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EARTH SCIENCE

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AN INTRODUCTION

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Earth Science: An Introduction

THIRD EDITION

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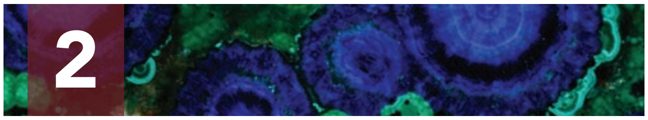

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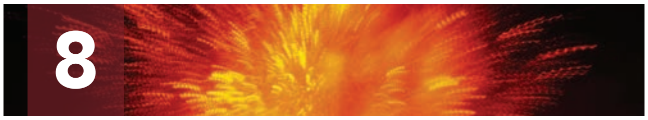
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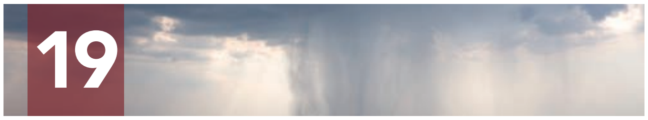

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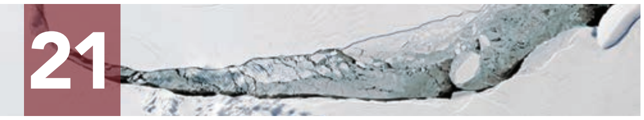
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PREFACE

From our very beginnings, humans have depended on the Earth for survival. The food we eat, air we breathe, and water we drink all exist here and now, because Earth has undergone roughly 4.5 billion years' worth of evolution. In other words, Earth and the current environment is a product of continuous change that resulted—at this point in geologic time—in a planet capable of supporting humans.

If the entire history of Earth were compressed into a single 24-hour period, all of human civilization would have occurred within the very last second, as would have the appearance of Earth's earliest preserved human remains (Homo sapiens). From the standpoint of Earth history, humans are very recent newcomers. The evolution of humans was made possible because Earth itself had evolved to a point in which its temperature, atmospheric composition, surface water chemistry, and food sources were compatible with human survival needs. The continued survival of humans on Earth will depend on whether future changes to the solid Earth, its water, atmosphere, and biology remain within the range of human tolerance.

Today, not only is the Earth and its water, air, and ecology changing rapidly but the changes that are taking place are moving our planet in a direction that is less likely to favor the survival of humans as a species. Changes to our atmosphere, oceans, soils, and ecology are causing the most severe rate of species extinction in 4.5 billion years of Earth's history, and we as humans are living in the midst of this global species extinction event. Either we as humans will adapt to these changing conditions by implementing sustainable uses of Earth's resources or Earth no longer will be able to support human civilization as it exists currently.

Today, more rock and soil on Earth's continents is moved annually by humans than is moved by natural erosion. This fact alone has enormous downstream consequences for Earth's future, because the landscapes and underlying subsurface geology originated over geologic time and the rate of their human-caused change today far surpasses the time needed for them to redevelop. Moreover, as we will explore in this book, planet Earth consists of many interdependent, constantly changing natural systems. The dynamics of each system directly or indirectly affects the others, and perturbation of one system often has unforeseen consequences for another. For example, the shift to biofuels and their increased consumption, particularly in the United States, has supported the widespread development of palm oil plantations in southeastern Asia, a region naturally covered by tropical rainforests. Replacing the rain forests with palm oil plantations requires leveling and plowing of the region. Doing so causes a huge and rapid release of carbon dioxide as the organic-rich rain forest floor is churned up and quickly decays. Ironically, the increased use of palm oil as a fuel has accelerated the release of carbon dioxide into the atmosphere and not decreased it, as intended.

This book is intended to provide a foundational understanding of Earth and the physical, chemical, and biological processes that have shaped it and that continue to shape it today. The entire 4.5-billion-year history of Earth and the big changes in the solid Earth, oceans, atmosphere, and biota over geologic time are examined. Like all modern texts on Earth Science, this book addresses processes that take place over geologic time, including plate tectonics, planetary differentiation, and the evolution of species. In addition, however, this text also examines the current and ongoing changes in Earth's systems taking place over historic time frames, including ocean acidification, global climate change, and the ongoing mass extinction of species. Thus, this book is intended to provide a reference frame for the rapid and unpredictable environmental changes taking place today.

