

## Earth Systems



Courtesy Gilbert W. Thompson/Janehan Turk

Havasu Creek, a tributary of the Colorado River in Grand Canyon

- 1.1** Flowers Bloom on Earth, Venus Boils, and Mars Freezes
- 1.2** The Earth's Four Spheres
- 1.3** Earth Systems

- 1.4** Time in Earth Science
- 1.5** Rates of Change in Earth History
- 1.6** Humans and Earth Systems

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## 1.1 Flowers Bloom on Earth, Venus Boils, and Mars Freezes

Earth is sometimes called the water planet or blue planet because more than two-thirds of its surface is covered by azure seas. Earth is the only planet or moon in the Solar System with rain falling from clouds, water running over the land in streams, and extensive oceans. It is also the only body in the Solar System that we know of that supports life.

Our Solar System originally evolved from a cloud of dust and gas rotating in the vast emptiness of space. Under the relentless pull of gravity, these particles condensed into discrete bodies that gradually evolved to form the Sun, the planets, and their moons. Thus, all of the planets formed from the same original mixture of materials. Yet today, the planets are distinctly different from one another. To appreciate these differences, let us briefly compare Earth with its two closest neighbors, Venus and Mars.

Of all the planets, Venus most closely resembles Earth in size, density, and distance from the Sun. Consequently, astronomers once thought that Venus might be similar to Earth, and that both water and life might be found there. However, data obtained from spacecraft reveal that Venus is extremely inhospitable (Figure 1.1). Any Earth-like life would quickly suffocate in the carbon dioxide-rich Venusian atmosphere. Caustic sulfuric acid clouds fill the sky. In addition, the surface of Venus is hot enough to melt lead, and therefore hot enough to destroy the organic molecules necessary for life.

Early in its history, Mars must have had a temperate climate somewhat like that of Earth today. Spacecraft images show extinct stream canyons, sea floors, and lake beds, indicating that flowing water must have been abundant on the planet (Figure 1.2). But today, the Martian surface is frigid and dry. Mars's winter ice caps are mostly frozen carbon dioxide, commonly called dry ice. If water is present on Mars, it lies frozen beneath the planet's surface.

If Earth, Venus, and Mars formed from the same materials, why are the three planets so different today? Why are we the only planet favored with great oceans, cascading waterfalls, blue skies, and abundant life?

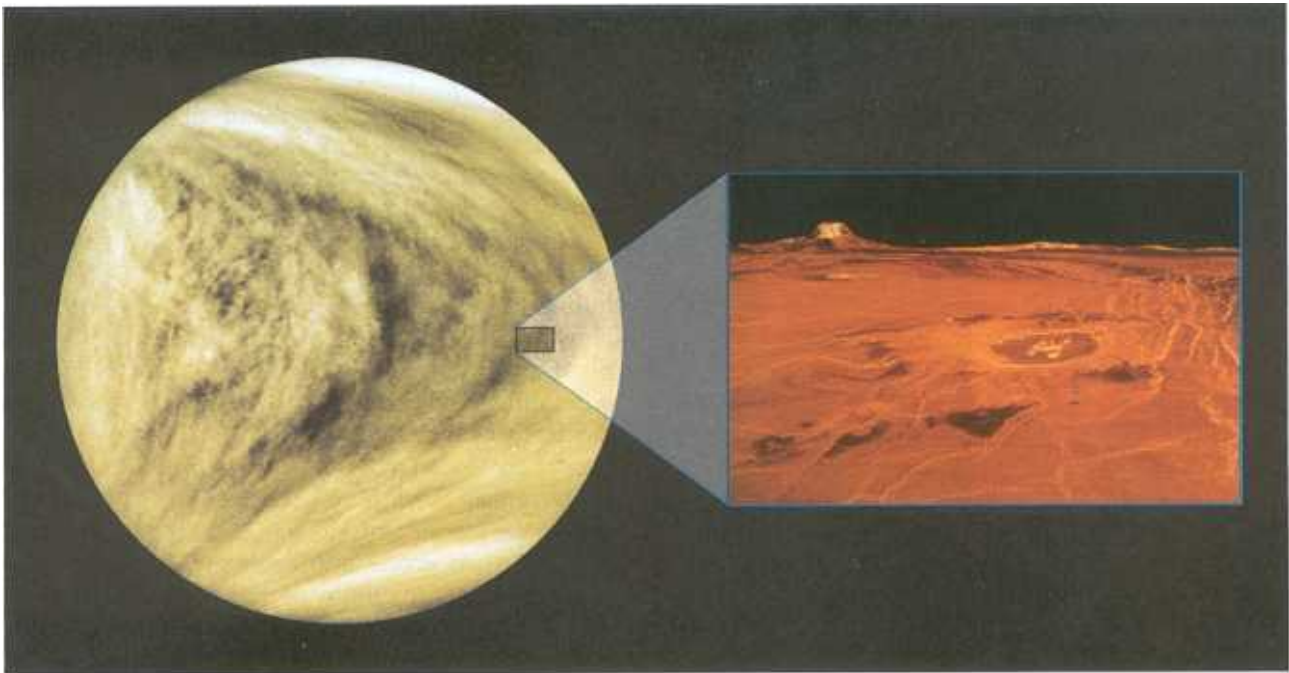
Shortly after the formation of the planets, the orig-

inal atmospheres of Earth, Venus, and Mars evolved into swirling mixtures of carbon dioxide, carbon monoxide, water, ammonia, methane, and other gases. To appreciate what happened next, we need to understand the behavior of carbon dioxide and water in planetary environments.

Water can be a solid, liquid, or gas. If liquid water cools, it turns to ice; when it is heated, it evaporates to form vapor. Thus water is removed from the atmosphere when it condenses or freezes whereas it is added to the atmosphere when it vaporizes. Carbon dioxide also exists in a variety of forms. At the Earth's surface, carbon dioxide occurs as an atmospheric gas, dissolves in seawater, and combines with calcium and oxygen to form a type of rock called limestone. (Carbon dioxide also exists as a liquid and a solid, but not within the Earth's natural environment). Carbon dioxide gas and water vapor are both greenhouse gases—they absorb infrared radiation and warm the atmosphere.

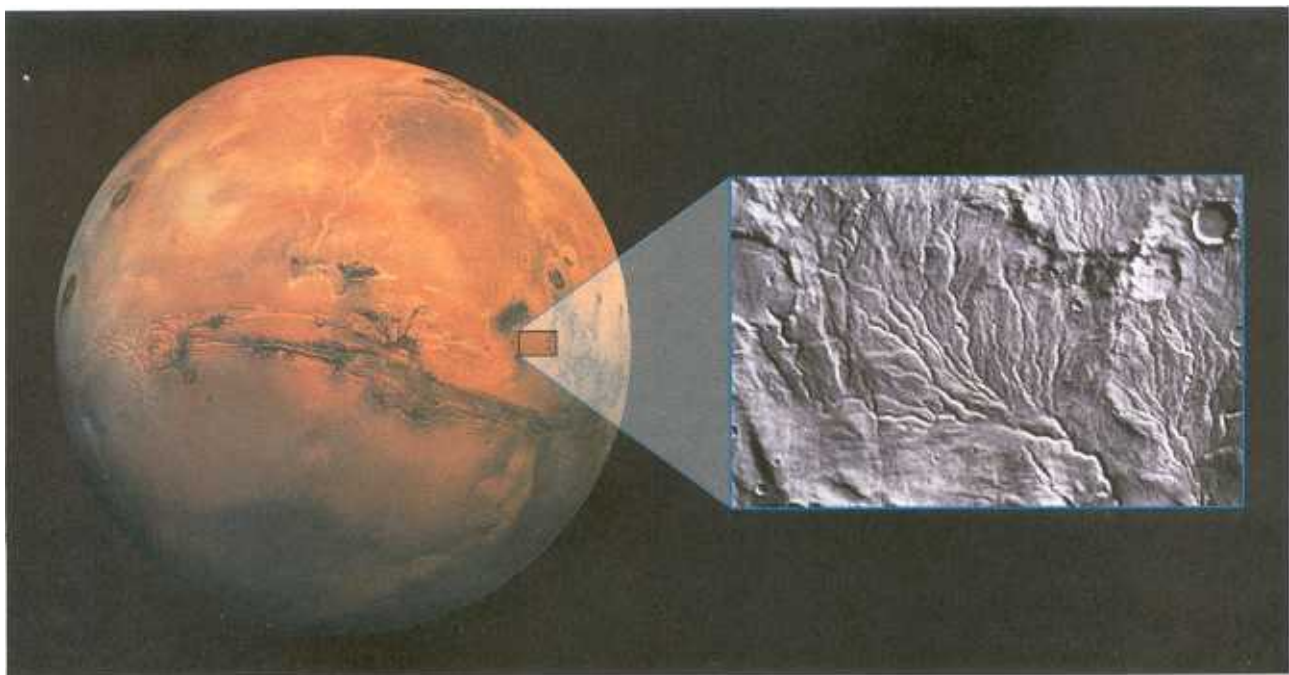
Because Venus is closer to the Sun than Earth is, it receives more solar radiation and was originally a bit warmer than it is now. Due to the higher temperature, water vapor never condensed, or if it did, it quickly evaporated again. Because there were no seas for carbon dioxide to dissolve into, most of the carbon dioxide also remained in the atmosphere. Both of these greenhouse gases caused Venus's atmosphere to heat up further. Heat released more water and carbon dioxide into the atmosphere and subsequently, these gases trapped more heat. The temperature spiraled higher and higher.

