We will also introduce you to a geologist's view of time. You will think about time differently as you begin to comprehend the immense span of geologic history. Earth and the other planets in our solar system formed about 4.5 billion years ago. More than 3 billion years ago, living cells developed on Earth's surface, and life has been evolving ever since. Yet our human origins date back only a few million years—less than a tenth of a percent of Earth's existence. The decades of individual lives or even the thousands of years of recorded human history are inadequate to study Earth's long existence.

The Scientific Method

The term *geology* (from the Greek words for "Earth" and "knowledge") was coined by scientific philosophers more than 200 years ago to describe the study of rock formations and fossils. Through careful observations and reasoning, their successors developed the theories of biological evolution, continental drift, and plate tectonics—major topics of this textbook. Today, **geology** identifies the branch of Earth science that studies all aspects of the planet: its history, its composition and internal structure, and its surface features.

The goal of geology—and of science in general—is to explain the physical universe. Scientists believe that physical events have physical explanations, even if they may be beyond our present capacity to understand them. The **scientific method,** on which all scientists rely, is the general procedure for discovering how the universe works through systematic observations and experiments. Using the scientific method to make new discoveries and to confirm old ones is the process of *scientific research* (**Figure 1.1**).

When scientists propose a *hypothesis*—a tentative explanation based on data collected through observations and experiments—they present it to the community of scientists for criticism and repeated testing. A hypothesis is supported if it explains new data or predicts the outcome of new experiments. A hypothesis that is confirmed by other scientists gains credibility.

Here are four interesting scientific hypotheses we will encounter in this textbook:

- Earth is billions of years old.
- Coal is a rock formed from dead plants.
- Earthquakes are caused by the breaking of rocks along geologic faults.
- The burning of fossil fuels is causing global warming.

The first hypothesis agrees with the ages of thousands of ancient rocks as measured by precise laboratory techniques, and the next two hypotheses have also been confirmed by many independent observations. The fourth hypothesis has been more controversial, though so many new data support it that most scientists now accept it as true (see Chapters 15 and 23).

FIGURE 1.1 ■ Scientific research is the process of discovery and confirmation through observations of the real world. These geologists are researching soil samples near a lake in Minnesota. [USGS.]

A coherent set of hypotheses that explains some aspect of nature constitutes a *theory.* Good theories are supported by substantial bodies of data and have survived repeated challenges. They usually obey *physical laws*, general principles about how the universe works that can be applied in almost every situation, such as Newton's law of gravity.

Some hypotheses and theories have been so extensively tested that all scientists accept them as true, at least to a good approximation. For instance, the theory that Earth is nearly spherical, which follows from Newton's law of gravity, is supported by so much experience and direct evidence (ask any astronaut) that we take it to be a fact. The longer a theory holds up to all scientific challenges, the more confidently it is held.

Yet theories can never be considered completely proved. The essence of science is that no explanation, no matter how believable or appealing, is closed to questioning. If convincing new evidence indicates that a theory is wrong, scientists will discard it or modify it to account for the data. A theory, like a hypothesis, must always be testable; any proposal about the universe that cannot be evaluated by observing the natural world should not be called a scientific theory.

For scientists engaged in research, the most interesting hypotheses are often the most controversial, rather than the most widely accepted. The hypothesis that fossil-fuel burning causes global warming has been widely debated. Because the long-term predictions of this hypothesis are so important, many Earth scientists are now vigorously testing it.

Knowledge based on many hypotheses and theories can be used to create a *scientific model*—a precise representation of how a natural process operates or how a natural system behaves. Scientists combine related ideas in a model to test the consistency of their knowledge and to make predictions. Like a good hypothesis or theory, a good model makes predictions that agree with observations.

A scientific model is often formulated as a computer program that simulates the behavior of a natural system through numerical calculations. The forecast of rain or sunshine you may see on TV tonight comes from a computer model of the weather. A computer can be programmed to simulate geologic phenomena that are too big to replicate in a laboratory or that operate over periods of time that are too long for humans to observe. For example, models used for predicting weather have been extended to predict climate changes decades into the future.

To encourage discussion of their ideas, scientists share those ideas and the data on which they are based. They present their findings at professional meetings, publish them in professional journals, and explain them in informal conversations with colleagues. Scientists learn from one another's work as well as from the discoveries of the past. Most of the great concepts of science, whether they emerge as a flash of insight or in the course of painstaking analysis, result from untold numbers of such interactions. Albert Einstein put it this way: "In science . . . the work of the individual is so bound up with that of his scientific predecessors and contemporaries that it appears almost as an impersonal product of his generation."

Because such free intellectual exchange can be subject to abuses, a code of ethics has evolved among scientists. Scientists must acknowledge the contributions of all others on whose work they have drawn. They must not falsify data, use the work of others without recognizing them, or be otherwise deceitful in their work. They must also accept responsibility for training the next generation of researchers and teachers. These principles are supported by the basic values of scientific cooperation, which a president of the National Academy of Sciences, Bruce Alberts, has aptly described as "honesty, generosity, a respect for evidence, openness to all ideas and opinions."

■ Geology as a Science

In the popular media, scientists are often portrayed as people who do experiments wearing white coats. That stereotype is not inappropriate: many scientific problems are best investigated in the laboratory. What forces keep atoms together? How do chemicals react with one another? Can viruses cause cancer? The phenomena that scientists observe to answer such questions are sufficiently small and happen quickly enough to be studied in the controlled environment of the laboratory.

The major questions of geology, however, involve processes that operate on much larger and longer scales. Controlled laboratory measurements yield critical data for testing geologic hypotheses and theories—the ages and properties of rocks, for instance—but they are usually insufficient to solve major geologic problems. Almost all of the great discoveries described in this textbook were made by observing Earth processes in their uncontrolled, natural environment.

For this reason, geology is an outdoor science with its own particular style and outlook. Geologists "go into the field" to observe nature directly (**Figure 1.2**). They learn how mountains were formed by climbing up steep slopes and examining the exposed rocks, and they deploy sensitive instruments to collect data on earthquakes, volcanic eruptions, and other activity within the solid Earth. They discover how ocean basins have evolved by sailing rough seas to map the ocean floor (**Figure 1.3**).

FIGURE 1.2 ■ Geology is principally an outdoor science. Here, Peter Gray welds one of the five Global Positioning System stations placed on the flanks of Mount St. Helens. The stations will monitor the changing shape of the land surface as molten rock moves upward within the volcano. [USGS/Lyn Topinka.]

FIGURE 1.3 ■ The research crew from the icebreaker Louis S. St-Laurent, lowers a corer that will gather mud and sediment from the ocean floor. [AP Photo/The Canadian Press, Jonathan Hayward.]

Geology is closely related to other areas of Earth science, including *oceanography,* the study of the oceans; *meteorology,* the study of the atmosphere; and *ecology,* which concerns the abundance and distribution of life. *Geophysics, geochemistry,* and *geobiology* are subfields of geology that apply the methods of physics, chemistry, and biology to geologic problems (**Figure 1.4**).

Geology is a *planetary science* that uses remote sensing devices, such as instruments mounted on Earth-orbiting spacecraft, to scan the entire globe (**Figure 1.5**). Geologists develop computer models that can analyze the huge quantities of data amassed by satellites to map the continents, chart the motions of the atmosphere and oceans, and monitor how our environment is changing.

A special aspect of geology is its ability to probe Earth's long history by reading what has been "written in stone." The **geologic record** is the information preserved in the rocks that have been formed at various times throughout Earth's history (**Figure 1.6**). Geologists decipher the geologic record by combining information from many kinds of work: examination of rocks in the field; careful mapping of their positions relative to older and younger rock formations; collection of representative samples; and determination of their ages using sensitive laboratory instruments (Figure 1.4b).

(a)

(b)

(c)

FIGURE 1.4 ■ A number of subfields contribute to the study of geology. (a) Geophysicists deploy instruments to measure the underground activity of a volcano. (b) A geochemist readies a rock sample for analysis by a mass spectrometer. (c) Geobiologists investigate underground life inside Spider Cave at Carlsbad Caverns, New Mexico. [(a) Hawaiian Volcano Observatory/USGS; (b) John McLean/Science Source; (c) AP Photo/Val Hildreth-Werker.]

FIGURE 1.5 ■ An astronaut checks out instrumentation for monitoring Earth's surface. [StockTrek/SuperStock.]

In *Annals of the Former World,* a compendium of colorful stories about geologists, the popular writer John McPhee offers his view of how geologists bring field and laboratory observations together to visualize the big picture:

They look at mud and see mountains, in mountains oceans, in oceans mountains to be. They go up to some rock and figure out a story, another rock, another story, and as the stories compile through time they connect—and long case histories are constructed and written from interpreted patterns of clues. This is detective work on a scale unimaginable to most detectives, with the notable exception of Sherlock Holmes.

The geologic record tells us that, for the most part, the processes we see in action on Earth today have worked in much the same way throughout the geologic past. This important concept is known as the **principle of uniformitarianism.** It was stated as a scientific hypothesis in the eighteenth century by a Scottish physician and geologist, James Hutton. In 1830, the British geologist Charles Lyell summarized the concept in a memorable line: "The present is the key to the past."

The principle of uniformitarianism does not mean that all geologic phenomena proceed at the same gradual pace. Some of the most important geologic processes happen as sudden events. A large meteorite that impacts Earth can gouge out a vast crater in a matter of seconds. A volcano can blow its top, and a fault can rupture the ground in an earthquake, almost as quickly. Other processes do occur much more slowly. Millions of years are required for continents to drift apart, for mountains to be raised and eroded, and for river systems to deposit thick layers of sediments. Geologic processes take place over a tremendous range of scales in both space and time (**Figure 1.7**).

