in Utah

FIGURE 2.17 Examples of rock types. The lava flows in Japan form basalt **(a),** a type of extrusive igneous rock. The layered formation in Paria Canyon, Arizona, is an example of sandstone **(b),** a type of sedimentary rock. Gneiss (pronounced "nice") **(c),** at Antelope Island, Utah, is a type of metamorphic rock.

Igneous rock All rocks can melt. At high enough temperatures, rock will enter the molten, liquid state called magma. If magma is released through the lithosphere (as in a volcanic eruption), it may flow or spatter across Earth's surface as **lava.** Rock that forms when magma or lava cools is called **igneous rock** (from the Latin *ignis*, meaning "fire").

Igneous rock comes in two main classes because magma can solidify in different ways. When magma cools slowly and solidifies while it is below Earth's surface, it forms intrusive igneous rock. Granite is the best-known type of intrusive rock. A slow cooling process allows minerals of different types to aggregate into large crystals, giving granite its multicolored, coarse-grained appearance. In contrast, when molten rock is ejected from a volcano, it cools quickly, so minerals have little time to grow into coarse crystals. This quickly cooled molten rock is classified as extrusive igneous rock, and its most common representative is basalt, the principal rock type of the Japanese islands (**FIGURE 2.17a**).

Sedimentary rock All exposed rock weathers away with time. The relentless forces of wind, water, freezing, and thawing eat away at rocks, stripping off one tiny grain (or large chunk) after another. Through weathering (p. 217) and erosion (pp. 229–230), particles of rock come to rest downhill, downstream, or downwind from their sources, forming **sediments.** Alternatively, some sediments form chemically from the precipitation of substances out of solution. Phosphates dissolved in ocean waters, for example, can precipitate out of the water as solids and settle to the ocean floor.

Over time, deep layers of sediment accumulate, causing the weight and pressure on the layers of sediment below them to increase. **Sedimentary rock** (**FIGURE 2.17b**) is formed as sediments are physically pressed together (compaction) and as dissolved minerals seep through sediments and act as a kind of glue, binding together sediment particles (a process termed lithification). Examples of sedimentary rock include sandstone, made of cemented sand particles; shale, comprising still smaller mud particles; and limestone, formed as dissolved calcite precipitates from water or as calcite from marine organisms settles to the ocean bottom.

These processes also create the fossils of organisms (p. 58), which we use to learn about the history of life on Earth and process for the fossil fuels we use for energy. Because sedimentary layers pile up in chronological order, scientists can assign relative dates to fossils they find in sedimentary rock.

Metamorphic rock Geologic forces may bend, uplift, compress, or stretch rock. When any type of rock is subjected to great heat or pressure, it may alter in form to become **metamorphic rock** (from the Greek word for "changed form"). The forces that metamorphose rock generally occur deep underground, at temperatures lower than the rock's melting point, but high enough to change its appearance and physical properties. Metamorphic rock (**FIGURE 2.17c**) includes rock such as slate, formed when shale is subjected to heat and pressure, and marble, formed when limestone is heated and pressurized. Gneiss, quartzite, and schist are other examples of metamorphic rocks.

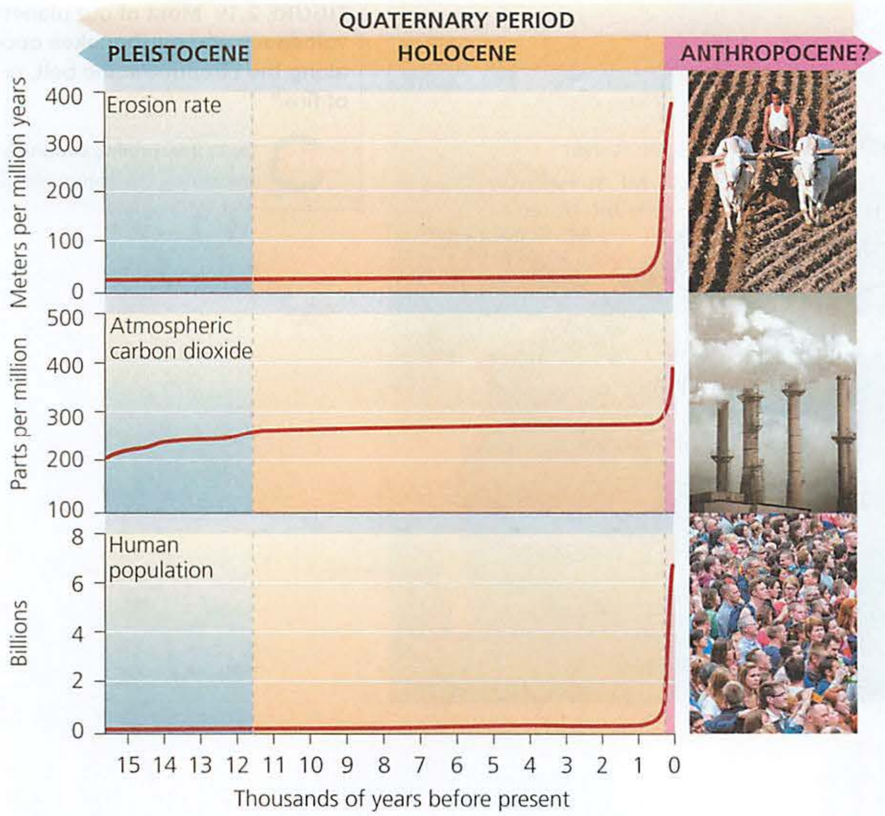


FIGURE 2.18 Global soil erosion rates (top) and atmospheric carbon dioxide concentrations (middle) have increased sharply in just the past few hundred years, along with human population (bottom). These patterns have persuaded some geologists that we should recognize a new epoch in Earth history: the Anthropocene.