In contrast, Earth was cool enough so that the water vapor condensed to form vast oceans. Large amounts of carbon dioxide then dissolved in the seas or reacted to form limestone. Thus, large quantities of these two greenhouse gases were removed from the atmosphere. As a result, the atmosphere cooled. Fortunately for us, the temperature stabilized in a range favorable for the existence of liquid water and for the emergence and evolution of life. Mars is a little farther from the Sun than Earth is, and consequently it receives a little less solar energy. A carbon dioxide- and water vapor-rich Martian atmosphere probably evolved between 4.0 and 3.5 billion years ago. Both of these greenhouse gases absorbed the Sun's heat, producing a temperate climate despite the planet's greater distance from the Sun. Rain fell from clouds, rivers flowed, wind blew over shallow seas. Perhaps life evolved in this favorable environment. But because Mars is a little further from the Sun than Earth, its atmosphere cooled more than Earth's. This small initial cooling caused more water vapor to condense and more carbon dioxide to dissolve into the seas, lowering the amounts of greenhouse gases in the Martian atmosphere. The temperature spiraled downward. Today, the Martian surface occasionally becomes as warm as an autumn afternoon on Earth (20°C), but more



JPL/USGS, nasa, NASA

**Figure 1.1** Space shot of Venus. Before astronomers could peer through the Venusian cloud cover or measure its temperature and composition, they speculated that Venus may harbor life. Today we know that the atmosphere is so hot and corrosive that living organisms could not possibly exist.



NASA/JPL

**Figure 1.2** Water once flowed over the surface of Mars, eroding canyons and depositing sediment. However, today the planet is frigid and dry.

commonly, the temperature is below freezing. Temperatures as low as  $-140^{\circ}\text{C}$  have been recorded. At this extreme, carbon dioxide freezes into dry ice.

In summary, Venus is closer to the Sun and receives more solar radiation than either Earth or Mars. This small amount of extra solar energy initiated atmospheric changes that caused the planet to heat up much more than can be accounted for by the difference in solar energy alone. Of the three planets, Mars is the farthest from the Sun and receives the least solar energy. Here the cool initial temperatures triggered different atmospheric changes, and in this case, the temperature plummeted.

On Earth, a temperate climate prevailed. Life evolved. Then, over the course of a few billion years, the carbon dioxide- and water vapor-rich atmosphere was gradually replaced by an atmosphere rich in nitrogen and oxygen.

This example highlights the major themes summarized here:

Planets are active, dynamic, and in a continuous state of change. On Earth, a primordial poisonous atmosphere evolved into a favorable one. At the same time, continents formed in a global ocean and barren rock weathered into soil. Life formed, probably in the seas, and migrated onto land. During its history, the Earth's temperature has oscillated frequently and dramatically. At times, the planet has been warm enough to support vast tropical swamps, while at other times it has cooled sufficiently so that continental glaciers oozed from the poles and the high mountains.

Planetary changes are driven by complex interactions among the atmospheres, the seas, and the solid ground. On Earth, living organisms also alter the planet that supports them. For example, plant roots help weather rock into soil, and soil supports plants. During photosynthesis, plants produce oxygen, which plants and animals need for respiration. In many cases, small, seemingly insignificant perturbations can trigger a chain of events that will magnify the initial perturbation far beyond its initial impact. These examples illustrate how small differences in solar energy led to dramatic differences in the modern planetary environments of Earth, Venus, and Mars.

## 1.2 The Earth's Four Spheres

Imagine walking along a rocky coast as a storm blows in from the sea. Wind whips the ocean into whitecaps, gulls wheel overhead, and waves crash onto shore. Before you have time to escape, blowing spray has soaked your clothes. A hard rain begins as you scramble over the rocks to your car. During this adventure, you have

observed the four major spheres of the Earth. The rocks and soil underfoot are the surface of the **geosphere**, or the solid Earth. The rain and sea are parts of the **hydrosphere**, the watery part of our planet. The gaseous layer above the Earth's surface is the **atmosphere**. Finally, you, the gulls, the beach grasses, and all other forms of life in the sea, on land, and in the air are parts of the **biosphere**, the realm of organisms.

You can readily observe that the atmosphere is in motion because clouds waft across the sky and wind blows against your face. Animals, and to a lesser extent, plants also move. Flowing streams, crashing waves, and falling rain are all familiar examples of motion in the hydrosphere. Although it is less apparent, the geosphere is also moving and dynamic. Vast masses of subterranean rock flow vertically and horizontally within the planet's interior, continents drift, mountains rise and then erode into sediment. Throughout this book we will study many of these phenomena to learn what energy forces set matter in motion and how the motion affects the world we live on. Figure 1.10 shows schematically all the possible interactions among the spheres. This figure will be repeated throughout the book with important arrows highlighted to emphasize interactions discussed in the accompanying text.

Figure 1.3 shows that the geosphere is by far the largest of the four spheres. The Earth's radius is about 6400 kilometers,  $1\frac{1}{2}$  times the distance from New York to Los Angeles. Despite this great size, nearly all of our direct contact with the Earth occurs at or very near its surface. The deepest well penetrates only about 12 kilometers,  $\frac{1}{533}$  of the total distance to the center. The oceans make up most of the hydrosphere, and the central ocean floor is about 5 kilometers deep. Most of the Earth's atmosphere lies within 30 kilometers of the surface, and the biosphere is a thin shell about 15 kilometers thick.

### The Geosphere

Our Solar System coalesced from a frigid cloud of dust and gas that was rotating slowly in space. The Sun was formed as gravity pulled material toward the swirling center. At the same time, rotational forces spun material in the outer cloud into a thin disk. When the turbulence of the initial accretion subsided, small grains stuck together to form fist-sized masses. These planetary seeds then accreted to form rocky clumps, which grew to form larger planetesimals, 100 to 1000 kilometers in diameter. Finally, the planetesimals collected to form the planets. This process was completed about 4.6 billion years ago.

As the Earth coalesced, the rocky chunks and planetesimals were accelerated by gravity so that they slammed together at high speeds. Particles heat up when they collide, so the early Earth warmed as it formed. Later, asteroids, comets, and more