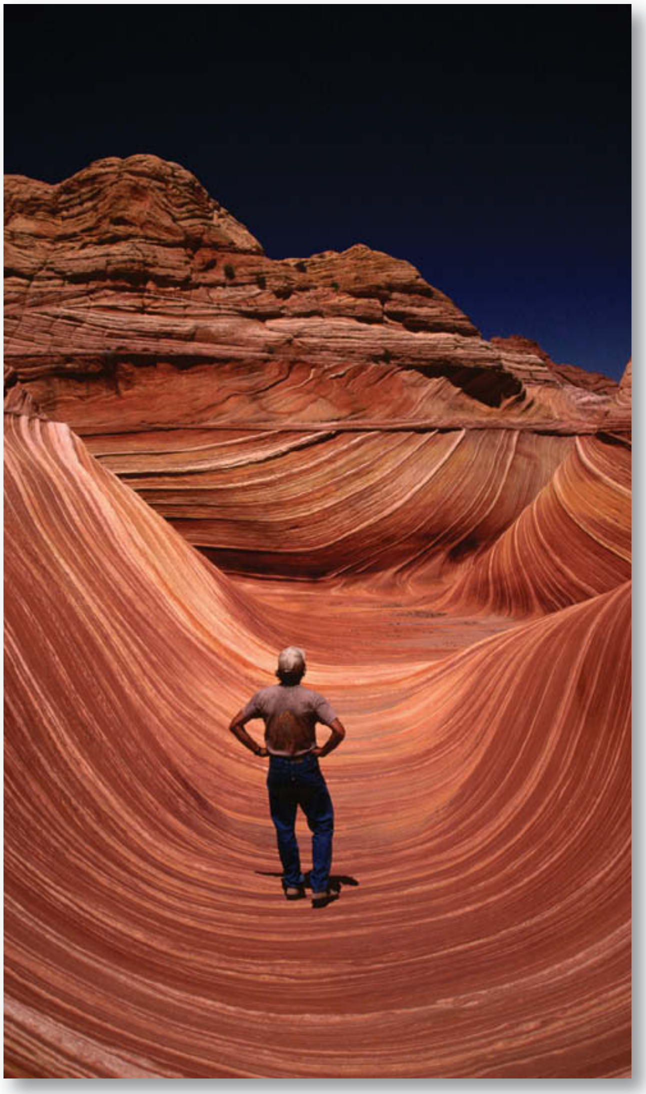


FIGURE 1.6 ■ The geologic record preserves evidence of Earth's long history. These multicolored layers of sand at Colorado National Monument were deposited more than 200 million years ago, when this part of the western United States was a vast Sahara-like desert. They were subsequently overlain by other rocks, welded by pressure into sandstone, uplifted by mountain-building events, and eroded by wind and water into today's stunning landforms. [Mark Newman/Lonely Planet Images/Getty Images, Inc.]

Nor does the principle of uniformitarianism mean that we have to observe a geologic event to know that it is important in the current Earth system. Humans have not witnessed a large meteorite impact in recorded history, but we know these impacts have occurred many times in the geologic past and will certainly happen again. The same

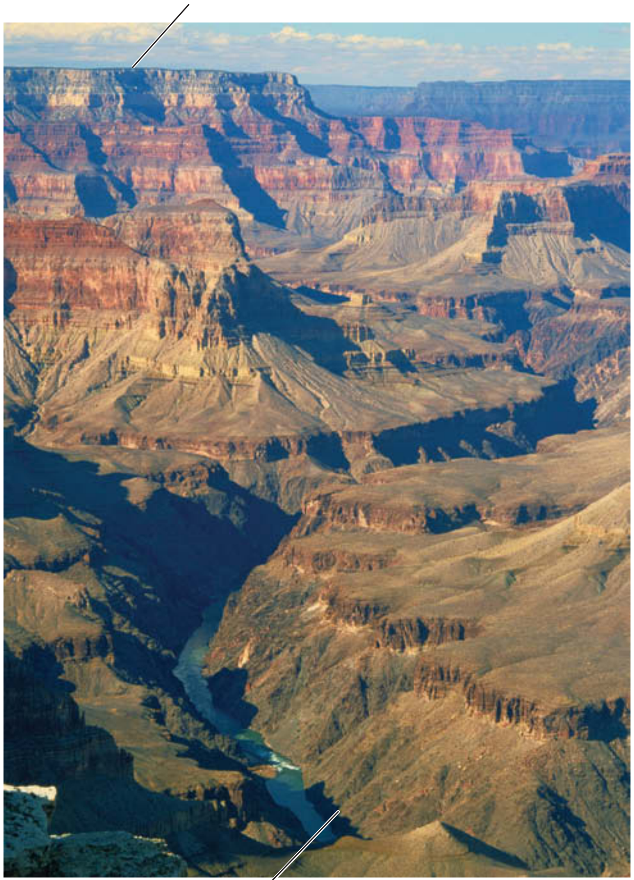


FIGURE 1.7 ■ Some geologic processes take place over thousands of centuries, while others occur with dazzling speed. (a) The Grand Canyon, Arizona. (b) Meteor Crater, Arizona. [(a) John Wang/PhotoDisc/Getty Images; (b) John Sanford/Science Source.]

can be said of the vast volcanic outpourings that have covered areas bigger than Texas with lava and poisoned the global atmosphere with volcanic gases. The long history of Earth is punctuated by many such extreme, though infrequent, events that result in rapid changes in the Earth system. Geology is the study of *extreme events* as well as gradual change.

From Hutton's day onward, geologists have observed nature at work and used the principle of uniformitarianism to interpret features found in rock formations. This approach has been very successful. However, Hutton's principle is too confining for geologic science as it is now practiced. Modern geology must deal with the entire range of Earth's history, which began more than 4.5 billion years ago. As we will see in Chapter 9, the violent processes that shaped Earth's early history were distinctly different from those that operate today. To understand that history, we will need some information about Earth's shape and surface, as well as its deep interior.

■ Earth's Shape and Surface

The scientific method has its roots in **geodesy,** a very old branch of Earth science that studies Earth's shape and surface. The concept that Earth is spherical rather than flat was advanced by Greek and Indian philosophers around the sixth century B.C., and it was the basis of Aristotle's theory of Earth put forward in his famous treatise, *Meteorologica,* published around 330 B.C. (the first Earth science

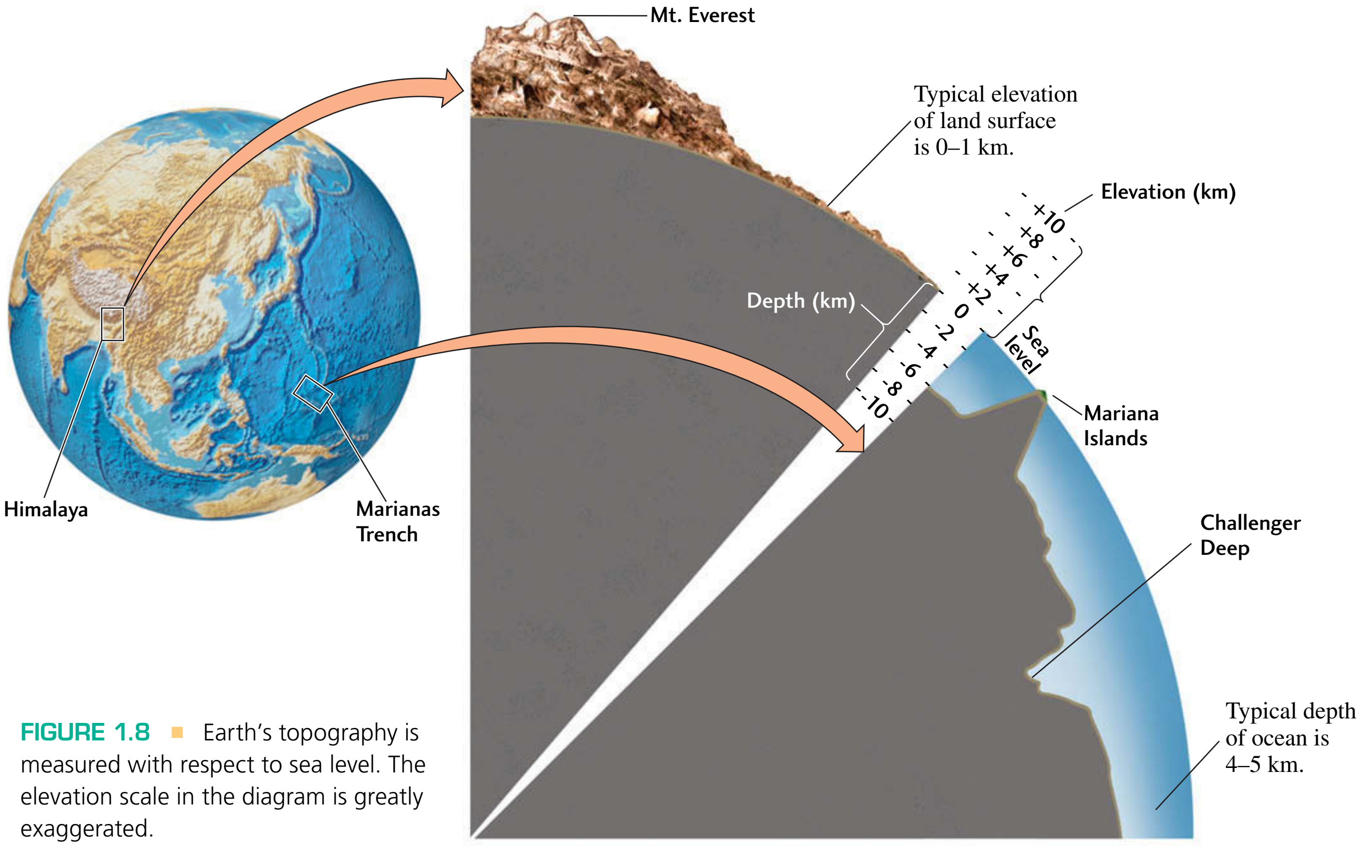


FIGURE 1.8 ■ Earth's topography is measured with respect to sea level. The elevation scale in the diagram is greatly exaggerated.

textbook!). In the third century B.C., Eratosthenes used a clever experiment to measure Earth's radius, which turned out to be 6370 km (see the Practicing Geology exercise at the end of the chapter).