Adapted from Zalasiewicz, J., et al., 2008. Are we now living in the Anthropocene? GSA Today *18(2): 4–8, Figure 1.*

Geologic processes occur across "deep time"

Geologic processes occur at timescales that are difficult to conceptualize. But perhaps it is only by appreciating the long time periods within which our planet's geologic forces operate that we can realize how exceedingly slow processes such as plate tectonics or the formation of sedimentary rock reshape our planet. This lengthy timescale is referred to as deep time, or geologic time.

The geologic timescale shows the full span of Earth's history—all 4.5 *billion* years of it—and focuses on the most recent 543 million years (**APPENDIX D**). Geologists have subdivided Earth's history into 3 eras and 11 periods. The Quaternary period, the most recent, occupies a thin slice of time at the top of the scale because this period began "only" 1.8 million years ago.

Geologists divide the geologic timescale using evidence from stratigraphy, the study of strata, or layers, of sedimentary rock. Where scientists find fossil evidence for major and sudden changes in the physical, chemical, or biological conditions present on Earth between one set of layers and the next, they assign a boundary between geologic time periods. For instance, fossil evidence for mass extinctions of species (pp. 60, 284) determines several boundaries, such as that between the Permian and Triassic periods.

We live in the Holocene epoch, the most recent slice of the Quaternary period. The Holocene epoch began about 11,500 years ago with a warming trend that melted glaciers and brought Earth out of its most recent ice age. Since then, Earth's climate has been remarkably constant, and this constancy provided our species with the long-term stability we needed to develop agriculture and civilization. However, since the industrial revolution, human activity has had major impacts on Earth's basic processes, including a sharp increase in soil erosion from clearing forests and cultivating land; an alteration in the composition of the atmosphere through emitting greenhouse gases, which elevates Earth's average temperature; and a recent explosion in human population, which has intensified all impacts on Earth. All these activities have set into motion a new mass extinction event (p. 285). These realizations led some geologists in 2000 to propose naming a new geologic era, encompassing the past 200 years, after ourselves—the Anthropocene (**FIGURE 2.18**).

Geologic and Natural Hazards

Plate tectonics shapes our planet, but the consequences of tectonic movement can also pose hazards to us. Earthquakes and volcanoes are examples of such geologic hazards. We can see how such hazards relate to tectonic processes by examining a map of the circum-Pacific belt, or "ring of fire" (**FIGURE 2.19**, p. 40). Ninety percent of earthquakes and over half of the world's volcanoes occur along this 40,000-km (25,000-mi) arc of subduction zones and fault systems. Like many locations along the circum-Pacific belt, Japan has experienced earthquakes and volcanism throughout its history.

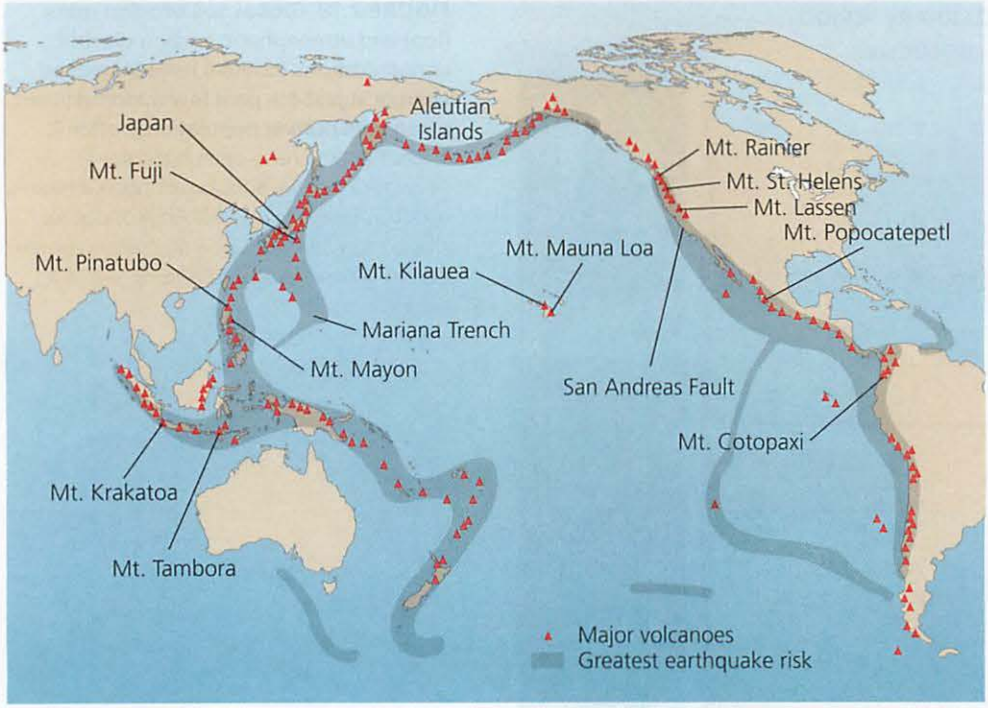


FIGURE 2.19 Most of our planet's volcanoes and earthquakes occur along the circum-Pacific belt, or "ring of fire."