The Earth and Its Four Spheres

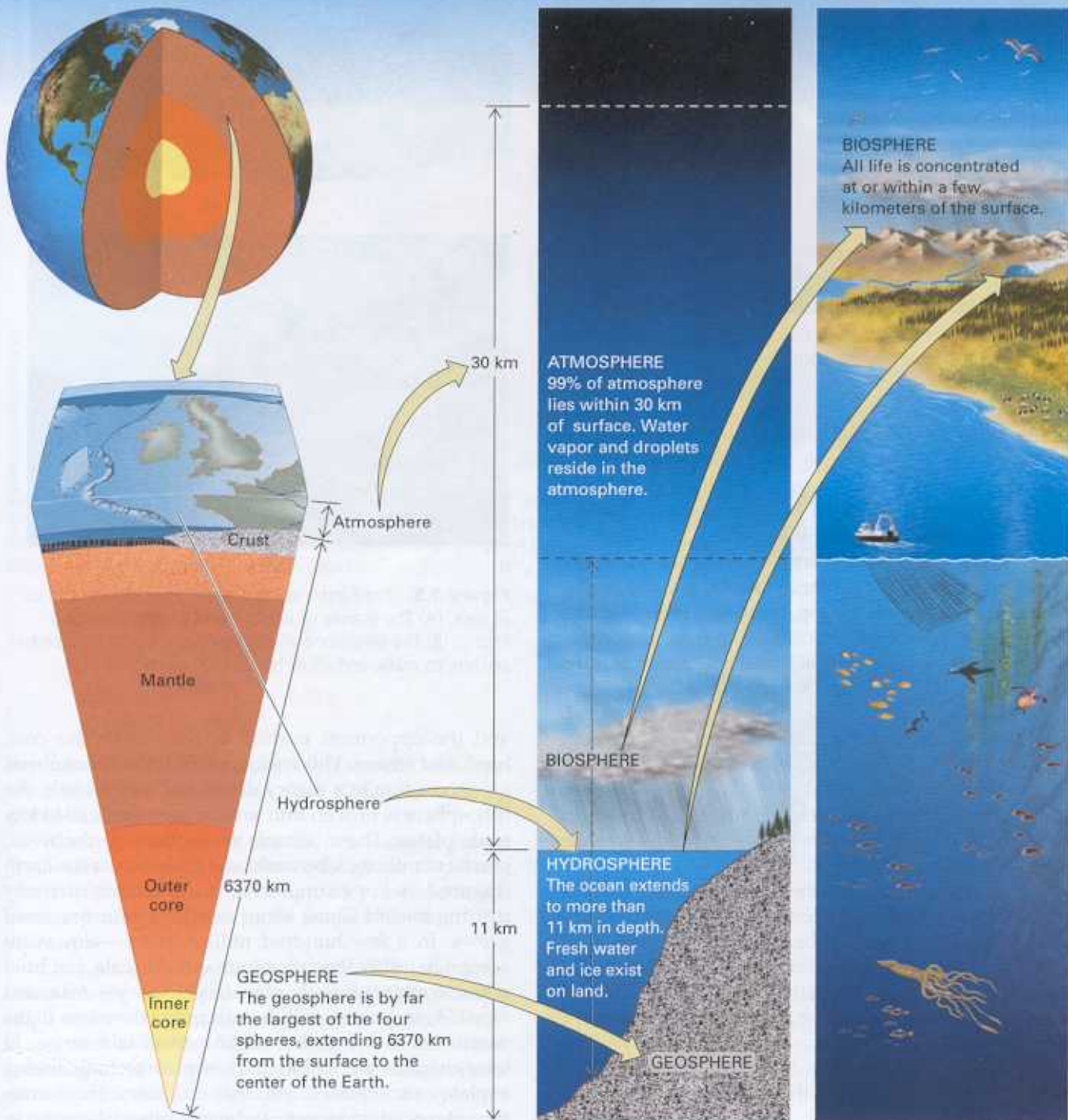
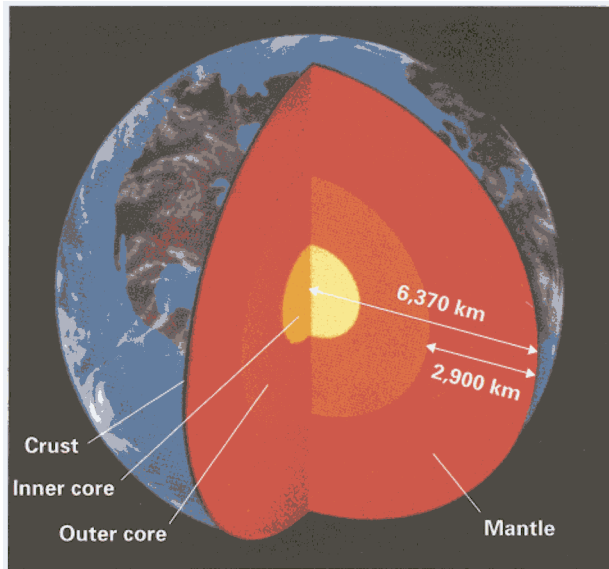


Figure 1.3 Most of the Earth is solid rock surrounded by the hydrosphere, the biosphere, and the atmosphere.



**Figure 1.4** The geosphere is divided into three major layers: the crust, mantle, and core.

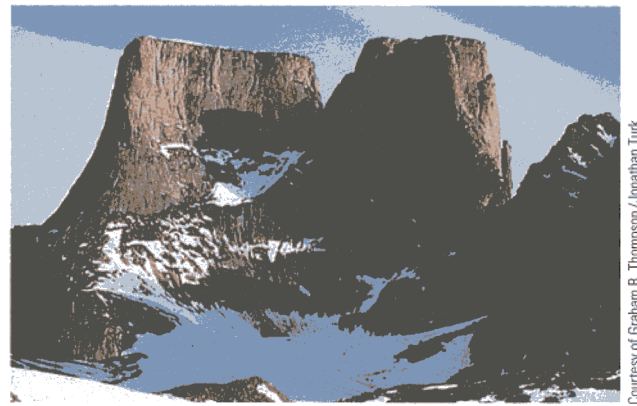
planetesimals crashed into the surface, generating additional heat. At the same time, radioactive decay heated the Earth's interior. As a result of all three of these processes, our planet became so hot that all or most of it melted soon after it formed.

Within the molten Earth, the denser materials gravitated toward the center, while the less dense materials floated toward the top, creating a layered structure. Today, the geosphere consists of three major layers: a dense, metallic **core**, a less dense rocky mantle, and an even less dense surface **crust** (Figure 1.4).

The core is composed mainly of iron and nickel, heated to 6000°C, about as hot as the surface of the Sun. At this extreme temperature, the outer core is molten to form a vast subterranean sea of liquid metal. However, at the center, the intense pressure of the Earth's weight overwhelms the temperature effect and compresses the inner core into a solid.

The **mantle** surrounds the core and lies beneath the crust. The physical characteristics of the mantle vary with depth. Near the surface, the outermost mantle is cool because the Earth's interior heat has escaped into space. This cool rock is relatively strong and hard. In contrast, the layer below the surface is so hot that the rock is weak, soft, plastic, and flows slowly—like cold honey. Even deeper in the Earth, pressure overwhelms temperature and the mantle rock becomes strong again.

The outermost layer is a thin veneer called the crust. Below a layer of soil and beneath the ocean water, the crust is composed almost entirely of solid rock. Even a casual observer sees that rocks of the crust are different from one another: Some are soft, others hard, and they come in many colors (Figure 1.5). Thus crust



A



B

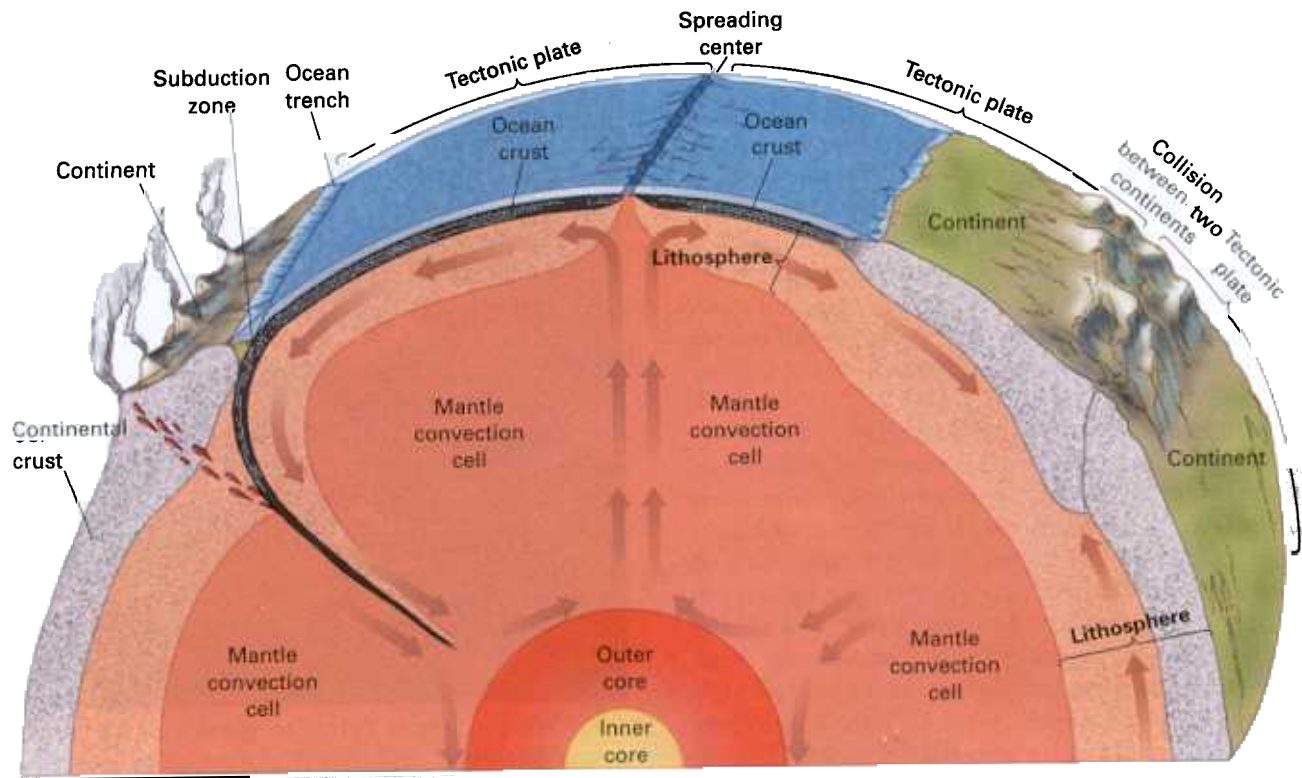
**Figure 1.5** The Earth's crust is made up of different kinds of rock. (A) The granite of Baffin Island is gray, hard, and strong. (B) The sandstone and limestone of the Utah desert are red, crumbly, and show horizontal layering.

and the uppermost portion of the mantle are cool, hard, and strong. This region is called the **lithosphere**.