Much more precise measurements have shown that Earth is not a perfect sphere. Because of its daily rotation, it bulges out slightly at its equator and is slightly squashed at its poles. In addition, the smooth curvature of Earth's surface is broken by mountains and valleys and other ups and downs. This **topography** is measured with respect to *sea level,* a smooth surface set at the average level of ocean water that conforms closely to the squashed spherical shape expected for the rotating Earth. Many features of geologic significance stand out in Earth's topography (**Figure 1.8**). Its two largest features are continents, which have typical elevations of 0 to 1 km above sea level, and ocean basins, which have typical depths of 4 to 5 km below sea level. The elevation of Earth's surface varies by nearly 20 km from its highest point (Mount Everest in the Himalaya at 8850 m above sea level) to its lowest point (Challenger Deep in the Marianas Trench in the Pacific Ocean at 11,030 m below sea level). Although the Himalaya may loom large to us, their elevation is a small fraction of Earth's radius, only about one part in a thousand, which is why the globe looks like a smooth sphere when seen from outer space.

Peeling the Onion: Discovery of a Layered Earth

Ancient thinkers divided the universe into two parts, the heavens above and Hades below. The sky was transparent and full of light, and they could directly observe its stars and track its wandering planets. But Earth's interior was dark and closed to human view. In some places, the ground quaked and erupted hot lava. Surely something terrible was going on down there!

So it remained until about a century ago, when geologists began to peer downward into Earth's interior, not with waves of light (which cannot penetrate rock), but with waves produced by earthquakes. An earthquake occurs when geologic forces cause brittle rocks to fracture, sending out vibrations like the cracking of ice on a river. These **seismic waves** (from the Greek word for earthquake, *seismos*), when recorded on sensitive instruments called *seismometers,* allow geologists to locate earthquakes and also to make pictures of Earth's inner workings, much as doctors use ultrasound and CAT scans to image the inside of your body. When the first networks of seismographs were installed around the world at the end of the nineteenth century, geologists began to discover that

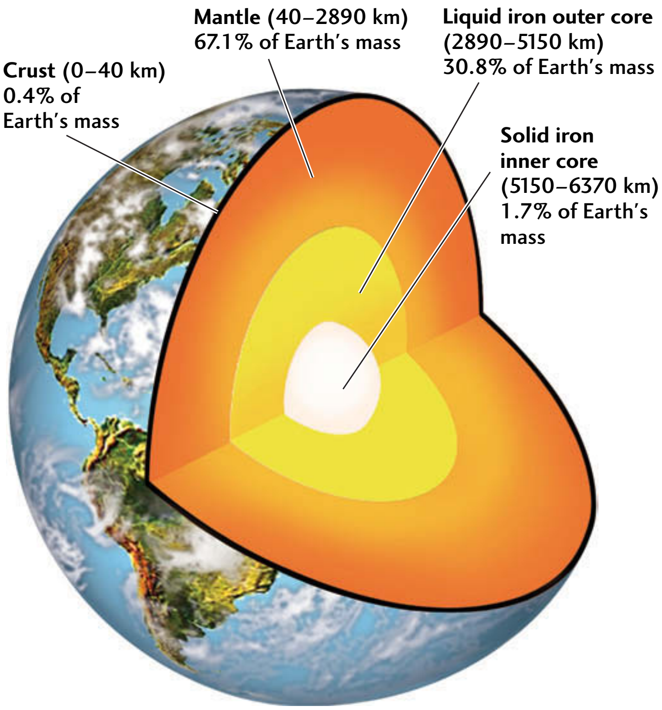


FIGURE 1.9 ■ Earth's major layers, showing their depths and their masses expressed as a percentage of Earth's total mass.

Earth's interior was divided into concentric layers of different compositions, separated by sharp, nearly spherical boundaries (**Figure 1.9**).

Earth's Density

Layering of Earth's deep interior was first proposed by the German physicist Emil Wiechert at the end of the nineteenth century, before much seismic data had become available. He wanted to understand why our planet is so heavy, or more precisely, so *dense.* The density of a substance is easy to calculate: just measure its mass on a scale and divide by its volume. A typical rock, such as the granite used for tombstones, has a density of about 2.7 grams per cubic centimeter (g/cm^3). Estimating the density of the entire planet is a little harder, but not much. Eratosthenes had shown how to measure Earth's volume in 250 B.C., and sometime around 1680, the great English scientist Isaac Newton figured out how to calculate its mass from the gravitational force that pulls objects to its surface. The details, which involved careful laboratory experiments to calibrate Newton's law of gravity, were worked out by another Englishman, Henry Cavendish. In 1798, he calculated Earth's average density to be about 5.5 g/cm^3, twice that of tombstone granite.

Wiechert was puzzled. He knew that a planet made entirely of common rocks could not have such a high density. Most common rocks, such as granite, contain a high proportion of silica (silicon plus oxygen; SiO_2) and have relatively low densities, below 3 g/cm^3. Some iron-rich rocks brought to Earth's surface by volcanoes have densities as high as 3.5 g/cm^3, but no ordinary rock approached Cavendish's value. He also knew that, going downward into Earth's interior, the pressure on rock increases with the weight of the overlying mass. The pressure squeezes the rock into a smaller volume, making its density higher. But Wiechert found that even the effect of pressure was too small to account for the density Cavendish had calculated.

The Mantle and Core

In thinking about what lay beneath his feet, Wiechert turned outward to the solar system and, in particular, to meteorites, which are pieces of the solar system that have fallen to Earth. He knew that some meteorites are made of an *alloy* (a mixture) of two heavy metals, iron and nickel, and thus have densities as high as 8 g/cm^3 (**Figure 1.10**). He also knew that these two elements are relatively abundant throughout our solar system. So, in 1896, he proposed a grand hypothesis: sometime in Earth's past, most of the iron and nickel in its interior had dropped inward to its center under the force of gravity. This movement created a dense **core,** which was surrounded by a shell of silicate-rich rock that he called the **mantle** (using the German word for "coat"). With this hypothesis, he could come up with a two-layered Earth model that agreed with Cavendish's value for Earth's average density. He could also explain the existence of iron-nickel meteorites: they were chunks from the core of an Earthlike planet (or planets) that had broken apart, most likely by collision with other planets.

Wiechert got busy testing his hypothesis using seismic waves recorded by seismographs located around the globe (he designed one himself). The first results showed a shadowy inner mass that he took to be the core, but he had problems identifying some of the seismic waves. These waves come in two basic types: *compressional waves,* which expand and compress the material they move through as they travel through a solid, liquid, or gas; and *shear waves,* which move the material from side to side. Shear waves can propagate only through solids, which resist shearing, and not through fluids (liquids or gases) such as air and water, which have no resistance to this type of motion.

In 1906, a British seismologist, Robert Oldham, was able to sort out the paths traveled by these two types of seismic waves and show that shear waves did not propagate through the core. The core, at least in its outer part, was liquid! This finding turns out to be not too surprising. Iron melts at a lower temperature than silicates, which is why metallurgists can use containers made of ceramics (which are silicate materials) to hold molten iron. Earth's deep interior is hot enough to melt an iron-nickel alloy, but not silicate rock. Beno Gutenberg, one of Wiechert's students, confirmed Oldham's observations and, in 1914, determined that the depth of the *core-mantle boundary* was about 2890 km (see Figure 1.9).

(a)

(b)

FIGURE 1.10 ■ Two common types of meteorites. (a) This stony meteorite, which is similar in composition to Earth's silicate mantle, has a density of about 3 g/cm^3. (b) This iron-nickel meteorite, which is similar in composition to Earth's core, has a density of about 8 g/cm^3. [John Grotzinger/Ramón Rivera-Moret/Harvard Mineralogical Museum.]

The Crust

Five years earlier, a Croatian scientist had detected another boundary at the relatively shallow depth of 40 km beneath the European continent. This boundary, named the *Mohorovičić discontinuity* (Moho for short) after its discoverer, separates a **crust** composed of low-density silicates, which are rich in aluminum and potassium, from the higher-density silicates of the mantle, which contain more magnesium and iron.

Like the core-mantle boundary, the Moho is a global feature. However, it was found to be substantially shallower beneath the oceans than beneath the continents. On average, the thickness of oceanic crust is only about 7 km, compared with almost 40 km for continental crust. Moreover, rocks in the oceanic crust contain more iron, and are therefore denser, than continental rocks. Because continental crust is thicker but less dense than oceanic crust, the continents ride higher by floating like buoyant rafts on the denser mantle (**Figure 1.11**), much as icebergs float on the ocean. Continental buoyancy explains the most striking feature of Earth's surface topography: why the elevations shown in Figure 1.8 fall into two main groups, 0 to 1 km above sea level for much of the land surface and 4 to 5 km below sea level for much of the deep sea.

Shear waves travel well through the mantle and crust, so we know that both are solid rock. How can continents float on solid rock? Rock can be solid and strong over the short term (seconds to years), but weak over the long term (thousands to millions of years). The mantle below a depth of about 100 km has little strength, and over very long periods, it flows as it adjusts to support the weight of continents and mountains.