DATA Go to **Interpreting Graphs & Data** on **Mastering Environmental Science**

Earthquakes result from movement at plate boundaries and faults

Along tectonic plate boundaries and in other places where faults occur, the earth may relieve built-up pressure in fits and starts. Each release of energy causes what we know as an **earthquake.** Most earthquakes are barely perceptible, but as shown by the Tohoku quake of 2011, they are occasionally powerful enough to cause significant losses of human life and property (**TABLE 2.2**). Earthquakes can also occur in the interior of tectonic plates, when faults are formed by continental plates being stretched and pulled apart by geologic forces within the earth. Such earthquakes are not only rare but also poorly understood. The New Madrid seismic zone, which lies beneath the lower Mississippi River basin in the central United States, is one area where such an "intraplate" earthquake may occur (**FIGURE 2.20**). And human activities may also induce earthquakes in areas far from the boundaries of tectonic plates by extracting substances from the earth or injecting liquids into underlying rock layers (see **THE SCIENCE BEHIND THE STORY**, pp. 42–43).

Volcanoes arise from rifts, subduction zones, or hotspots

Where molten rock, hot gas, or ash erupts through Earth's surface, a **volcano** is formed, often creating a mountain over time as cooled lava accumulates. As we have seen, lava can extrude along mid-ocean ridges or over subduction zones as one tectonic plate dives beneath another. Due to its position along subduction zones, Japan has more than 100 active volcanoes, which is 10% of the world total and more than any

TABLE 2.2 Examples of Large Earthquakes

YEAR	LOCATION	FATALITIES	MAGNITUDE[1]
1556	Shaanxi Province, China	830,000	~8
1755	Lisbon, Portugal	70,000[2]	8.7
1906	San Francisco, California	3000	7.8
1923	Kwanto, Japan	143,000	7.9
1964	Anchorage, Alaska	128[2]	9.2
1976	Tangshan, China	255,000+	7.5
1985	Michoacan, Mexico	9500	8.0
1989	Loma Prieta, California	63	6.9
1994	Northridge, California	60	6.7
1995	Kobe, Japan	5502	6.9
2004	Northern Sumatra	228,000[2]	9.1
2005	Kashmir, Pakistan	86,000	7.6
2008	Sichuan Province, China	50,000+	7.9
2010	Port-au-Prince, Haiti	236,000	7.0
2010	Maule, Chile	500	8.8
2011	Northern Japan	18,000[2]	9.0
2015	Kathmandu, Nepal	8900	7.8

[1]Measured by moment magnitude; each full unit is roughly 32 times as powerful as the preceding full unit.
[2]Includes deaths from the resulting tsunami.

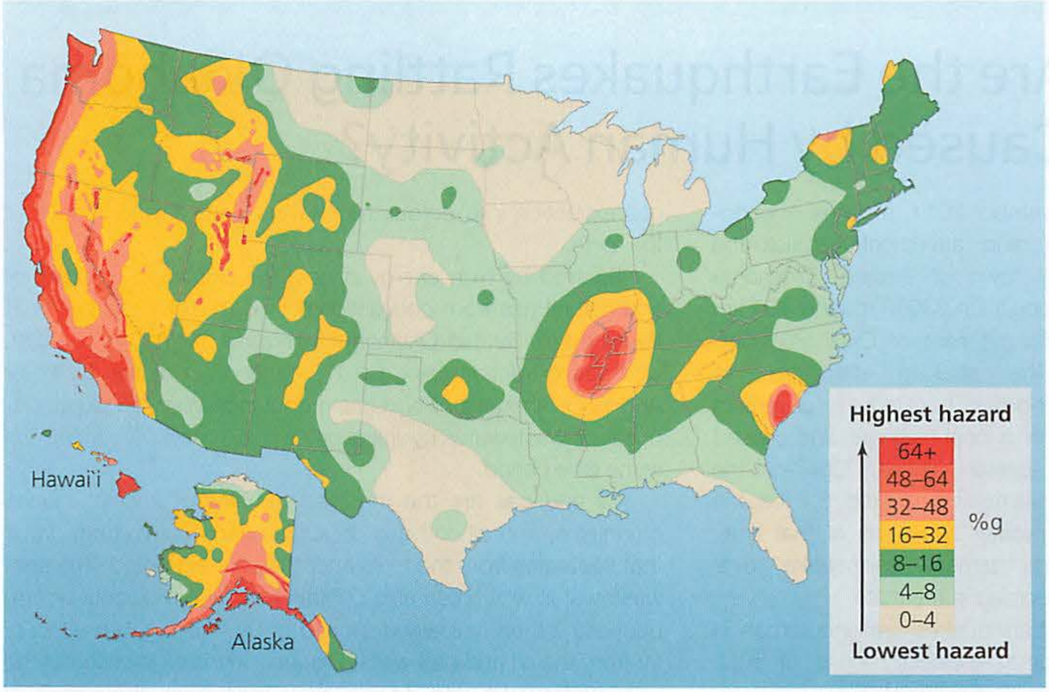
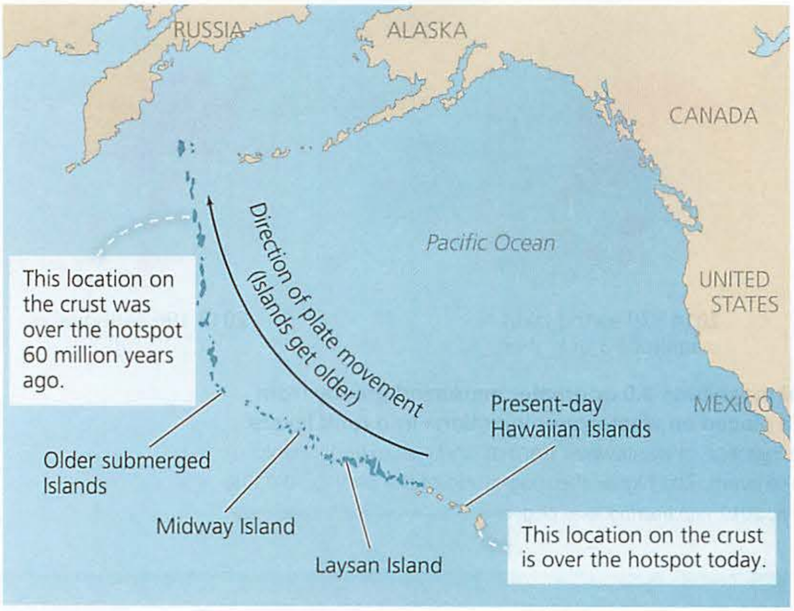