According to a theory developed in the 1960s, the lithosphere is broken into several segments called **tectonic plates**. These tectonic plates float on the weak, plastic mantle rock beneath, and glide across the Earth (Figure 1.6). For example, North America is currently drifting toward China about as fast as your fingernail grows. In a few hundred million years—almost incomprehensibly long on a human time scale, but brief when compared with planetary history—Asia and North America may collide, crumpling the edges of the continents and building a giant mountain range. In later chapters we will learn how plate tectonic theory explains earthquakes, volcanic eruptions, the formation of mountain ranges, and many other phenomena.

## The Hydrosphere

The hydrosphere includes all of the Earth's water, which circulates among oceans, continents, glaciers, and the atmosphere. Oceans cover 71 percent of the

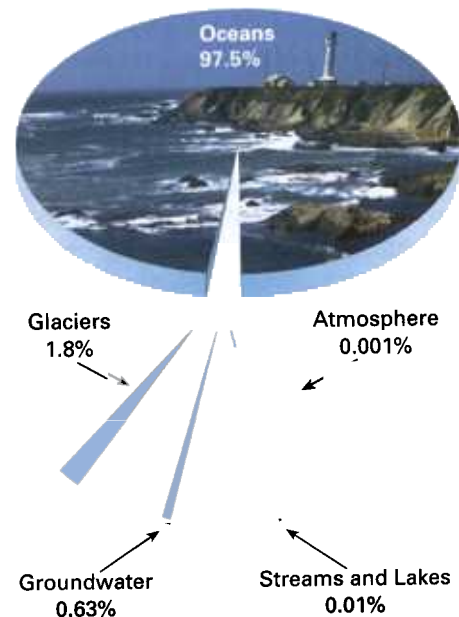


**Figure 1.6** The lithosphere is composed of the crust and the uppermost mantle. It is a 100-kilometer-thick layer of strong rock that floats on the underlying plastic mantle. The lithosphere is broken into seven major segments, called tectonic plates, that glide horizontally over the plastic mantle at rates of a few centimeters per year. In the drawing, the thickness of the mantle and the lithosphere are exaggerated to show detail.

Earth and contain 97.5 percent of its water. Ocean currents transport heat across vast distances, altering global climate.

About 1.8 percent of the Earth's water is frozen in glaciers. Although glaciers cover about 10 percent of the Earth's land surface today, they covered much greater portions of the globe as recently as 18,000 years ago.

Only about 0.64 percent of the Earth's total water exists on the continents as a liquid. While this is a small amount from a global perspective, fresh water is essential to life on Earth. Lakes, rivers, and clear, sparkling streams are the most visible reservoirs of continental water, but they constitute only 0.01 percent of the total. In contrast, **ground water**, which saturates rock and soil of the upper few kilometers of the geosphere, is much more abundant and accounts for 0.63 percent of the Earth's water. A minuscule amount, 0.001 percent, exists in the atmosphere, but this water is so mobile that it profoundly affects both the weather and climate of our planet (Figure 1.7).



**Figure 1.7** The oceans contain most of the Earth's surface water. Most fresh water is frozen into glaciers. Most available fresh water is stored underground as ground water.

**Interactive Question:** How would a doubling of the amount of water in the atmosphere affect the oceans? How would it affect weather and climate?

**Figure 1.8** Winds often drive clouds into great swirls. At the same time, global winds carry warm air to cooler regions and cool air to equatorial parts of the Earth. The flow of heat makes the climates of both regions more favorable to humans.



## The Atmosphere

The atmosphere is a mixture of gases, mostly nitrogen and oxygen, with smaller amounts of argon, carbon dioxide, and other gases. It is held to the Earth by gravity and thins rapidly with altitude. Ninety-nine percent is concentrated in the first 30 kilometers, but a few traces remain even 10,000 kilometers above the Earth's surface.

The atmosphere supports life because animals need oxygen, and plants need both carbon dioxide and oxygen. In addition, the atmosphere supports life indirectly by regulating climate. Air acts both as a filter and as a blanket, retaining heat at night and shielding us from direct solar radiation during the day. Wind transports heat from the equator toward the poles, cooling equatorial regions and warming temperate and polar zones (Figure 1.8).

## The Biosphere

The biosphere is the zone inhabited by life. It includes the uppermost geosphere, the hydrosphere, and the lower parts of the atmosphere. Sea life concentrates near the surface, where sunlight is available. Plants also grow on the Earth's surface, with roots penetrating a few meters into the soil. Animals live on the surface, fly a kilometer or two above it, or burrow a few meters underground. Large populations of bacteria live in rock to depths of as much as four kilometers, some organisms live on the ocean floor, and a few windblown microorganisms drift at heights of 10 kilometers or

more. But even at these extremes, the biosphere is a very thin layer at the Earth's surface.

Plants and animals are clearly affected by the Earth's environment. Organisms breathe air, require water, and thrive in a relatively narrow temperature range. Terrestrial organisms ultimately depend on soil, which is part of the geosphere. Although it is not as obvious, plants and animals also alter and form the environment that they live in. For example, living organisms contributed to the evolution of the modern atmosphere. We will discuss these interactions throughout the book.

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## 1.3 Earth Systems

A **system** is any assemblage or combination of interacting components. For example, the human body is a system composed of stomach, bones, nerves, and many other organs. Each organ is discrete, yet all the organs interact to produce a living human. Blood nurtures the stomach; the stomach helps provide energy to maintain the blood.

The Earth is also composed of components: geosphere, hydrosphere, atmosphere, and biosphere.



Just as organs in the human body are interrelated, these seemingly separate systems of the Earth are all part of an integrated whole. To understand any component of the Earth, we first study its physical and chemical properties and the energy sources that drive it. Then we look at interactions with all the other components of the planet. For example, if we were studying volcanic eruptions, we would examine the chemical properties of molten rock, determine when and where the rock melts, and study how and why such melting occurs. Once we understand the mechanism of a single volcanic eruption, we may take a broader scope and observe that lava spewing to the surface may build a mountain and alter nearby drainage systems. Hot lava kills living organisms in its path. Gas and dust rise into the atmosphere, reflecting sunlight and cooling the Earth. Changes in temperature and evaporation rates alter rainfall patterns. Thus a single event, powered by heat originating hundreds or even thousands of kilometers beneath the surface, can initiate change throughout the planet.

In the laboratory, scientists often create closed systems, where no energy or matter enters or leaves. Yet, few natural systems are closed. Our body is an open system because we ingest food and oxygen and excrete wastes and carbon dioxide. Very little matter enters or leaves the Earth, but it is an open system because it receives energy in the form of sunlight and dissipates heat energy out into space.

Systems are driven by the flow of energy and matter, but energy and matter behave in fundamentally different ways: Once used, energy becomes less useful; however, matter can be reused in the same way over and over again.

## Energy and the Laws of Thermodynamics

A gallon of gasoline has a specific amount of potential energy. If you burn the gasoline in the engine of a car, the potential energy is first converted to heat; then some of that heat is converted to work and the remainder is released through the tailpipe as heat. The laws of thermodynamics describe the flow of energy through a car or any other system.

The **first law of thermodynamics** states that *energy is always conserved*. If we continue to use the example of a car engine, when fuel is burned, some energy is converted to heat; if you drive the car up a hill, some may be stored in what is called potential energy of position—but we can account for every last joule. (A joule is the standard unit of energy.) Energy is never lost or gained.

The **second law of thermodynamics** states that *a closed system always shifts toward disorder, or homogeneity*.

Thus, if you place a drop of dark blue ink in a glass of water, the drop will disperse until the water becomes homogeneously light blue. The original order—ink in one region and clear water throughout the remainder of the glass—spontaneously morphs into disorder—ink and water all mixed together. In a similar manner, if you place a hot rock into a cold glass of water, the rock will cool and the water will warm up until both reach the same temperature. No one has ever observed any other behavior. **Entropy** is a measure of the disorder, or homogeneity in a system. One statement of the second law is that *the entropy of a closed system always increases*.