The Inner Core

Because the mantle is solid and the outer part of the core is liquid, the core-mantle boundary reflects seismic waves, just as a mirror reflects light waves. In 1936, Danish seismologist

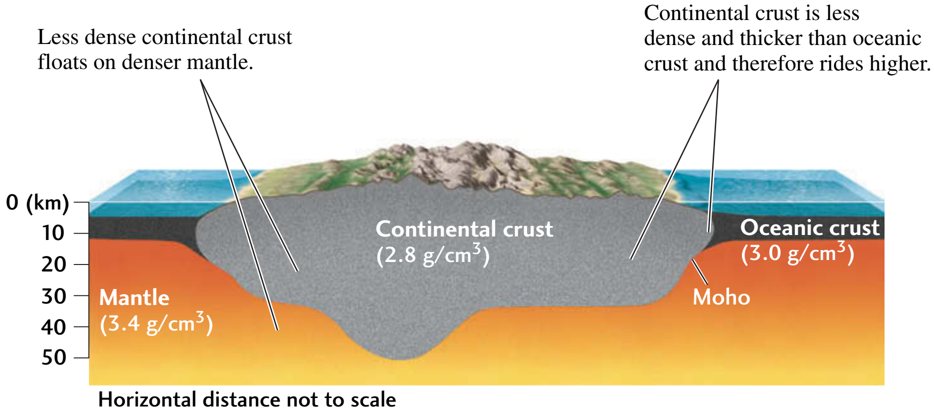


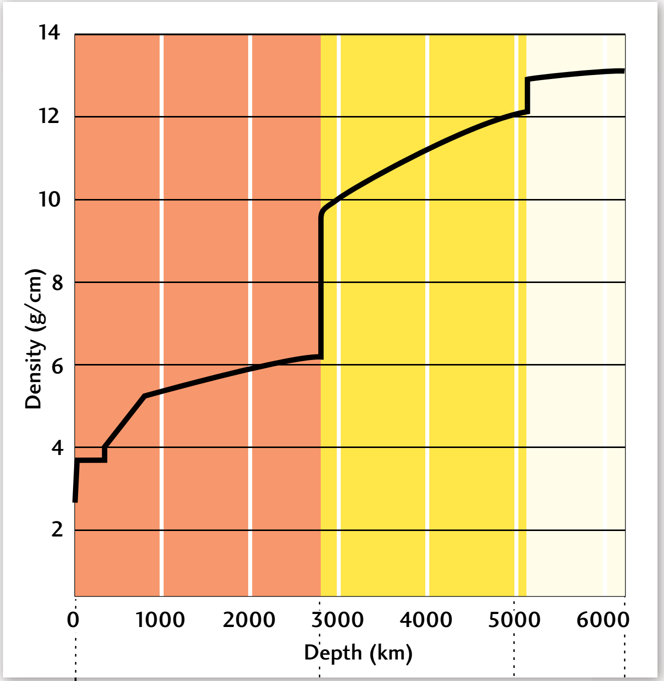
FIGURE 1.11 ■ Because crustal rocks are less dense than mantle rocks, Earth's crust floats on the mantle. Continental crust is thicker and has a lower density than oceanic crust, which causes it to ride higher, explaining the difference in elevation between continents and the deep seafloor.

Inge Lehmann discovered another sharp spherical boundary at the much greater depth of 5150 km, indicating a central mass with a higher density than the liquid core. Studies following her pioneering research showed that the inner core can transmit both shear waves and compressional waves. The **inner core** is therefore a solid metallic sphere suspended within the liquid **outer core**—a "planet within a planet." The radius of the inner core is 1220 km, about two-thirds the size of the Moon.

Geologists were puzzled by the existence of this "frozen" inner core. They knew that temperatures inside Earth should increase with depth. According to the best current estimates, Earth's temperature rises from about 3500°C at the core-mantle boundary to almost 5000°C at its center. If the inner core is hotter, how could it be solid while the outer core is molten? The mystery was eventually solved by laboratory experiments on iron-nickel alloys, which showed that the "freezing" was due to higher pressures, rather than lower temperatures, at Earth's center.

Chemical Composition of Earth's Major Layers

By the mid-twentieth century, geologists had discovered all of Earth's major layers—crust, mantle, outer core, and inner core—plus a number of more subtle features in its interior. They found, for example, that the mantle itself is layered into an *upper mantle* and a *lower mantle,* separated by a *transition zone* where the rock density increases in a series of steps. These density steps are not caused by changes in the rock's chemical composition, but rather by changes in the compactness of its constituent minerals due to the increasing pressure with depth. The two largest density jumps in the transition zone are located at depths of about 410 km and 660 km, but they are smaller than the density increases across the Moho and core-mantle boundaries, which *are* due to changes in chemical composition (**Figure 1.12**).



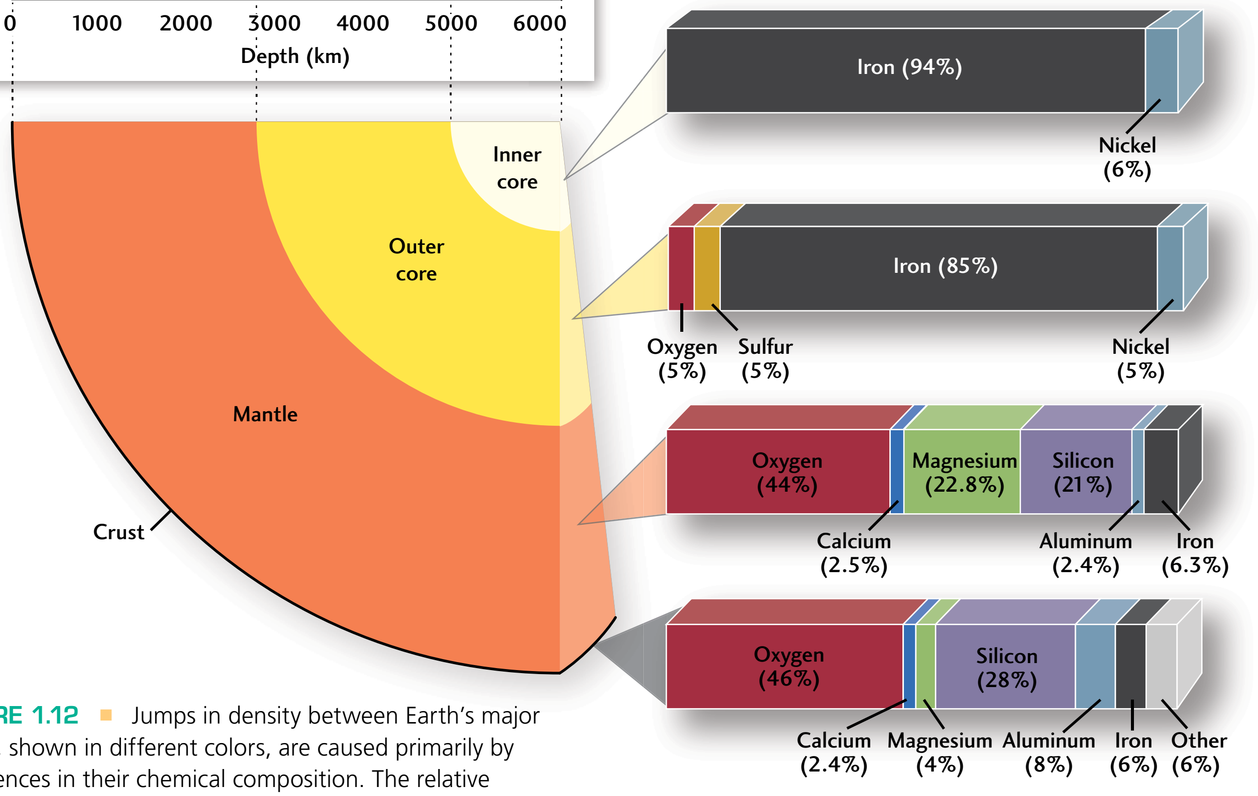


FIGURE 1.12 ▪ Jumps in density between Earth's major layers, shown in different colors, are caused primarily by differences in their chemical composition. The relative amounts of the main elements are depicted in the bars on the right.

Geologists were also able to show that Earth's outer core cannot be made of a pure iron-nickel alloy, because the densities of these metals are higher than the observed density of the outer core. About 10 percent of the outer core's mass must be made of lighter elements, such as oxygen and sulfur. On the other hand, the density of the solid inner core is slightly higher than that of the outer core and is consistent with a nearly pure iron-nickel alloy.

By bringing together many lines of evidence, geologists have put together a model of the composition of Earth and its various layers. In addition to the seismic data, that evidence includes the compositions of crustal and mantle rocks as well as the compositions of meteorites, thought to be samples of the cosmic material from which planets like Earth were originally made.

Only eight elements, out of more than a hundred, make up 99 percent of Earth's mass (see Figure 1.12). In fact, about 90 percent of Earth consists of only four elements: iron, oxygen, silicon, and magnesium. The first two are the most abundant elements, each accounting for nearly a third of the planet's overall mass, but they are distributed very differently. Iron, the densest of these common elements, is concentrated in the core, whereas oxygen, the least dense, is concentrated in the crust and mantle. The crust contains more silica than the mantle, and the core almost none. These relationships confirm Wiechert's hypothesis that the different compositions of Earth's layers are primarily the work of gravity. As you can see in Figure 1.12, the crustal rocks on which we stand are almost 50 percent oxygen!

■ Earth as a System of Interacting Components

Earth is a restless planet, continually changing through geologic activity such as earthquakes, volcanoes, and glaciation. This activity is powered by two heat engines: one internal, the other external (**Figure 1.13**). A *heat engine*—for example, the gasoline engine of an automobile—transforms heat into mechanical motion or work. Earth's *internal heat engine* is powered by the heat energy trapped in its deep interior during its violent origin and released inside the planet by radioactivity. This internal heat drives movement in the mantle and core, supplying the energy that melts rock, moves continents, and lifts up mountains. Earth's *external heat engine* is driven by solar energy: heat supplied to Earth's surface by the Sun. Heat from the Sun energizes the atmosphere and oceans and is responsible for Earth's climate and weather. Rain, wind, and ice erode mountains and shape the landscape, and the shape of the landscape, in turn, influences the climate.