FIGURE 2.20 Many parts of the United States are at elevated risk for earthquakes. The West Coast faces threats from earthquakes due to its position at the boundary of tectonic plates. Portions of the continental interior have elevated risk due to naturally occurring intraplate earthquakes or human-induced earthquakes, typically from wastewater injection or hydraulic fracturing. The units for the figure are %g, a measure of acceleration related to the force of gravity. *Data from* U.S. Geological Survey.

other nation. Mount Fuji, one of Japan's most prominent and recognizable natural features, is one such active volcano.

Lava may also emit at hotspots, localized areas where plugs of molten rock from the mantle erupt through the crust. As a tectonic plate moves across a hotspot, repeated eruptions from this source may create a linear series of volcanoes. The Hawaiian Islands provide an example of this process (**FIGURE 2.21a**).

At some volcanoes, lava flows slowly downhill, such as at Mount Kilauea in Hawai'i (**FIGURE 2.21b**), which has been erupting continuously since 1983! At other times, a volcano may let loose large amounts of ash and cinder in a sudden explosion, such as during the 1980 eruption of Mount Saint Helens (Figure 17.10, p. 457). Very large eruptions can even alter Earth's climate, because the released ash blocks



(a) Current and former Hawaiian Islands, formed as crust moves over a volcanic hotspot

(b) Mt. Kilauea erupting

FIGURE 2.21 The Hawaiian Islands are the product of a hotspot on Earth's mantle. The Hawaiian Islands **(a)** have been formed by repeated eruptions from a hotspot of magma in the mantle as the Pacific Plate passes over the hotspot. The Big Island of Hawai'i was most recently formed, and it is still volcanically active. The other islands are older and have already begun eroding. To their northwest stretches a long series of former islands, now submerged. The active volcano Kilauea **(b)**, on the Big Island's southeast coast, is currently located above the edge of the hotspot.

THE SCIENCE **behind** the **story**

Are the Earthquakes Rattling Oklahoma Caused by Human Activity?

Geophysicist, Katie Keranen, Cornell University

In November 2011, a series of earthquakes and aftershocks struck the small town of Prague, Oklahoma (population 2300), roughly 100 km (60 mi) east of Oklahoma City. The shaking damaged 14 homes, buckled the pavement of a local highway, and caused several injuries. One of the tremors measured 5.7 on the Richter scale—as of that time, the largest earthquake ever recorded in the state.

Earthquakes are uncommon in Oklahoma, especially ones of such magnitude. But scientists were not completely surprised by the 2011 event, because they had already noted an increase in earthquake activity in the state (**FIGURE 1**). For example, between 1978 and 2008, Oklahoma experienced a yearly average of only about 1.5 earthquakes of 3.0 magnitude or greater. In 2009, that number rose to 20, and by 2016 it had jumped to 641. Scientists have even proposed an explanation for the increase—the injection of wastewater from oil and gas extraction into porous rock layers beneath the surface of the earth.

Spurred by high energy prices, the extraction of crude oil and natural gas from conventional wells (p. 530) and hydraulic fracturing (p. 390) in Oklahoma increased from 2010 to 2013, with gas extraction rising by 17% and oil extraction by 65%. And as Oklahoma's oil and gas output increased, so did its disposal of wastewater by injection, which rose 20% during the same time period.

Oil and gas are the modified remains of ancient marine organisms, and oil and gas deposits often contain briny water that separates from the fuels after they are extracted. The salty wastewater, which can also contain toxic and radioactive compounds, is then typically disposed of by trucking it to a facility far from the oil and gas wells. Disposal involves injection of the salty wastewater into porous rock formations thousands of feet underground, well below the more shallow rock layers that contain groundwater aquifers. This approach is designed to dispose of wastewater in a manner that prevents it from contaminating sources of drinking water, both aboveground and belowground.