Starting with this basic premise, scientists have shown that whenever heat is converted to work, some of the energy is always degraded so that it becomes less useful to perform work. No one can ever devise a way to efficiently trap all of the energy in the hot exhaust from a car to power the car again. In other words, no heat engine is 100 percent efficient. Plants trap sunlight, animals eat plants, plants and animals die and decompose to form petroleum, petroleum burns in the engine of a car, and finally the energy is dissipated as heat. If we want to drive the car farther, we need to find another gallon of gasoline.

The Earth's surface systems—the atmosphere, hydrosphere, and biosphere—are ultimately powered by the Sun. Wind is powered by uneven solar heating of the atmosphere, ocean waves are driven by the wind, currents move in response to wind or temperature differences, and so on. Luckily for us, the Earth receives a continuous influx of solar energy, and will continue to receive this energy for another 5 billion years or so.

In contrast, the Earth's interior is powered by the decay of radioactive elements and by residual heat from the primordial coalescence of the planet. We will discuss these sources further in later chapters.

However, matter, unlike energy, can be recycled. Imagine that you mine iron ore, smelt the ore to make metal, and use the metal to manufacture a car. When the car is old and worn out, you can melt it back down and make a new car. The process could be repeated over and over, indefinitely.

Several material cycles are fundamental to our study of Earth systems. These include the rock cycle (Chapter 3), the hydrological cycle (or water cycle) (Chapter 11), the carbon cycle (Chapter 17), and the nitrogen cycle (Chapter 17). During the course of these cycles, matter is always conserved—however, matter continuously and commonly changes form.

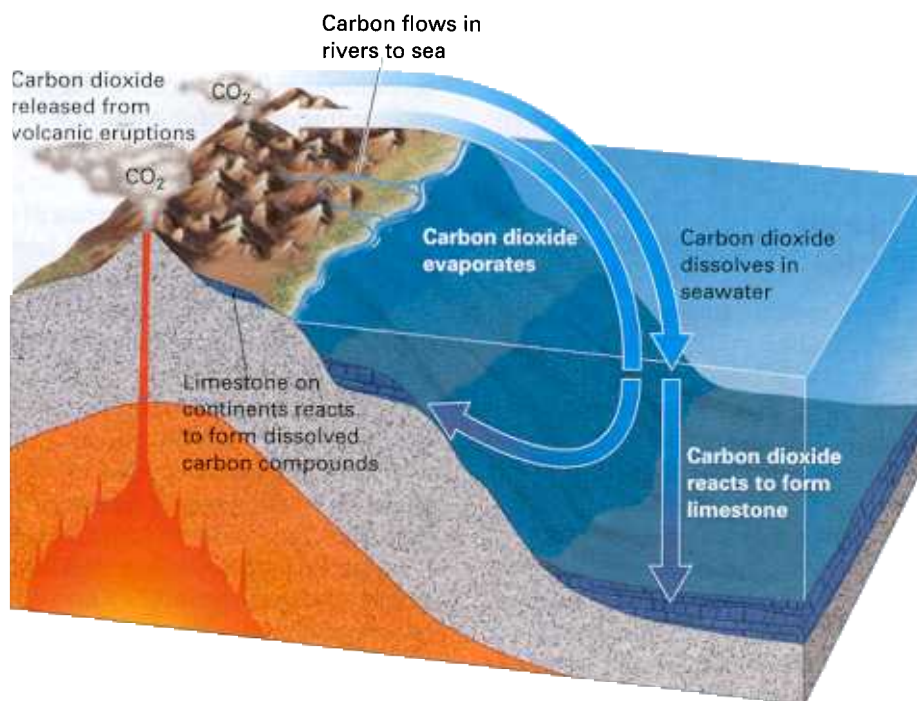
For example, solid water (ice) melts to form liquid, and if more heat is added, liquid vaporizes to a gas. Reverse processes occur when heat is removed. Thus, in the hydrological cycle, water evaporates from the ocean, is transported as vapor or small droplets

in the atmosphere, falls to Earth as rain or snow, and eventually flows back to the oceans. Chemical reactions also change the physical properties of matter. Common table salt is a solid, crystalline mineral. If you drop a crystal of salt in water, it dissolves, thus altering the properties of both the salt and the water. Or, as another example, carbon dioxide gas reacts with other matter to form solid rock, limestone—and limestone reacts to form carbon dioxide gas and other products.

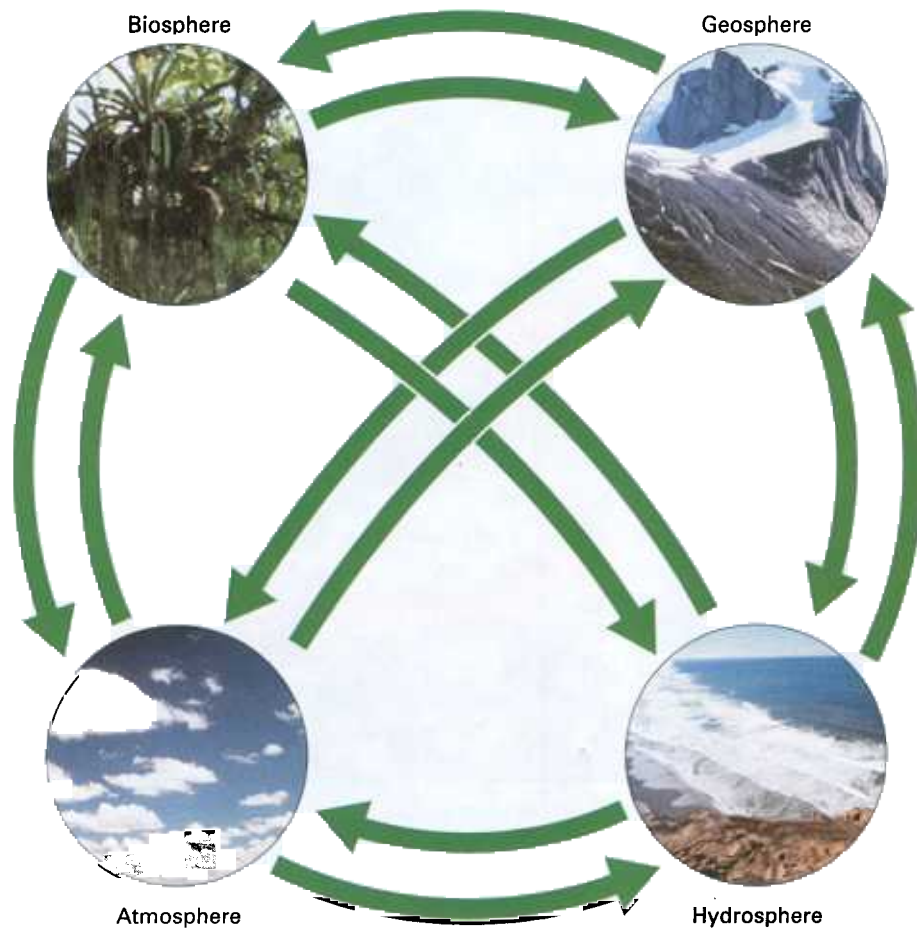
Because matter exists in so many different chemical and physical forms, most materials occur in all four of Earth's major spheres: geosphere, hydrosphere, atmosphere, and biosphere. This is illustrated by the following examples. On Earth, water is chemically bound into clays and other minerals, as a component of the geosphere. It is the primary constituent of the hydrosphere. It exists in the atmosphere as vapor and clouds. Water is an essential part of all living organisms. The mineral salt provides another example of a material found in the four spheres: Thick layers of salt occur as sedimentary rocks, large quantities of salt are dis-

solved in the oceans, salt aerosols are suspended in the atmosphere, and salt is an essential component of life. Thus, all the spheres are interconnected.

Material cycles illustrate the exchange of matter among the four spheres. Because matter exists in so many different forms, these cycles are also interconnected. Recall from the earlier discussion about planetary environments that carbon exists in many forms. It occurs as dioxide gas in the atmosphere, it dissolves in seawater, and it combines with calcium and oxygen to form a type of rock called limestone (Figure 1.9). The formation of limestone from carbon dioxide is part of the rock cycle, because limestone is a rock. But at the same time, the exact same process—the formation of limestone from carbon dioxide—is part of the carbon cycle because both limestone and carbon dioxide are composed of carbon. It is no contradiction that two cycles intersect. In our study of Earth systems, we categorize the four separate spheres and numerous material cycles independently, but, we also recognize that Earth materials and processes are all part of one integrated system (Figure 1.10).



**Figure 1.9** All of Earth's cycles and spheres are interconnected. For example, the formation and decomposition of limestone is part of the rock cycle because limestone is a rock. The same process is also part of the carbon cycle because limestone is composed partly of carbon.