All the parts of our planet and all their interactions, taken together, constitute the **Earth system.** Although Earth scientists have long thought in terms of natural systems, it was not until the late twentieth century that they had the tools to investigate how the Earth system actually works. Networks of instruments and Earth-orbiting satellites now collect information about the Earth system on a global scale, and computers are powerful enough to calculate the

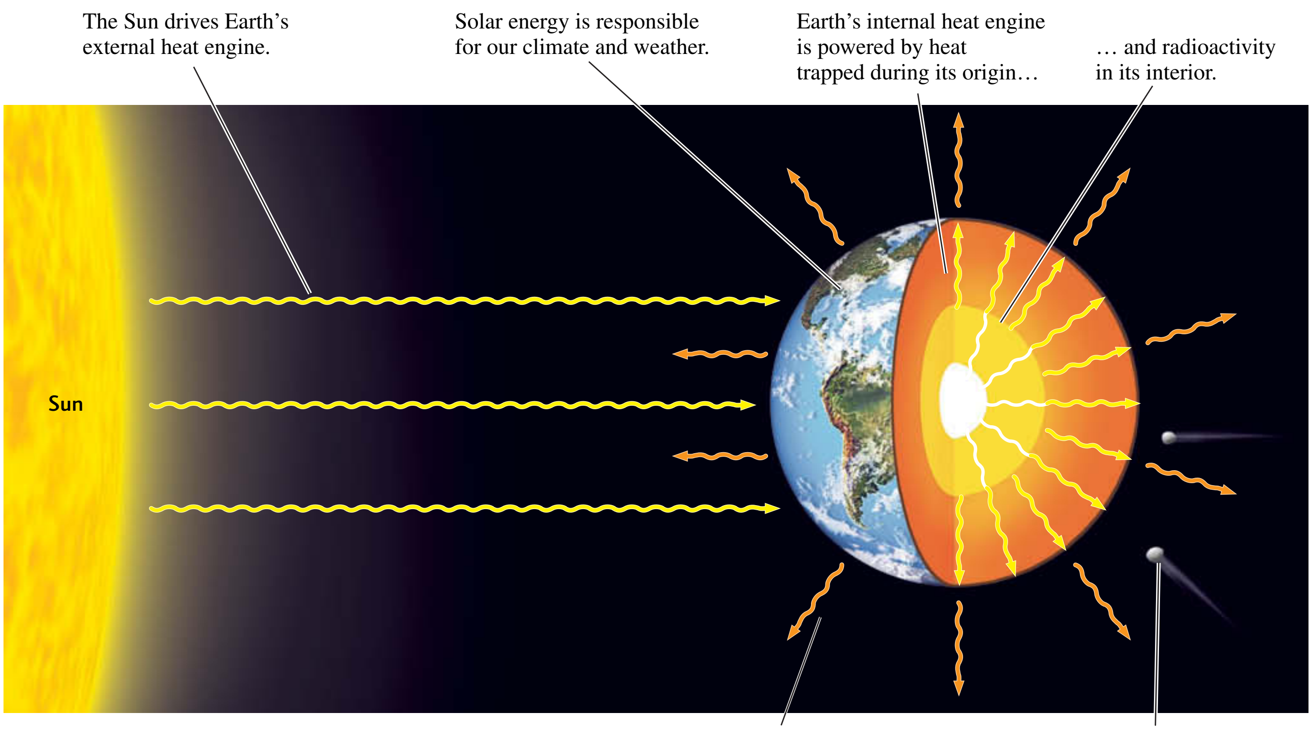


FIGURE 1.13 ■ The Earth system is an open system that exchanges energy and mass with its surroundings.

mass and energy transfers within the system. The major components of the Earth system can be represented as a set of domains, or "spheres" (**Figure 1.14**). We have discussed some of these components already; we will define the others shortly.

We will talk about the Earth system throughout this textbook. Let's get started by looking at some of its basic features. The Earth system is an *open system* that exchanges energy and mass with its surroundings (see Figure 1.14). Radiant energy from the Sun energizes the weathering and erosion of Earth's surface, as well as the growth of plants, which feed almost all living things. Earth's climate is controlled by the balance between the solar energy coming into the Earth system and the heat energy Earth radiates back into space.

Early in the life of the solar system, collisions between Earth and other solid bodies were a very important process, growing the planet's mass and forming the Moon. These days, the exchange of mass between Earth and space is relatively small: on average, only about 40,000 tons of material—equivalent to a cube 24 m on a side—fall into Earth's atmosphere each year in the form of meteors and meteorites. Most meteors we see streaking across the sky are very small, perhaps a few grams in mass, although occasionally Earth encounters a larger chunk, with dangerous results (**Figure 1.15**).

Although we think of Earth as a single system, it is a challenge to study the whole thing all at once. Instead, we will focus our attention on the particular components of the Earth system (subsystems) that we are trying to

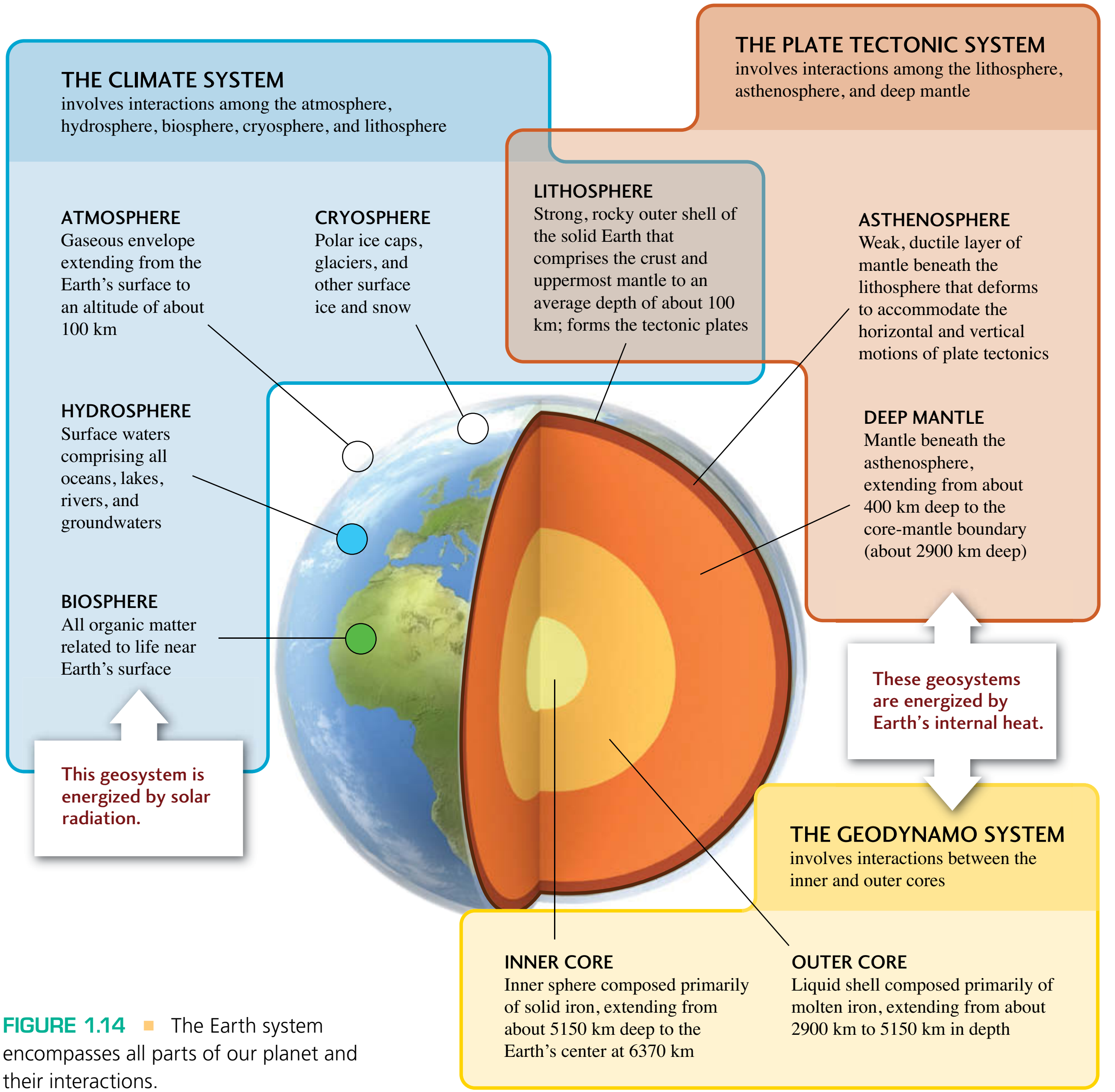


FIGURE 1.14 ■ The Earth system encompasses all parts of our planet and their interactions.

FIGURE 1.15 ■ Explosion of the Chelyabinsk meteor above central Russia on Feb 15, 2013, released 20–30 times more energy than the Hiroshima atomic bomb, and its shock wave injured 1,500 people. This small asteroid had a diameter of about 20 meters and weighed about 11,000 tons, a reminder that Earth is an open system that continues to exchange both mass and energy with the solar system. [Camera Press/Ria Novosti//Redux.]

understand. For instance, in our discussion of global climate change, we will primarily consider interactions between the atmosphere and several other components that are driven by solar energy: the *hydrosphere* (Earth's surface waters and groundwaters), the *cryosphere* (Earth's ice caps, glaciers, and snowfields), and the *biosphere* (Earth's living organisms). Our coverage of how the continents are deformed to raise mountains will focus on interactions between the crust and the mantle that are driven by Earth's internal heat engine. Specialized subsystems that produce specific types of activity, such as climate change or mountain building, are called **geosystems.** The Earth system can be thought of as a collection of many open, interacting (and often overlapping) geosystems.

In this section, we will introduce three important geosystems that operate on a global scale: the climate system, the plate tectonic system, and the geodynamo. Later in this textbook, we will discuss a number of smaller geosystems, such as volcanoes that erupt hot lava (Chapter 12), hydrologic systems that give us our drinking water (Chapter 17), and petroleum reservoirs that produce oil and gas (Chapter 23).

The Climate System

Weather is the term we use to describe the temperature, precipitation, cloud cover, and winds observed at a particular location and time on Earth's surface. We all know how variable the weather can be—hot and rainy one day, cool and dry the next—depending on the movements of storm systems, warm and cold fronts, and other atmospheric disturbances. Because the atmosphere is so complex, even the best forecasters have a hard time predicting the weather more than 4 or 5 days in advance. However, we can guess in rough terms what our weather will be much further into the future, because weather is governed primarily by the changes in solar energy input on seasonal and daily cycles: summers are hot, winters cold; days are warmer, nights cooler. The **climate** produced by these weather cycles can be described by averaging temperatures and other variables over many years of observation. A complete description of climate also includes measures of how variable the weather has been, such as the highest and lowest temperatures ever recorded on a given day of the year.

The **climate system** includes all the Earth system components that determine climate on a global scale and how climate changes with time. In other words, the climate system involves not only the behavior of the atmosphere, but also its interactions with the hydrosphere, cryosphere, biosphere, and lithosphere (see Figure 1.15).