This book is the third edition of *Earth* (2011 and 2014). The first edition was written by Graham R. Thompson and Jon Turk. Both the second edition and this book were substantially revised by Marc S. Hendrix.

This book presents the planet Earth as an integrated system involving the solid Earth, water, the atmosphere, and living organisms and their co-evolution over geologic time at a level suitable for science or nonscience undergraduate students or advanced high-school students. Along with descriptions of Earth's internal and surficial geologic processes, this book examines Earth's oceans, atmosphere, and life forms and the evolution of each through geologic time. The first chapter introduces the four Earth Systems, and Chapters 2 and 3 focus on the materials of solid Earth—rocks and minerals. Geologic time, the evolution of life, and the processes of fossilization are covered in Chapters 4 and 5. Following are four chapters describing geological processes associated with Earth's interior. These chapters expand on plate tectonics, earthquakes, magmatic processes, and mountain building. Chapters 10, 13, and 14 describe surficial processes and how these have shaped Earth's natural landscapes.

Along with the focus on geologic time and Earth's internal and surficial processes, *Earth Science: An Introduction* focuses on Earth's fresh water (Chapter 11) and oceans

(Chapters 15 and 16). Following are three chapters dedicated to understanding Earth's atmosphere (Chapters 17 and 19). Chapters 20 and 21 address Earth's climate and climate change. The last three (Chapters 22–24) examine the moon, planet, and solar system.

Each major topic in this book is viewed through the lens of human impact, both in terms of how Earth's evolution has benefited human society and in terms of how human activity is altering Earth and its solid, liquid, gaseous, and living components. To these ends, one entire chapter is dedicated to Earth's mineral and energy resources (Chapter 5), and another is dedicated to Earth's water resources (Chapter 12). Both chapters are presented against the complicated global sociopolitical backdrop surrounding the extraction, transport, and use of mineral, energy, and water resources.

ACKNOWLEDGMENTS

This book results from over a decade of scientific work and writing by the three contributing authors, and it is not possible to recognize all of the people, both scientists and nonscientists, who have helped to make its publication possible. Included among those whose scientific interactions, insights, and discussions helped to shape the contents of this book (knowingly or not) are Steve Graham, Don Winston, James Sears, James Staub, Bill Woessner, Steve Sheriff, George Stanley, Andrew Wilcox, and Rebecca Bendick. Special thanks must go to product manager Lauren Bakker at Cengage Learning, who initiated this third edition, and to our learning designer Lauren Oliveira and content manager Nicole Evans, who not only kept us on task but also superbly edited and managed the content for this edition as well as provided a fresh perspective on this edition. Thanks to senior designer Helen Bruno for the fresh design. I would also like to recognize marketing manager Andrew Stock and market development manager Roxanne Wang.

I am deeply grateful for the support of my parents, Carol A and Sherman S. Hendrix, and my wife Brigette, without whom the writing of this book would not have been possible. I dedicate this book to our sons Gabriel and Michael Hendrix, whose natural curiosity and frequent requests for explanations as to the book's detailed contents both opened my eyes and kept me on my toes.

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EARTH SYSTEMS

Central California coastline showing elements of the geosphere (sea cliffs), atmosphere (sky), hydrosphere (ocean), and biosphere (vegetation).

LEARNING OBJECTIVES

- **LO1** Describe Earth's four spheres.
- **LO2** Explain the processes that heated up the early Earth.
- **LO3** Compare the layers of the Earth in terms of physical characteristics.
- **LO4** Discuss the distribution of water in the hydrosphere.
- **LO5** Explain how the Earth can be viewed as a system and a group of systems.
- **LO6** Compare geologic time to the timeframe of human history.
- **LO7** Summarize James Hutton's perspectives on geologic time.
- **LO8** Contrast William Whewell's and James Hutton's viewpoints of Earth history.
- **LO9** Give an example of a threshold effect and feedback mechanism.
- **LO10** Discuss the effect humankind has had on the biosphere.