**Figure 1.10** All of Earth's cycles and spheres are interconnected.

## 1.4 Time in Earth Science

James Hutton was a gentleman farmer who lived in Scotland in the late 1700s. Although trained as a physician, he never practiced medicine and, instead, turned to geology. Hutton observed that a certain type of rock, called **sandstone**, is composed of sand grains cemented together (Figure 1.11). He also noted that rocks slowly decompose into sand, and that streams carry sand into the lowlands. He inferred that sandstone is composed of sand grains that originated by the erosion of ancient cliffs and mountains.

Hutton tried to deduce how much time was required to form a thick bed of sandstone. He studied sand grains slowly breaking away from rock outcrops. He watched sand bouncing down stream beds. Finally he traveled to beaches and river deltas where sand was accumulating. By estimating the time needed for thick

layers of sand to accumulate on beaches, Hutton concluded that sandstone must be much older than human history. Hutton, overwhelmed by the magnitude of geological time, wrote:

On us who saw these phenomena for the first time, the impression will not easily be forgotten. . . . We felt ourselves necessarily carried back to the time . . . when the sandstone before us was only beginning to be deposited, in the shape of sand and mud, from the waters of an ancient ocean. . . . The mind seemed to grow giddy by looking so far into the abyss of time . . .

We find no vestige of a beginning, no prospect of an end.

Hutton had no way to measure the magnitude of geologic time. However, modern geologists have learned that certain radioactive materials in rocks act as clocks to record the passage of time. Using these clocks and other clues embedded in the Earth's crust, the moon, and in meteorites fallen from space, ge-



Louise K. Broman/Photo Researchers

**Figure 1.11** Hutton observed that a sandstone outcrop, like this cliff rising above the Escalante River, Utah, is composed of tiny round sand grains cemented together.

ologists estimate that the Earth formed 4.6 billion years ago.

The primordial planet was vastly different from our modern world. There was no crust as we know it today, no oceans, and the diffuse atmosphere was vastly different from the modern one. There were no living organisms.

No one knows exactly when the first living organisms evolved, but we know that life existed at least as early as 3.8 billion years ago, 800 million years after the planet formed. For the following 3.3 billion years, life evolved slowly, and although some multicellular organisms developed, most of the biosphere consisted of single-celled organisms. Organisms rapidly became more complex, abundant, and varied about 544 million years ago. The dinosaurs flourished between 225 million and 65 million years ago.

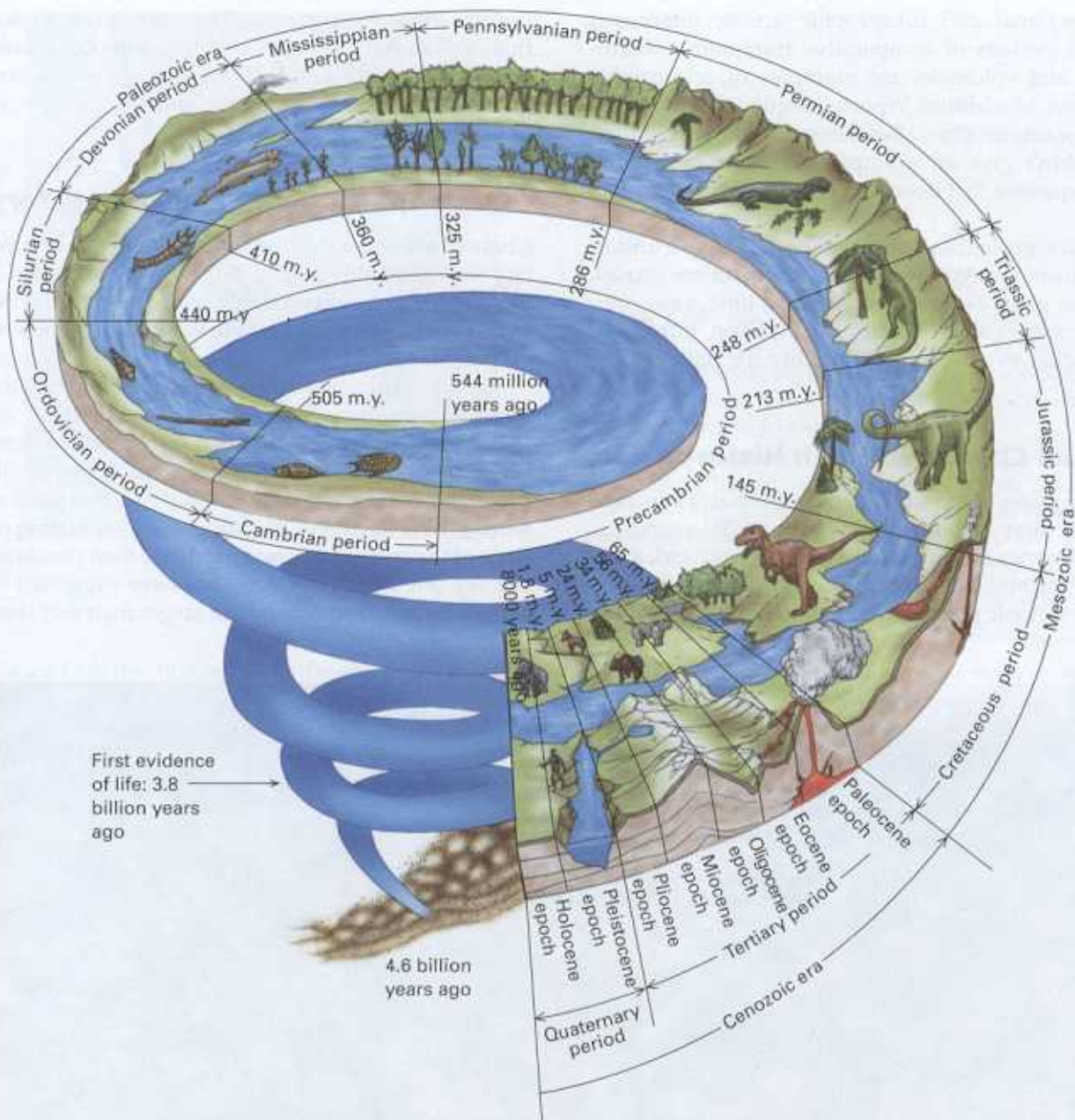
*Homo sapiens* and our direct ancestors have been on Earth for 5 to 7 million years, only about 0.1 percent of the planet's history. In his book *Basin and Range*, John McPhee offers us a metaphor for the magnitude of geologic time. If the history of the Earth were represented by the old English measure of a yard—the distance from the king's nose to the end of his outstretched hand—all of human history could be erased by a single

stroke of a file on his middle fingernail. Figure 1.12 summarizes Earth history in graphical form.

Geologists routinely talk about events that occurred millions or even billions of years ago. If you live on the East Coast of North America, you may be familiar with the Appalachian mountains, which started rising from a coastal plain nearly half a billion years ago. If you live in Seattle, the land you are standing on was an island in the Pacific between 80 and 100 million years ago, when dinosaurs walked the Earth.

There are two significant consequences of the vast span of geologic time:

1. Events that occur slowly become significant. If a continent moves a few centimeters a year, the movement makes no noticeable alteration of Earth systems over decades or centuries. But over hundreds of millions of years, the effects are significant.
2. Improbable events occur regularly. The chances are great that a large meteorite won't crash into Earth tomorrow, or next year, or during the next century. But during the past 500 million years, several catastrophic impacts have occurred and they will probably occur sometime in the future.



**Figure 1.12** The geologic time scale is shown as a spiral to indicate the great length of time before multicellular organisms became abundant, about 544 million years ago.

## 1.5 Rates of Change in Earth History

Recall that James Hutton deduced that sandstone forms when rocks slowly decompose to sand, the sand is transported to lowland regions, and the grains cement together. This process occurs step by step—over many years. Hutton's conclusions led him to formulate a principle now known as **gradualism** or **uniformitarianism**. The principle states that geologic change occurs

over long periods of time, by a sequence of almost imperceptible events. Hutton surmised that geologic processes operating today also operated in the past. Thus scientists can explain events that occurred in the past by observing changes occurring today. Sometimes this idea is summarized in the statement, "The present is the key to the past."

However, not all geologic change is gradual. William Whewell, another early geologist, argued that geologic change was sometimes rapid. He wrote that the geologic past may have "consisted of epochs

of paroxysmal and catastrophic action, interposed between periods of comparative tranquility." Earthquakes and volcanoes are examples of catastrophic events but, in addition, Whewell argued that occasionally huge catastrophes alter the course of Earth history. He couldn't give an example because they happen so infrequently that none had occurred within human history.