Wastewater had been injected into the rocks beneath Oklahoma for decades without any measurable increase in seismic activity, but scientists were aware that continued pumping of wastewater into underground rock formations could lead to

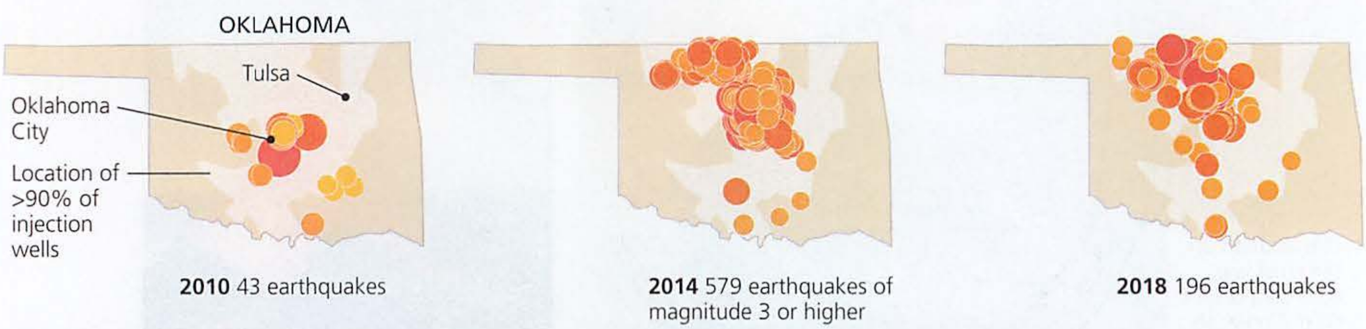


FIGURE 1 The number of earthquakes in Oklahoma of magnitude 3.0 or greater increased greatly from 2009 to 2015 and then declined once restrictions were placed on wastewater injections into rock layers. Many of these earthquakes are thought to be related to the injection of wastewater from oil and gas extraction into underground rock layers. Each circle indicates an earthquake event. The higher the magnitude of the earthquake, the darker and wider the circle. *Data from* Oklahoma Geological Survey, *2019, http://earthquakes.ok.gov/what-we-know/earthquake-map/.*

sunlight, and sulfur emissions lead to a sulfuric acid haze that blocks radiation and cools the atmosphere.

Sometimes a volcano can unleash a pyroclastic flow—a fast-moving cloud of toxic gas, ash, and rock fragments that races down the slopes at speeds up to 725 km/hr (450 mph), enveloping everything in its path. Such a flow buried the inhabitants of the ancient Roman cities of Pompeii and Herculaneum in A.D. 79, when Mount Vesuvius erupted.

One of the world's largest volcanoes—so large it is called a supervolcano—lies in the United States. The entire basin of earthquakes. As pores within underground rocks become saturated with water, pressure grows in the rocks, causing them to expand. The expanding rock, in turn, expands rock layers, which then push against existing faults in the earth, "lubricating" them and causing them to slip and produce earthquakes.

As seismic activity in Oklahoma increased, scientists grew more and more convinced that the phenomenon was due to wastewater injections. However, persuading legislators, regulators, and the public of the cause proved challenging. Oil and gas extraction is big business in Oklahoma. By some estimates, one in five jobs in the state is connected to the industry. Landowners benefit from royalties earned by fossil fuel extractions on their land. Tax revenue from sales of oil and gas is the state's third-largest revenue source—behind only sales taxes and personal income taxes. With such widespread economic benefits, the oil and gas industry enjoys high levels of support in Oklahoma government. When, following the Prague quake, calls arose to temporarily halt further wastewater injections, the state government urged a cautious approach and echoed the oil and gas industry's position that greater study was needed before decisive action should be taken.

Although the connection between underground fluid injection and earthquakes was well known, studies directly connecting specific events with injection sites were rare. A scientific study published in 2013 changed that, as it directly linked the Prague earthquake to nearby injections of wastewater from oil and gas extraction. The study, headed up by geophysicist Katie Keranen of the University of Oklahoma (now at Cornell University) and published in the journal *Geology*, measured the aftershocks produced by the 2011 earthquake to determine the location of the fault that produced the quake.

When that earthquake hit, researchers reacted quickly, deploying seismic sensors near Prague and gathered detailed readings on two major tremors and the 1183 aftershocks that followed. Analysis of the tremor patterns revealed that the cause was a rupture at the tip of a fault within about 200 m (650 ft) of an active wastewater-injection well at depths consistent with injected rock layers. Keranen's work also showed that it is possible for nearly two decades to pass between the initiation of wastewater injection and a subsequent seismic event, calling into question the safety of many other injection sites. A follow-up study led by Keranen found that earthquakes could be induced as far as 30 km (19 mi) from the fields of injection wells and concluded that up to 20% of the induced seismic activity over an area covering 2000 km^2 (770 mi^2) in the Central United States could be traced to the activity of four high-volume wastewater disposal wells in Oklahoma.

As research continued into the connection between wastewater injection and seismic activity, and the issue gained public attention, the state incrementally increased its regulation of wastewater injection wells. The government mandated regular monitoring of well pressures in injection sites and directed operators to slow injection rates or stop injections altogether if underground conditions were deemed conducive to initiating a seismic event. These actions led to lower levels of wastewater injection starting in 2016 and may have resulted in immediate relief, as the number of earthquakes of magnitude 3.0 or greater in Oklahoma dropped from 903 in 2015 to 623 in 2016, 304 in 2017, and 196 in 2018.

Although recent events seem to show progress in the efforts to reduce earthquakes in Oklahoma, research has shown that seismic activity is likely to occur in the state long after the practice has ceased, even in locations far from the fields of wastewater injection. Therefore, much like the U.S. West Coast with its well-known propensity for earthquakes, the South Central United States will be a hotbed for seismic study in the decades to come (**FIGURE 2**).