INTRODUCTION

Earth is sometimes called the water planet or the blue planet because azure seas cover more than two-thirds of its surface. Earth is the only planet or moon in the Solar System in which water falls from clouds as rain, runs across the land surface, and collects in extensive oceans. It is also the only body we know of that supports life.

THE EARTH'S FOUR SPHERES

Imagine walking along a sandy beach as a storm blows in from the sea. Wind whips the ocean into whitecaps, while large waves crash onto shore. Blowing sand stings your eyes as gulls overhead frantically beat their wings en route to finding shelter. In minutes, blowing spray has soaked your clothes. A hard rain begins as you hurry back to your vehicle. During this adventure, you have experienced the four major spheres of Earth. The beach sand underfoot is 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 blowing wind belongs to 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 drift across the sky and wind blows against your face. In the biosphere, 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 on a day-to-day basis, the geosphere is also moving and dynamic. Vast masses of solid rock flow very slowly within the planet's interior. Continents move, while intervening ocean basins slowly open, then collapse. Mountains rise and then erode into sediment. Throughout this book, we will study many of these phenomena to learn which energy forces set matter in motion and how these motions affect the planet on which we live. ●**FIGURE 1.1** shows schematically all the possible interactions among the spheres.

●**FIGURE 1.2** shows that the geosphere is by far the largest of the four spheres. The Earth's radius is about 6,400 kilometers, roughly the same distance as Miami to Anchorage. Despite this great size, nearly all of our direct contact with Earth occurs at or very near its surface. The deepest well penetrates little more than 12 kilometers, less than two-tenths of 1 percent of the distance to Earth's center. The oceans make up most of the hydrosphere, and although it can extend as deep as 11 kilometers, the ocean floor averages only about 4 kilometers in depth. Most of Earth's atmosphere lies within 30 kilometers of the surface, and the biosphere is a thin shell about 15 kilometers thick.