Today, geologists know that both Hutton's uniformitarianism and Whewell's **catastrophism** are correct. Over the great expanses of geologic time, slow, uniform processes alter the Earth. In addition, infrequent catastrophic events radically modify the path of slow change.

### Gradual Change in Earth History

Tectonic plates creep slowly across the Earth's surface. Since the first steam engine was built 200 years ago, North America has migrated 8 meters westward, a distance a sprinter can run in 1 second. Thus, the movement of tectonic plates is too slow to be observed with-

out sensitive instruments. However, over geologic time, this movement alters the shapes of ocean basins, forms lofty mountains and plateaus, generates earthquakes and volcanic eruptions, and affects our planet in many other ways.

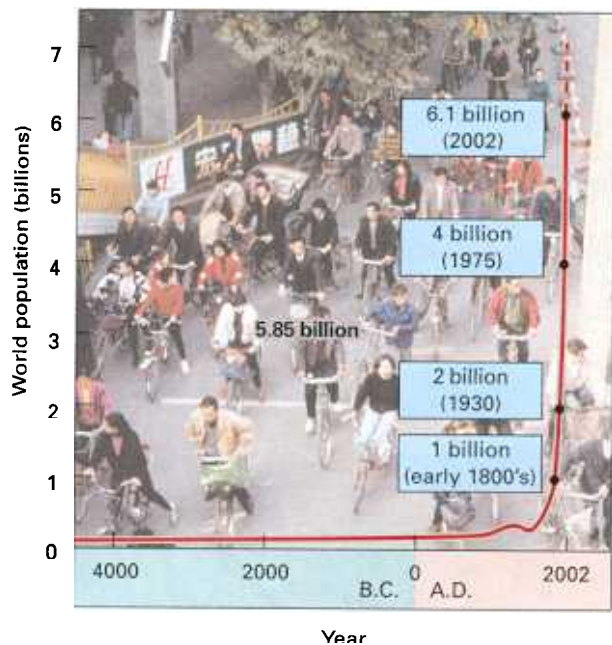
### Catastrophic Change in Earth History

Chances are small that the river flowing through your city will flood this spring, but if you lived to be 100 years old, you would probably see a catastrophic flood. In fact, destructive floods occur every year, somewhere on the planet.

When geologists study the 4.6 billion years of Earth history, they find abundant evidence of catastrophic events that are highly improbable in a human lifetime or even in human history. For example, clues preserved in rock and sediment indicate that giant meteorites have smashed into our planet, vaporizing portions of the crust and spreading dense dust clouds over the sky (Figure 1.13). Geologists have suggested that some meteorite impacts (much larger than that shown



**Figure 1.13** Fifty thousand years ago, a meteorite crashed into the northern Arizona desert, creating Meteor Crater. Catastrophic events have helped shape Earth history.



**Figure 1.14** The human population has increased rapidly since the 1700s. For most of human history, there were fewer than one-half billion people on Earth. In mid-year 2002, 6.1 billion people inhabited our planet. *Source:* Data from the Population Reference Bureau

**Interactive Question:** Approximately how many years did it take for the human population to double from 2 billion to 4 billion? If that doubling rate were to continue, how many people would live on Earth in the year 2500? 3000?

in Figure 1.13) have almost instantaneously driven millions of species into extinction. As another example, when the continental glaciers receded at the end of the last Ice Age, huge floods were orders of magnitude larger than any floods in historic times. In addition, periodically throughout Earth history, catastrophic volcanic eruptions changed conditions for life across the globe.

### Threshold and Feedback Effects

Imagine that some process gradually warmed the atmosphere. Imagine further that the summer temperature of coastal Greenland glaciers was  $-1.0^{\circ}\text{C}$ . If gradual change warmed the atmosphere by  $0.2^{\circ}\text{C}$ , the glaciers would not be affected appreciably because ice melts at  $0^{\circ}\text{C}$  and the summer temperature would remain below freezing,  $-0.8^{\circ}\text{C}$ . But now imagine that gradual warming brought summer temperature to  $-0.2^{\circ}\text{C}$ . At this point, the system is at a threshold. Another small increment of change would raise the temperature to the melting point of ice. As soon as ice starts to melt, large changes occur rapidly: Glaciers recede and global sea level rises. A **threshold effect** occurs when the environment initially changes slowly (or not at all) in response to a small perturbation, but after the threshold is crossed, an additional small perturbation causes rapid and dramatic change.

A **feedback mechanism** occurs when a small initial perturbation affects another component of the Earth systems, which amplifies the original effect, which perturbs the system even more, which leads to an even greater effect, and so on. (Picture a falling

stack of dominos.) The evolution of the Venusian climate is a perfect example of a feedback mechanism: Solar energy evaporated surface water. The water vapor trapped more heat in the atmosphere. The temperature rose. Without surface water, carbon dioxide remained in the atmosphere. Carbon dioxide trapped even more heat. The temperature rose further. And so on.

Threshold and feedback mechanisms remind us that Earth systems often change in ways that are difficult to predict. These complexities provide the challenge and fascination of Earth Science.

## 1.6 Humans and Earth Systems

Ten thousand years ago, a mere eye-blink in Earth history, human population was low and technology was limited. Sparsely scattered bands hunted and gathered for their food, built simple dwellings, and warmed themselves with small hearth fires. Human impact was not appreciably different from that of many other species on the planet. But today there are 6.1 billion people on Earth (Figure 1.14). Farms, pasture lands and cities cover 40 percent of the land area of the planet (Figure 1.15). We divert half of all the fresh water on the continents and control 45 percent of the total net terrestrial biological productivity. As the land and its waters have been domesticated, other animal and plant species have perished. The species extinction rate today is 1000 times more rapid than it was before the Industrial Revolution. In fact, species extinction hasn't



**Figure 1.15** This cloverleaf near Denver, Colorado, is but one example of the global conversion of natural ecosystems into developed landscapes.

been this rapid since a giant meteorite smashed into the Earth's surface 65 million years ago, leading to the demise of the dinosaurs and many other species.

Emissions from our fires, factories, and transportation machines have raised the atmospheric carbon dioxide concentration to its highest level in 420,000 years. In turn, the increased carbon dioxide level has raised the Earth's average surface temperature by almost 1°Celsius.

Roughly 20 percent of the human population lives in wealthy industrialized nations where food, shelter, clean drinking water, efficient sewage disposal, and advanced medical attention are all readily available. At the same time as those in the industrialized, developed nations enjoy opulent sustenance and infrastructure, in the impoverished regions of the world, 1.5 billion people survive on less than one dollar per day. One eighth to one half of the human population on this planet is malnourished and 14 million infants or young children starve to death every year. If you lived in a family in the Himalayan region of northern India, where you spent hours every day gathering scant firewood or cow dung for fuel, where meals consisted of an endless repetition of barley gruel and peas, where

you brought your sheep and goats into the house during the winter so you could all huddle together for warmth, then your view of the planet would be different from what it is now (Figure 1.16).

Regardless of whether we are rich or poor, our survival is interconnected with the flow of energy and materials within Earth systems. We affect the Earth, and at the same time the Earth affects us; it is the most intimate and permanent of marriages.

Predictions for the future are, by their very nature, uncertain. Over 200 years ago, in 1798, the Reverend Thomas Malthus argued that human population was growing exponentially while food production was increasing much more slowly. As a result, humankind was facing famine, "misery and vice." But technological advancements led to an exponential increase in food production, keeping pace—more or less—with population growth. Today, the rate of population growth is slowing, so optimists predict that we may soon reach a halcyon age when people have enough to eat and global ecosystems stabilize.

But many scientists are not so sanguine about our future. These people argue that human population is likely to reach 10 billion and that there are ultimate



## Hypothesis, Theory, and Law

On an afternoon field trip, you may find several different types of rocks or watch a river flow by. But you can never see the rocks or river as they existed in the past or as they will exist in the future. Yet a geologist might explain how the rocks formed millions or even a few billion years ago and might predict how the river valley will change with time.

Scientists not only study events that they have never observed and never will observe, but they also study objects that can never be seen, touched, or felt. In this book we describe the center of the Earth 6400 kilometers beneath our feet and distant galaxies billions of light-years away, even though no one has ever visited these places and no one ever will.

Much of science is built on inferences about events and objects outside the realm of direct experience. An inference is a conclusion based on available information, thought, and reason. How certain are we that a conclusion of this type is correct?

Scientists develop an understanding of the natural world according to a set of guidelines known as the **scientific method**, which involves three basic steps: (1) observation, (2) forming a preliminary conclusion or hypothesis, and (3) testing the hypothesis and developing a theory.