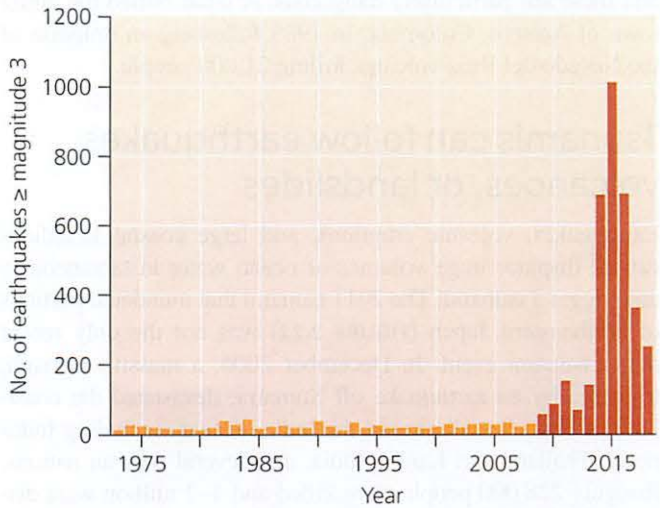


FIGURE 2 Larger earthquakes are becoming more common in the Central and Eastern United States. Much of the increase is centered in Oklahoma, where the local geology, coupled with the use of seismic-inducing activities, such as oil extraction and wastewater injection, has led to more frequent tremors. *Data from Rubinstein, J. L., and A. B. Mahani, 2015. Myths and facts on wastewater injection, hydraulic fracturing, enhanced oil recovery, and induced seismicity.* Seismol. Res. Lett. *86: 1–8 and* U.S. Geological Survey, *2016.*

DATA Go to **Interpreting Graphs & Data** on **Mastering Environmental Science**

Yellowstone National Park is an ancient supervolcano that has at times erupted so massively as to cover large parts of the continent deeply in ash. Although another eruption is not expected imminently, the region is still geothermally active, as evidenced by its numerous hot springs and geysers.

Landslides are a form of mass wasting

At a smaller scale than volcanoes and earthquakes, a **landslide** occurs when large amounts of rock or soil collapse and flow downhill. Landslides are a severe and often sudden

WEIGHING **the issues**

Assessing Your Risk from Natural Hazards

What types of natural hazards are likely to occur where you live? Name three actions you personally can take to minimize your risk from these hazards. If a natural disaster strikes, should people be allowed to rebuild in the same areas if those areas are prone to experience the hazard again? Should rebuilding costs be supported by taxpayer funds? Should insurance companies be required to insure the rebuilt structures?

manifestation of the phenomenon of **mass wasting,** the downslope movement of soil and rock due to gravity. Mass wasting occurs naturally, but often is brought about by human land use practices that expose or loosen soil, making slopes more prone to collapse.

Most often, mass wasting erodes unstable hillsides, damaging property one structure at a time. Occasionally, mass wasting events can be colossal and deadly; mudslides that followed the torrential rainfall of Hurricane Mitch in Nicaragua and Honduras in 1998 killed more than 11,000 people. Mudslides caused when volcanic eruptions melt snow and send huge volumes of destabilized mud racing downhill are called lahars, and these are particularly dangerous. A lahar buried the entire town of Armero, Colombia, in 1985 following an eruption of the Nevado del Ruiz volcano, killing 21,000 people.

Tsunamis can follow earthquakes, volcanoes, or landslides

Earthquakes, volcanic eruptions, and large coastal landslides can all displace huge volumes of ocean water instantaneously and trigger a tsunami. The 2011 tsunami that inundated portions of northeastern Japan (**FIGURE 2.22**) was not the only recent major tsunami event. In December 2004, a massive tsunami, triggered by an earthquake off Sumatra, devastated the coastlines of countries all around the Indian Ocean, including Indonesia, Thailand, Sri Lanka, India, and several African nations. Roughly 228,000 people were killed and 1–2 million were displaced. Since the 2004 tsunami, nations and international agencies have stepped up efforts to develop systems to give coastal residents advance warning of approaching tsunamis.

Those of us who live in the United States and Canada should not consider tsunamis to be something that occurs only in faraway places. Residents of the Pacific Northwest—such as the cities of Seattle, Washington, and Portland, Oregon—could be at risk if there is a slip in the Cascadia subduction zone that lies 1100 km (700 mi) offshore. The tsunami produced by such a slip would inundate 1.1 million km^2 (440,000 mi^2) of coastal land and cause massive destruction over an area that is currently home to over 7 million people.

We can worsen or lessen the impacts of natural hazards

Aside from geologic hazards, people face other types of natural hazards. Heavy rains can lead to flooding that ravages low-lying areas near rivers and streams (p. 403). Coastal erosion can eat away at beaches. Wildfire can threaten life and property in fire-prone areas. Tornadoes and hurricanes (p. 456) can cause extensive damage and loss of life.

Although we refer to such phenomena as "natural hazards," the magnitude of their impacts on us often depends on choices we make. We sometimes worsen the impacts of so-called natural hazards in various ways. For example, we choose to build homes and businesses in areas that are prone to hazards, such as the floodplains of rivers or in coastal areas susceptible to flooding. People also use and engineer the landscapes around us in ways that can increase the frequency or severity of natural hazards. Damming and diking rivers to control floods can sometimes lead to catastrophic flooding (p. 403), and the clear-cutting of forests on slopes (p. 320) can induce mass wasting and increase water runoff. Human-induced climate change (Chapter 18) can cause sea levels to rise and promote coastal flooding, and can increase the risks of drought, fire, flooding, and mudslides by altering precipitation patterns.