When the Sun warms Earth's surface, some of the heat is trapped by water vapor, carbon dioxide, and other gases in the atmosphere, much as heat is trapped by frosted glass in a greenhouse. This *greenhouse effect* explains why Earth has a climate that makes life possible. If its atmosphere contained no greenhouse gases, Earth's surface would be frozen solid! Therefore, greenhouse gases, particularly carbon dioxide, play an essential role in regulating climate. As we will learn in later chapters, the concentration of carbon dioxide in the atmosphere is a balance between the amount spewed out of Earth's interior in volcanic eruptions and the amount withdrawn during the weathering of silicate rocks. In this way, the behavior of the atmosphere is regulated by interactions with the lithosphere.

To understand these types of interactions, scientists build numerical models—virtual climate systems—on large computers, and they compare the results of their computer simulations with data from their observations. A particularly urgent problem to which these models are being applied is the global warming that is being caused by *anthropogenic* (human-generated) emissions of carbon dioxide and other greenhouse gases. Part of the public debate about global warming centers on the accuracy of predictions based on computer models. Skeptics argue that even the most sophisticated computer models are unreliable because they lack many features of the real Earth system. In Chapter 15, we will discuss some aspects of how the climate system works, and in Chapter 23, we will examine the practical problems posed by anthropogenic climate change.

The Plate Tectonic System

Some of Earth's most dramatic geologic events—volcanic eruptions and earthquakes, for example—result from interactions within Earth's interior. These phenomena are driven by Earth's internal heat, which is transferred upward through the circulation of material in Earth's mantle.

We have seen that Earth is zoned by chemistry: its crust, mantle, and core are chemically distinct layers. Earth is also zoned by *strength,* a property that measures how much an Earth material can resist being deformed. Material strength depends on both chemical composition (bricks are strong, soap bars are weak) and temperature (cold wax is strong, hot wax is weak).

In some ways, the outer part of the solid Earth behaves like a ball of hot wax. Cooling of the surface forms a strong outer shell, or **lithosphere** (from the Greek *lithos,* meaning "stone"), which encases a hot, weak **asthenosphere** (from the Greek *asthenes,* meaning "weak"). The lithosphere includes the crust and the top part of the mantle down to an average depth of about 100 km. The asthenosphere is the portion of mantle, perhaps 300 km thick, immediately below the lithosphere. When subjected to force, the lithosphere tends to behave like a nearly rigid and brittle shell, whereas the underlying asthenosphere flows like a moldable, or *ductile,* solid.

According to the remarkable theory of *plate tectonics,* the lithosphere is not a continuous shell; it is broken into about a dozen large plates that move over Earth's surface at rates of a few centimeters per year. Each lithospheric plate is a rigid unit that rides on the asthenosphere, which is also in motion. The lithosphere that forms a plate may vary from just a few kilometers thick in volcanically active areas to more than 200 km thick beneath the older, colder parts of continents. The discovery of plate tectonics in the 1960s led to the first unified theory that explained the worldwide distribution of earthquakes and volcanoes, continental drift, mountain building, and many other geologic phenomena. Chapter 2 describes the basic concepts of plate tectonics.

Why do the plates move across Earth's surface instead of locking up into a completely rigid shell? The forces that push and pull the plates come from the mantle. Driven by Earth's internal heat engine, hot mantle material rises at boundaries where plates separate, forming new lithosphere. The lithosphere cools and becomes more rigid as it moves away from these boundaries, eventually sinking back into the mantle under the pull of gravity at other boundaries where plates converge. This general process, in which hotter material rises and cooler material sinks, is called **convection** (**Figure 1.16**). Convection in the mantle can

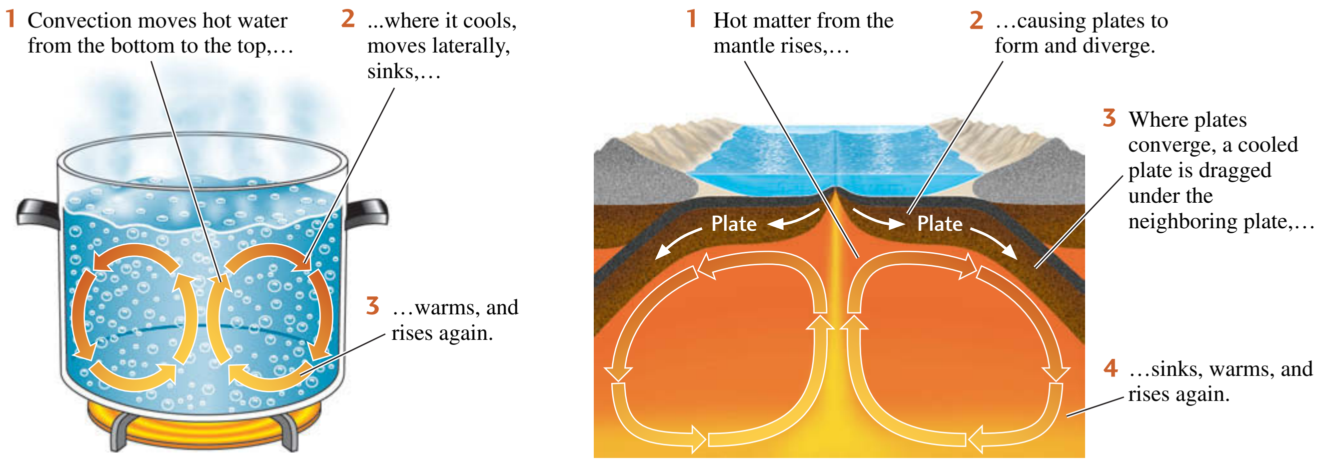


FIGURE 1.16 ■ Convection in Earth's mantle can be compared to the pattern of movement in a pot of boiling water. Both processes carry heat upward through the movement of matter.

be compared to the pattern of movement in a pot of boiling water. Both processes transfer energy by the movement of mass, but mantle convection is much slower because the solid mantle rocks are much more resistant to deformation than ordinary fluids such as water.

The convecting mantle and its overlying mosaic of lithospheric plates constitute the **plate tectonic system**. As with the climate system (which involves a wide range of convective processes in the atmosphere and oceans), scientists use computer simulations to study the plate tectonic system and test the agreement of their models against observations.

The Geodynamo

The third global geosystem involves interactions that produce a **magnetic field** deep inside Earth in its liquid outer core. This magnetic field reaches far into outer space, causing compass needles to point north and shielding the biosphere from harmful solar radiation. When rocks form, they become slightly magnetized by this magnetic field, so geologists can study how the field behaved in the past and use it to help them decipher the geologic record.

Earth rotates about an axis that goes through its north and south poles. Earth's magnetic field behaves as if a powerful bar magnet were located at Earth's center and inclined about 11° from this rotational axis. The magnetic force points into Earth at the north magnetic pole and outward from Earth at the south magnetic pole (**Figure 1.17**). At any place on Earth (except near the magnetic poles), a compass needle that is free to swing under the influence of the magnetic field will rotate into a position parallel to the local line of force, approximately in the north-south direction.

Although a permanent magnet at Earth's center could explain the dipolar (two-pole) nature of the observed magnetic field, this hypothesis can be easily rejected. Laboratory experiments have demonstrated that the field of a permanent magnet is destroyed when the magnet is heated above about 500°C. We know that the temperatures in Earth's deep interior are much higher than that—thousands of degrees at its center—so, unless the magnetism were constantly regenerated, it could not be maintained.

Scientists theorize that heat flowing out of Earth's core causes convection that generates and maintains the magnetic field. Why is a magnetic field created by convection in the outer core, but not by convection in the mantle? First, the outer core is made primarily of iron, which is a very good electrical conductor, whereas the silicate rocks of the mantle are poor electrical conductors. Second, the convective flow is a million times more rapid in the liquid outer core than in the solid mantle. The rapid flow stirs up electric currents in the liquid iron-nickel alloy to produce the magnetic field. Thus, this **geodynamo** is more like an electromagnet than a bar magnet (see Figure 1.17).

For some 400 years, scientists have known that a compass needle points north because of Earth's magnetic field. Imagine how stunned they were half a century ago when they found geologic evidence that the direction of the magnetic force can be reversed. Over about half of geologic time, a compass needle would have pointed south! These *magnetic reversals* occur at irregular intervals ranging from tens of thousands to millions of years. The processes that cause them are not well understood, but computer models of the geodynamo show sporadic reversals occurring in

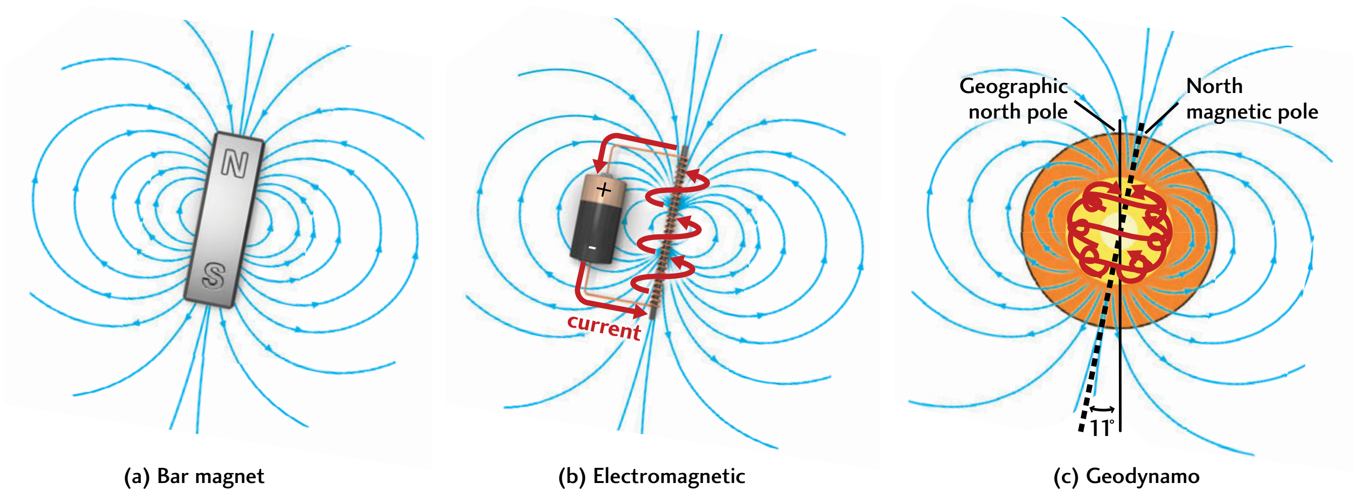


FIGURE 1.17 ■ (a) A bar magnet creates a dipolar field with north and south poles. (b) A dipolar field can also be produced by electric currents flowing through a coil of metallic wire, as shown for this battery-powered electromagnet. (c) Earth's magnetic field, which is approximately dipolar above Earth's surface, is produced by electric currents flowing in the liquid-metal outer core, which are powered by convection.