### Observation

All modern science is based on observation. Recall that James Hutton observed that ocean currents and rivers transported and deposited sand. He observed that the sand accumulates slowly, layer by layer. Then he saw cliffs of layered sandstone hundreds of meters high. Observations of this kind are the starting point of science.

### Forming a Hypothesis

A scientist tries to organize observations to recognize patterns. Hutton noted that the sand layers deposited along the coast look just like the layers of sand in the sandstone cliffs. Starting with these observed facts, he then concluded that the thick layers of sandstone had been deposited in an ancient ocean or river delta. He further inferred that, because layers of sand are deposited slowly, the thick layers of sandstone must have accumulated over a long time. Finally, he took one more step of logic to hypothesize that the Earth is old.

A **hypothesis** is a tentative explanation built on strong supporting evidence. Once a scientist or group of scientists proposes a hypothesis, others test it by comparison with additional observations and experiments. If the hypothesis explains some of the facts but not all of them, it must be altered,

or if it cannot be changed satisfactorily, it must be discarded and a new hypothesis developed.

### Testing the Hypothesis and Forming a Theory

If a hypothesis explains new observations as they accumulate and is not substantively contradicted, it becomes accepted by more and more people. As the tentative nature of a hypothesis is gradually dispelled, it is elevated to a **theory**. Theories differ widely in form and content, but all obey four fundamental criteria:

1. A theory must be based on a series of confirmed observations or experimental results.
2. A theory must explain all relevant observations or experimental results.
3. A theory must not contradict any relevant observations or other scientific principles.
4. A theory must be internally consistent. Thus, it must be built in a logical manner so that the conclusions do not contradict any of the original premises.

For example, the theory of plate tectonics states that the outer layer of the Earth is broken into a number of plates that move horizontally relative to one another. As you will see in Chapter 6, this theory is supported by many observations and seems to have no major inconsistencies.

Many theories cannot be absolutely proven. For example, even though scientists are just about certain that their image of atomic structure is correct, no one has or ever will watch an individual electron travel in its orbit. Therefore, our interpretation of atomic structure is called atomic theory.

In some instances, observations are so universal that there is no doubt of their verity. A **law** is a statement of how events always occur under given conditions. It is considered to be factual and correct. For example, the law of gravity states that all objects are attracted to one another in direct proportion to their masses. We cannot conceive of any contradiction to this principle, and none has been observed. Hence, the principle is called a law. Modern science is in such constant flux and our Universe is so complex, that very few laws are formulated any more.

### FOCUS QUESTION:

Obtain a copy of a news article in a weekly news magazine. Underline the facts with one color pencil and the authors' opinions with another. Did the authors follow the rules for the scientific method outlined here to reach their conclusion?



**Figure 1.16** People in the Himalayas scratch a meager living out of thin soil. This photo was taken in Ladakh, northern India.

limits to Earth resources and productivity. John Holdren, professor at the John F. Kennedy School of Government, argues that the problem is “not that we are running out of energy, food, or water but that we are running out of environment—that is, running out of the capacity of air, water, soil and biota to absorb, without intolerable consequences for human well-being, the effects of resource extraction, transportation, transformation, and use.”<sup>1</sup> Professor Holdren and many other like-minded scientists are studying the effects of burgeoning human population and resource consumption. Will we have enough energy to drive the fossil fuel intensive farming needed to feed 10 billion people? But beyond the question of food, many scien-

tists are concerned that we are pushing Earth systems close to thresholds where feedback mechanisms will spiral catastrophically out of control. Will a small additional increase in carbon dioxide concentration trigger a rapid and cataclysmic climate change? If we continue to log our tropical rain forests and fragment existing ecosystems, could we trigger dramatic changes in local weather that destroys the remaining forests, which in turn alters global rainfall patterns?

These are extremely complex questions. This book will not provide definite answers—because there are none—but it will provide a background so that you can understand important issues concerning our stewardship of the planet.

<sup>1</sup>John P. Holdren, “Energy: Asking the Wrong Question.” *Scientific American* (January 2002): 65.

## Summary

On Venus, a runaway greenhouse effect produced torridly hot temperatures; on Mars a reverse greenhouse effect plunged the planet into a deep freeze, while temperate conditions have prevailed on Earth.

Earth consists of four spheres: The **geosphere** is composed of a dense, hot, central **core**, surrounded by a large **mantle** that comprises 80 percent of the Earth's volume, with a thin, rigid **crust**. The crust and mantle are composed of rock while the core is composed of iron and nickel. The **hydrosphere** is mostly ocean water. Most of the Earth's fresh water is locked in glaciers. Most of the liquid fresh water lies in ground water reservoirs; streams, lakes, and rivers account for only 0.01 percent of the planet's water. The **atmosphere** is a mixture of gases, mostly nitrogen and oxygen. The Earth's atmosphere supports life and regulates climate. The **biosphere** is the thin zone inhabited by life.

A **system** is composed of interrelated, interacting components. Energy cannot be recycled, but matter is recycled continuously. The **first law of thermodynamics** states that energy is always conserved. The **second**

**law of thermodynamics** states that energy is always degraded so that it becomes less useful to perform work. In order to understand a system, we must study the exchange of energy and matter both within the system and with the outside surroundings.

The Earth is about 4.6 billion years old; life formed at least 3.8 billion years ago; abundant multicellular life evolved about 544 million years ago, and hominids have been on this planet for a mere 5 to 7 million years.

The principle of **gradualism** or **uniformitarianism** states that geologic change occurs over a long period of time by a sequence of almost imperceptible events. In contrast, **catastrophism** postulates that geologic change occurs mainly during infrequent catastrophic events. In many instances, **threshold** and **feedback** effects modify simple gradualistic or catastrophic processes.

Due to our sheer numbers and technological prowess, humans have become a significant engine of change in Earth systems.

## Key Terms

geosphere 4	tectonic plates 6	sandstone 11	hypothesis 17
hydrosphere 4	ground water 7	gradualism 13	theory 17
atmosphere 4	system 8	uniformitarianism 13	law 17
biosphere 4	first law of	catastrophism 14	
core 6	thermodynamics 9	threshold effect 15	
crust 6	second law of	feedback	
mantle 6	thermodynamics 9	mechanism 15	
lithosphere 6	entropy 9	scientific method 17	

## For Review

1. Explain how water vapor and carbon dioxide influenced the evolution of the climate and atmosphere on Venus, Earth, and Mars.
2. List and briefly describe each of the Earth's four spheres.
3. List the three major layers of the Earth. Which is/are composed of rock, which is/are metallic? Which is the largest; which is the thinnest?
4. List six types of reservoirs that collectively contain most of the Earth's water.
5. What is ground water? Where in the hydrosphere is it located?
6. What two gases compose most of the Earth's atmosphere?
7. How thick is the Earth's atmosphere?
8. Briefly discuss the size and extent of the biosphere.
9. Define a system and explain why a systems approach is useful in Earth science.
10. Briefly explain the statement: "Matter can be recycled, but energy cannot."

11. Summarize the first and second laws of thermodynamics.
12. How old is the Earth? When did life first evolve? How long have humans and their direct ancestors been on this planet?
13. Compare and contrast uniformitarianism and catastrophism. Give an example of each type of geologic change.
14. Briefly explain threshold and feedback effects.
15. Briefly outline the magnitude of human impact on the planet.

### For Discussion

1. What cautionary warnings can you deduce from your knowledge of the evolution of climate and atmospheric composition on Venus, Earth, and Mars?
2. Only 0.64 percent of Earth's water is fresh and liquid—the rest is salty seawater or is frozen in glaciers. What are the environmental implications of such a small proportion of fresh water?
3. List five ways that organisms, including humans, change the Earth. What kinds of Earth processes are unaffected by humans and other organisms?
4. Twelve generic types of interactions are possible among the four spheres. These are:
  - (a) Changes in the solid Earth perturb the hydrosphere.
  - (b) Changes in the hydrosphere perturb the solid Earth.
  - (c) Changes in the solid Earth perturb the atmosphere.
  - (d) Changes in the atmosphere perturb the solid Earth.
  - (e) Changes in the solid Earth perturb the biosphere.
  - (f) Changes in the biosphere perturb the solid Earth.
  - (g) Changes in the hydrosphere perturb the atmosphere.
  - (h) Changes in the atmosphere perturb the hydrosphere.
  - (i) Changes in the hydrosphere perturb the biosphere.
  - (j) Changes in the biosphere perturb the hydrosphere.
  - (k) Changes in the atmosphere perturb the biosphere.
  - (l) Changes in the biosphere perturb the atmosphere.

Write an example to illustrate each possibility.
5. A windmill produces energy from the wind, which is free. Is this a contradiction of the second law of thermodynamics? Explain.
6. Give an example of a threshold or feedback effect in science, politics, human relationships, or any field you can think of.

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