We can often reduce or lessen the impacts of hazards through the thoughtful use of technology, engineering, and policy, informed by a solid understanding of geology and ecology. Examples include building earthquake-resistant structures; designing early warning systems for earthquakes, tsunamis, and volcanoes; and conserving reefs and shoreline vegetation to protect against tsunamis and coastal erosion. In addition, better forestry, agriculture, and mining practices can help prevent mass wasting. Zoning regulations, building codes, and insurance incentives that discourage development in areas prone to landslides, floods, fires, and storm surges can help keep us out of harm's way. Finally, addressing global climate change may help reduce the frequency of natural hazards in many regions.

FIGURE 2.22 A man surveys the destruction caused by the Tohoku earthquake and tsunami in Japan in 2011. Ocean waters pushed miles inland in some locations, scouring everything in their path, and pulling debris out to sea as the waters receded.

CENTRAL CASE STUDY

connect & continue

TODAY, efforts persist at the Fukushima Daiichi power plant to secure the radioactive material that remains in the crippled reactors. Groundwater beneath the plant continues to be contaminated with radioactive isotopes and leaches into the nearby Pacific Ocean. On land, the government has scoured away the upper soil layers in highly contaminated areas near the power plant in an effort to reduce radioactivity levels. This soil is currently being stored in holding areas in large bags until a comprehensive disposal strategy can be determined. Bioremediation studies are being undertaken—many involving the use of plants or microbes—to find cost-effective ways to decontaminate soils in the region. The remediation efforts at the nuclear power plant and in the surrounding area are anticipated to cost over $112 billion and will take decades to complete. As radiation levels have declined, some of the evacuated areas around the Fukushima nuclear power plant have been reopened to residents. Few people appear interested in doing so, however, as only about 13% of those displaced have returned to their homes.

Opposition to the indefinite use of nuclear power in Japan still remains high, with some 90% of people expressing a desire to phase out the nation's use of nuclear power. But while, shortly after the accident, the government proposed fully eliminating Japan's use of nuclear power by 2040, it has since changed course and views nuclear power as a long-term source of power for the nation. At the time of this writing, 8 of the nation's 54 nuclear power reactors are back online and producing power after completing a recertification process. The Japanese government is also investing heavily in renewable energy and aims to produce, by 2030, nearly half of the nation's power from carbon-free or low-carbon sources of energy, which includes nuclear power.

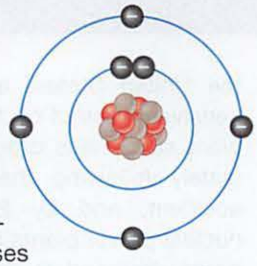
The nuclear meltdown at Fukushima also forced countries around the world to reassess the role of nuclear power in their societies. Some nations sought to eliminate their use of nuclear power altogether. Germany shut down half of its nuclear power plants and plans to decommission all its reactors by 2022. Switzerland opted to phase out the operation of its five nuclear reactors over the next 20 years. Other nations have chosen to continue their use of nuclear power but with added safeguards. In Japan, a new regulatory agency was formed to inspect and recertify nuclear power plants, as the regulatory apparatus in place before the accident had been criticized for being too closely affiliated with the power companies it was tasked to regulate. In the United States, a comprehensive review of nuclear power plant safety was ordered immediately following the Fukushima accident, and by 2019, all U.S. nuclear power plants had met new standards designed to make domestic nuclear power plants less susceptible to events like those that caused the meltdown in Fukushima.

As we have seen, the legacy of the Tohoku earthquake and nuclear meltdown at Fukushima Daiichi may be very different from one nation to the next. But one common thread is that our world contains natural geologic hazards, such as earthquakes and tsunamis, as well as hazards posed by human activities, such as nuclear power. And although we cannot ever fully eliminate hazards, we can certainly lessen their potential impacts by thinking carefully about what we build, where we build it, and what we will do should a disaster strike.

- **CASE STUDY SOLUTIONS** Imagine that you live in a coastal community in a region prone to earthquakes and you are a board member of your regional electrical utility. The utility is considering constructing a nuclear power plant 10 miles up the coast from your town. Some of your fellow citizens support the project because it will bring employment to the region and provide a carbon-free source of electricity. However, some residents fear a repeat of the events of 2011 in northeastern Japan if there should be a significant earthquake along one of the onshore or offshore faults. List three specific pieces of information that you would insist on obtaining from geologists and other scientists before casting your vote on the project.
- **LOCAL CONNECTIONS** Nuclear power has both risks and benefits, and people's opinions on its use can differ greatly. Informally interview at least 10 people—friends, family members, or classmates—and solicit their view on the role that nuclear power should play in future U.S. energy production. Should we increase our nation's use of nuclear power, reduce it, or ban it completely? Will people's opinions likely change if a new nuclear power plant is proposed for construction nearby their community?
- **EXPLORE THE DATA** Did the nuclear meltdown in Japan affect energy production from nuclear power in the years since the accident? → **Explore Data** relating to the case study on **Mastering Environmental Science.**

REVIEWING **Objectives**

You should now be able to:



+ **Explain the fundamentals of matter and chemistry, and apply them to real-world situations.**

  Everything in the universe that has mass and occupies space is matter, which can neither be created nor destroyed. Matter comprises atoms and elements, and changes at the atomic level can result in alternate forms of elements, such as ions and isotopes. Atoms bond with one another to form molecules and compounds and are conserved in such reactions. Carbon-based organic compounds are particularly important because they are the building blocks of life and provide energy in the form of fossil fuels (pp. 25–29).