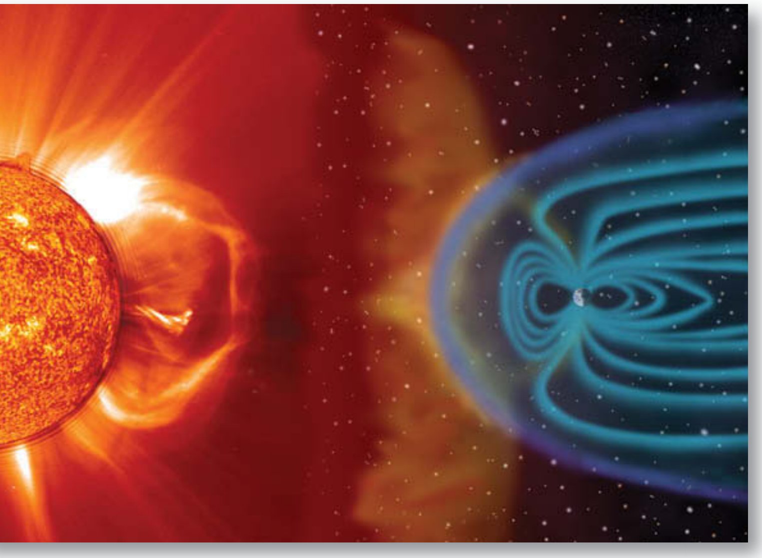


FIGURE 1.18 ■ Earth's magnetic field protects life by shielding Earth's surface from harmful solar radiation. This solar wind contains highly energetic charged particles ejected from the Sun, which distorts Earth's magnetic field lines, shown here in light blue. The distances in this picture are not to scale. [SOHO (ESA and NASA).]

the absence of any external factors—that is, purely through interactions within Earth's core. As we will see in the next chapter, magnetic reversals, which leave their imprint on the geologic record, have helped geologists figure out the movements of the lithospheric plates.

Interactions Among Geosystems Support Life

The natural environment—the habitat of life—is largely controlled by the climate system. The biosphere participates as an active component of this geosystem, regulating, for example, the amount of carbon dioxide, methane, and other greenhouse gases in the atmosphere, which in turn determines the planet's surface temperature. As we shall see in Chapter 11, the evolution of the biosphere and atmosphere have gone hand-in-hand throughout the last 3.5 billion years of climate-system history.

Perhaps less obvious is the coupling of the natural environment to the other two global geosystems. Plate tectonics produces volcanoes that resupply the atmosphere and oceans with water and gases from Earth's deep interior, and it is responsible for the tectonic processes that raise mountains. The interactions of the atmosphere, hydrosphere, and cryosphere with the surface topography create a variety of habitats that enrich the biosphere and, through the erosion of rock and dissolution of minerals, provide life with essential nutrients.

Unlike the convective motions of plate tectonics, the swirling currents in Earth's outer core are too deep to deform the crust or alter its chemistry. However, the magnetic field produced by this geodynamo reaches outward into space far beyond Earth's atmosphere (see Figure 1.17). There it forms a barrier to highly energetic particles that stream outward from the Sun at speeds of more than 400 km/s—the *solar wind* (**Figure 1.18**). Without this shield, Earth's surface would be bombarded by harmful solar radiation, which would kill many forms of life that now prosper in its biosphere.

■ An Overview of Geologic Time

So far, we have discussed Earth's size and shape, its internal layering and composition, and the operation of its three major geosystems. How did Earth get its layered structure

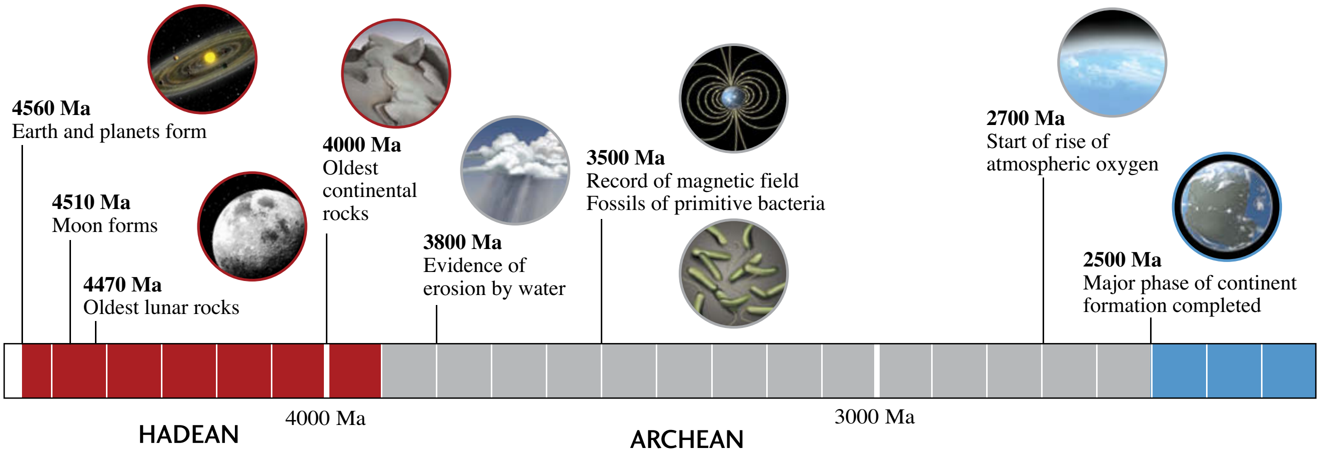


FIGURE 1.19 ■ This geologic time line shows some of the major events observed in the geologic record, beginning with the formation of the planets. (Ma, million years ago.)

in the first place? How have the global geosystems evolved through geologic time? To begin to answer these questions, we present a brief overview of geologic time from the birth of the planet to the present. Later chapters will fill in the details.

Comprehending the immensity of geologic time is a challenge. John McPhee notes that geologists look into the "deep time" of Earth's early history (measured in billions of years), just as astronomers look into the "deep space" of the outer universe (measured in billions of light-years). **Figure 1.19** presents the "arrow of geologic time," marked with some major events and transitions.

The Origin of Earth and Its Global Geosystems

Using evidence from meteorites, geologists have been able to show that Earth and the other planets of the solar system formed about 4.56 billion years ago through the rapid condensation of a dust cloud that circulated around the young Sun. This violent process, which involved the aggregation and collision of progressively larger clumps of matter, will be described in more detail in Chapter 9. Within just 100 million years (a relatively short time, geologically speaking), the Moon had formed and Earth's core had separated from its mantle. Exactly what happened during the next several hundred million years is hard to know. Very little of the rock record survived intense bombardment by the large meteorites that were constantly smashing into Earth. This early period of Earth's history is appropriately called the geologic "dark ages."

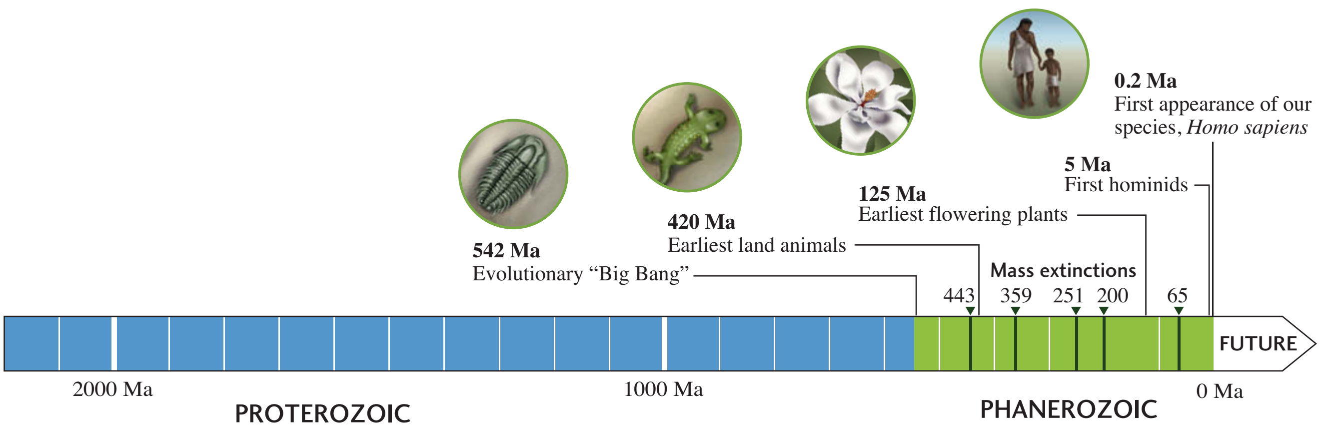
The oldest rocks now found on Earth's surface are over 4 billion years old. Rocks as ancient as 3.8 billion years show evidence of erosion by water, indicating the existence of a hydrosphere and the operation of a climate system not too different from that of the present. Rocks only slightly younger, 3.5 billion years old, record a magnetic field about as strong as the one we see today, showing that the geodynamo was operating by that time. By 2.5 billion years ago, enough low-density crust had collected at Earth's surface to form large continental masses. The geologic processes that then modified those continents were very similar to those we see operating today.