+ **Differentiate among forms of energy, and explain the first and second laws of thermodynamics.**

  Energy is the capacity to change the position, physical composition, or temperature of matter. Energy can convert from one form to another—for instance, from potential to kinetic energy, and vice versa—and, like matter, energy is conserved during conversions (the first law of thermodynamics). Systems tend to increase in entropy, or disorder, unless energy is added to build or maintain order and complexity (the second law of thermodynamics) (pp. 30–33).

+ **Distinguish photosynthesis, cellular respiration, and chemosynthesis, and summarize their importance to living things.**

  In photosynthesis, autotrophs use carbon dioxide, water, and solar energy to produce oxygen and chemical energy in sugars. In cellular respiration, organisms extract energy from sugars by converting the sugars, in the presence of oxygen, into carbon dioxide and water. Organisms use the energy to combat entropy and sustain life. In chemosynthesis, specialized autotrophs use carbon dioxide, water, and chemical energy from minerals (instead of energy from sunlight) to produce sugars (pp. 33–35).

+ **Explain how plate tectonics and the rock cycle shape the landscape around us.**

  The crust of our planet is modified by plate tectonics, which shapes Earth's physical geography and produces earthquakes and volcanoes. On a smaller scale, the rock cycle is the mechanism whereby rocks transform from one type to another (pp. 35–39).

+ **Identify major types of geologic hazards, and describe ways to minimize their impacts.**

  Volcanoes, earthquakes, mass wasting, and tsunamis are all natural geologic hazards that affect people and the environment. We can minimize the impact of geologic hazards by making informed decisions about where and how to build (establishing strict zoning regulations and engineering codes within our communities) and by ensuring that our public officials make sound policy decisions when global climate change is a factor (pp. 39–44).

SEEKING **Solutions**

1. Think of an example of an environmental problem not mentioned in this chapter. How could chemistry help us address the problem?
2. Think about the ways we harness and use energy sources in our society—both renewable sources, such as solar energy, and nonrenewable sources, such as coal, oil, and natural gas. What implications does the first law of thermodynamics have for our energy usage? How is the second law of thermodynamics relevant to our use of energy?
3. Consider rising carbon dioxide levels in the atmosphere and their impact on global climate change (Chapter 18) and then refer to the chemical reactions for photosynthesis and respiration. Provide an argument for why increasing amounts of carbon dioxide in the atmosphere might potentially increase amounts of oxygen in the atmosphere. Now give an argument for why increasing amounts of carbon dioxide might potentially decrease amounts of atmospheric oxygen. What would you need to know to determine which of these two outcomes might occur?
4. Describe how plate tectonics accounts for the formation of (a) mountains, (b) volcanoes, and (c) earthquakes.
5. **THINK IT THROUGH** You serve as city manager and have been asked to develop basic emergency plans for your city in case of natural disaster. For each of the following natural hazards, describe one thing that you would recommend the city do to minimize the impact of such a hazard on lives and property: (a) earthquakes, (b) landslides, (c) flooding.

CALCULATING **Ecological Footprints**

The second law of thermodynamics has profound implications for human impacts on the environment, as it affects the efficiency with which we produce our food. In ecological systems, a general rule of thumb is that when energy is transferred from plants to plant-eaters or from prey to predator, efficiency is only about 10% (p. 82). Much of this low efficiency is a consequence of the second law of thermodynamics, as some energy is lost to entropy with each transfer. Another way to think of this low efficiency is that eating 1 Calorie of meat from an animal is the ecological equivalent of eating 10 Calories of plant material. So, when we raise animals for meat using grain, it is less energetically efficient than if we ate the grain directly.

Humans are considered omnivores because we can eat both plants and animals. The choices we make about what to eat have significant ecological consequences. With this in mind, calculate the ecological energy requirements for five different diets, each of which provides a total of 2000 dietary Calories per day.

DIET	SOURCE OF CALORIES	NUMBER OF CALORIES CONSUMED	ECOLOGICALLY EQUIVALENT CALORIES	TOTAL ECOLOGICALLY EQUIVALENT CALORIES
100% plant 0% animal	Plant Animal			
90% plant 10% animal	Plant Animal	1800 200	1800 2000	3800
50% plant 50% animal	Plant Animal			
70% plant 30% animal	Plant Animal			
0% plant 100% animal	Plant Animal			

1. How many ecologically equivalent Calories would it take to support you for a year for each of the five diets listed?
2. How does the ecological impact from a diet consisting strictly of animal products (e.g., dairy products, eggs, and meat) compare with that of a strictly vegetarian diet? How many additional ecologically equivalent Calories do you consume each day by including as little as 10% of your Calories from animal sources?
3. What percentages of the Calories in your own diet do you think come from plant versus animal sources? Estimate the ecological impact of your diet, relative to a strictly vegetarian one.
4. List the major factors influencing your current diet (e.g., financial considerations, convenience, access to groceries, taste preferences). Do you envision your diet's distribution of plant and animal Calories changing in the near future? Why or why not?

Mastering Environmental Science

Students Go to **Mastering Environmental Science** for assignments, an interactive e-text, and the Study Area with practice tests, videos, and activities.

Instructors Go to **Mastering Environmental Science** for automatically graded activities, videos, and reading questions that you can assign to your students, plus Instructor Resources.