The Evolution of Life

Life also began very early in Earth's history, as we can tell from the study of **fossils**, traces of organisms preserved in the geologic record. Fossils of primitive bacteria have been found in rocks dated at 3.5 billion years ago. A key event was the evolution of organisms that release oxygen into the atmosphere and oceans. The buildup of oxygen in the atmosphere was under way by 2.7 billion years ago. Atmospheric oxygen concentrations probably rose to modern levels in a series of steps over a period as long as 2 billion years.

Life on early Earth was simple, consisting mostly of small, single-celled organisms that floated near the surface of the oceans or lived on the seafloor. Between 1 billion and 2 billion years ago, more complex life-forms such as algae and seaweeds evolved. The first animals appeared about 600 million years ago, evolving in a series of waves. In a period starting 542 million years ago and probably lasting less than 10 million years, eight entirely new branches of the animal kingdom were established, including the ancestors of nearly all animals inhabiting Earth today. It was during this evolutionary explosion, sometimes called biology's "Big Bang," that animals with shells first left their shelly fossils in the geologic record.

Although biological evolution is often viewed as a very slow process, it is punctuated by brief periods of rapid change. Spectacular examples are *mass extinctions,* during



which many kinds of organisms suddenly disappeared from the geologic record. Five of these huge turnovers are marked on the geologic time line in Figure 1.19. The most recent one was caused by a large meteorite impact 65 million years ago. The meteorite, not much larger than 10 km in diameter, caused the extinction of half of Earth's species, including all the dinosaurs.

The causes of the other mass extinctions are still being debated. In addition to meteorite impacts, scientists have proposed other kinds of extreme events, such as rapid climate changes brought on by glaciations and massive eruptions of volcanic material. The evidence is often ambiguous or inconsistent, however. For example, the largest mass extinction of all time took place about 251 million years ago, wiping out nearly 95 percent of all species. A meteorite impact has been proposed by some investigators as the cause, but the geologic record shows that ice sheets expanded and seawater chemistry changed at this time—a finding that is consistent with a major climate change. At the same time, an enormous volcanic eruption covered an area in Siberia almost half the size of the United States with 2 million to 3 million cubic kilometers of lava. This mass extinction has been dubbed "Murder on the Orient Express" because there are so many suspects!

Google Earth Project

Earth is a dynamic and complex system of interrelated components. A great many factors work to shape Earth's surface, and they are brought together by the overarching theory of plate tectonics. In our first exercise, we will use GE to explore the topographic extremes of our planet; we will use subsequent exercises in later chapters to explore the origin of those features. Let's start at the roof of the world: the Himalaya.

LOCATION Topographic exploration from the Himalaya, in central Asia, to the Challenger Deep, off the southern coast of Guam in the Pacific Ocean

GOAL Demonstrate the topographic variation of our planet and introduce the tools of Google Earth

LINKED Figure 1.8

Data SIO, NOAA, U.S. Navy, NGA, GEBCO Image © 2009 TerraMetrics Data @ MIRC/JHA Image ©2009 DigitalGlobe

Mass extinctions reduce the number of species competing for space in the biosphere. By "thinning out the crowd," these extreme events can promote the evolution of new species. After the demise of the dinosaurs 65 million years ago, mammals became the dominant class of animals. The rapid evolution of mammals into species with bigger brains and more dexterity led to the emergence of humanlike species (*hominids*) about 5 million years ago and our own species, *Homo sapiens* (Latin for "knowing human"), about 200,000 years ago. As newcomers to the biosphere, we are just beginning to leave our mark on the geologic record. Indeed, our short history as a species can be appreciated by noting that it spans less than a line's width on the geologic time line (see Figure 1.19).

■ Welcome to Google Earth

Google Earth (GE) is a spatial dataset interface available through the Internet search engine Google that can be downloaded free. This interface uses aerial and satellite photographs at a variety of spatial resolutions overlaid on

1. Enter "Mt. Everest" into your GE search engine and use the cursor to find its highest point. What is its approximate elevation above sea level (*a*bove *m*ean *s*ea *l*evel, or amsl)? It may be helpful to tilt your frame of view to the north in order to pick out the highest point.

- ***a.*** 10,400 m amsl
- ***b.*** 7380 m amsl
- ***c.*** 8850 m amsl
- ***d.*** 9230 m amsl

2. Zoom out from Mt. Everest proper and take a look at the shape of the Himalaya as a whole (try an eye altitude of 4400 km). Which of the following descriptions best captures what you see?

- ***a.*** A triangular mountain range composed of a single high peak
- ***b.*** An east-west–oriented mountain range composed of dozens of high peaks along the southern rim of a high plateau
- ***c.*** A north-south–oriented mountain range composed of high peaks in the middle and lower peaks around the edges
- ***d.*** A circular mountain range closed around a central broad dome

3. From the Himalaya, move to one of the deepest places on Earth's surface by typing "Challenger Deep" into the search panel. GE should take you immediately out to sea off the coast of the Philippines. Use the GE "line" measurement tool to determine the approximate horizontal surface distance between the two locations. What is that distance?

- ***a.*** 6300 km
- ***b.*** 2200 km
- ***c.*** 185,000 km
- ***d.*** 75,500 km

4. Zoom out from Challenger Deep to an eye altitude of 4200 km. Notice the unique surface feature that links Challenger Deep to deep regions of the ocean here. How would you describe this large-scale feature?

- ***a.*** Challenger Deep is part of an undersea mountain range with a roughly north-south orientation.
- ***b.*** Challenger Deep is part of an arcuate deep-sea trench in the Pacific Ocean that trends almost east-west at this location.
- ***c.*** Challenger Deep is the deepest part of a broad, almost flat plain near the middle of the Pacific Ocean.
- ***d.*** Challenger Deep is at the top of an undersea volcano that rises above the Pacific Ocean floor.

Optional Challenge Question

5. Using the answer to question 1 and using your cursor to note the maximum depth of Challenger Deep below mean sea level, calculate the approximate total difference in elevation of the two locations. Which of the following numbers is closest to that difference?

- ***a.*** 14,000 m
- ***b.*** 20,000 m
- ***c.*** 18,000 m
- ***d.*** 26,000 m

digital elevation model datasets to give the images a three-dimensional quality. Since the data are geo-referenced in all three dimensions, they can be used to make measurements of distance with GE's "path" and "line" measurement tools. Elevation, latitude, and longitude are continuously tracked for any specific location of the cursor and are displayed at the bottom of the screen. GE also offers navigation tools in the upper right corner of the screen that allow you to zoom in and out as well as to alter the azimuth and aspect of your view.

One of the newest functions of GE is the ability to move backward in time at some locations by accessing archived spatial datasets. In the spirit of all Internet search engines, Google also provides a "Fly to" search window you can use to transport yourself to specific virtual locations. You can bookmark favorite locations as well as link locations to geo-referenced digital images taken at the same locations. Please make use of some or all of these tools while familiarizing yourself with the interface, and have fun doing it! For specific instruction on using Google Earth, go to *Google Earth Tutorial* at www.whfreeman.com/understandingearth7e.

SUMMARY

What is geology? Geology is the study of Earth—its history, its composition and internal structure, and its surface features.

How do geologists study Earth? Geologists, like other scientists, use the scientific method. They develop and test hypotheses, which are tentative explanations for natural phenomena based on observations and experiments. They share their data and test one another's hypotheses. A coherent set of hypotheses that have survived repeated challenges constitutes a theory. Hypotheses and theories can be combined into a scientific model that represents a natural system or process. Confidence grows in those hypotheses, theories, and models that withstand repeated tests and are able to predict the results of new observations or experiments.

What is Earth's shape? Earth's overall shape is a sphere with an average radius of 6370 km that bulges slightly at the equator and is slightly squashed at the poles due to the planet's rotation. Its topography varies by about 20 km from the highest point on its surface to the lowest point. Its elevations fall into two main groups: 0 to 1 km above sea level over much of the continents and 4 to 5 km below sea level for much of the ocean basins.

What are Earth's major layers? Earth's interior is divided into concentric layers of different compositions separated by sharp, nearly spherical boundaries. The outer layer is the crust, made up mainly of silicate rock, which varies in thickness from about 40 km in the case of continental crust to about 7 km for oceanic crust. Below the crust is the mantle, a thick shell of denser silicate rock that extends to the core-mantle boundary at a depth of about 2890 km. The core, which is composed primarily of iron and nickel, is divided into two layers: a liquid outer core and a solid inner core, separated by a boundary at a depth of 5150 km. Jumps in density between these layers are caused primarily by differences in their chemical composition.

How do we study Earth as a system of interacting components? When we try to understand a complex system such as the Earth system, we find that it is often easier to focus on its subsystems (which we call geosystems). This textbook focuses on three major global geosystems: the climate system, which involves interactions among the atmosphere, hydrosphere, cryosphere, biosphere, and lithosphere; the plate tectonic system, which involves interactions among Earth's solid components; and the geodynamo, which involves interactions within Earth's core. The climate system is driven by heat from the Sun, whereas the plate tectonic system and the geodynamo are driven by Earth's internal heat.

What are the basic elements of plate tectonics? The lithosphere is broken into about a dozen large plates. Driven by convection in the mantle, these plates move over Earth's surface at rates of a few centimeters per year. Each plate acts as a rigid unit riding on the ductile asthenosphere, which is also in motion. Hot mantle material rises at boundaries where plates form and separate, cooling and becoming more rigid as it moves away. Eventually, most of it sinks back into the mantle at boundaries where plates converge.

What are some major events in Earth's history? Earth formed 4.56 billion years ago. Rocks as old as 4.3 billion years have survived in Earth's crust. Liquid water existed on Earth's surface by 3.8 billion years ago. Rocks about 3.5 billion years old show evidence of a magnetic field, and the earliest evidence of life has been found in rocks of the same age. By 2.7 billion years ago, the oxygen content of the atmosphere was rising because of oxygen production by early organisms, and by 2.5 billion years ago, large continental masses had formed. Animals appeared suddenly about 600 million years ago, diversifying rapidly in a great evolutionary explosion. The subsequent evolution of life was marked by a series of extreme events that killed off many species, allowing new species to evolve. A dramatic example was the impact of a large meteorite 65 million years ago. Our species, *Homo sapiens,* first appeared about 200,000 years ago.