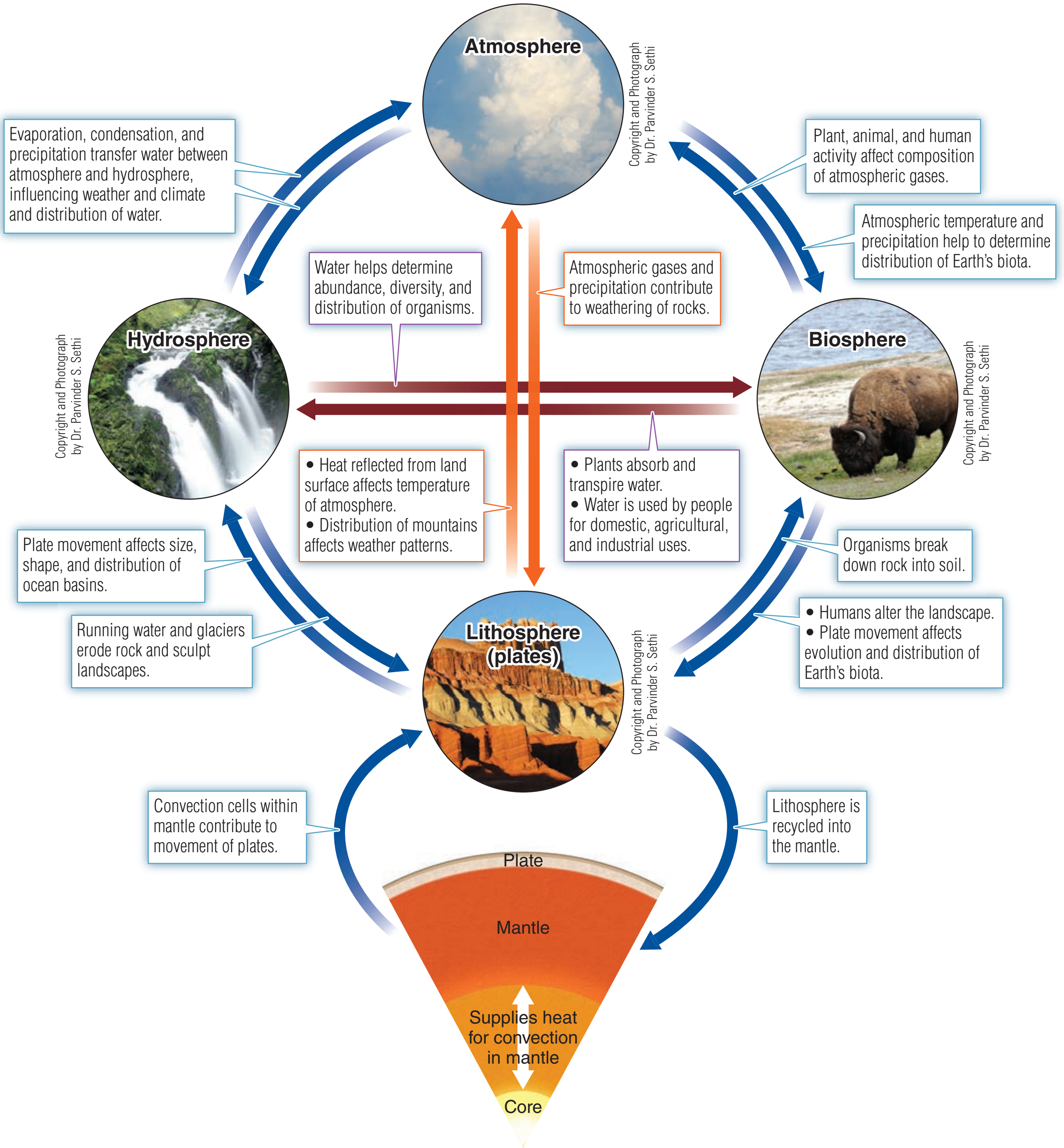
The Geosphere

Our Solar System coalesced from a frigid cloud of dust and gas rotating slowly in space. The Sun 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. Eventually, small grains of matter within the disk stuck together to form fist-sized masses. These planetary "seeds" then accreted to form rocky clumps, which grew to form larger bodies, called *planetesimals*, 100 to 1,000 kilometers in diameter. Finally, the planetesimals consolidated to form the planets. This process was completed about 4.6 billion years ago.

As the Earth coalesced, gravity caused the rocky chunks and planetesimals to accelerate 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 planetesimals crashed into the surface, generating additional heat. At the same time, radioactive decay heated the Earth's interior. These three processes caused the early Earth to become so hot that much of the planet melted as it formed.

Within the molten Earth, the denser materials sunk 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 1.2).

The temperature of modern Earth increases with depth. At its center, Earth is 6,000°C—as hot as the Sun's surface. The core is composed mainly of iron and nickel. The outer core is molten metal. However, the inner core, although hotter yet, is solid because the great pressure compresses the metal to a solid state.



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● **FIGURE 1.1** All of Earth's cycles and spheres are interconnected.

geosphere The solid Earth, consisting of the entire planet from the center of the core to the outer crust.

hydrosphere All of Earth's water, which circulates among oceans, continents, glaciers, and atmosphere.

atmosphere The gaseous layer above the Earth's surface, mostly nitrogen and oxygen, with smaller amounts of argon, carbon dioxide, and other gases. The atmosphere is held to Earth by gravity and thins rapidly with altitude.

biosphere The zone of Earth comprising all forms of life in the sea, on land, and in the air.

core The dense, metallic, innermost region of Earth's geosphere, consisting mainly of iron and nickel. The outer core is molten, but the inner core is solid.

mantle The rocky, mostly solid layer of Earth's geosphere lying beneath the crust and above the core. The mantle extends from the base of the crust to a depth of about 2,900 kilometers.

crust The outermost layer of Earth's geosphere, ranging from 4 to 75 kilometers thick and composed of relative low-density silicate rocks.

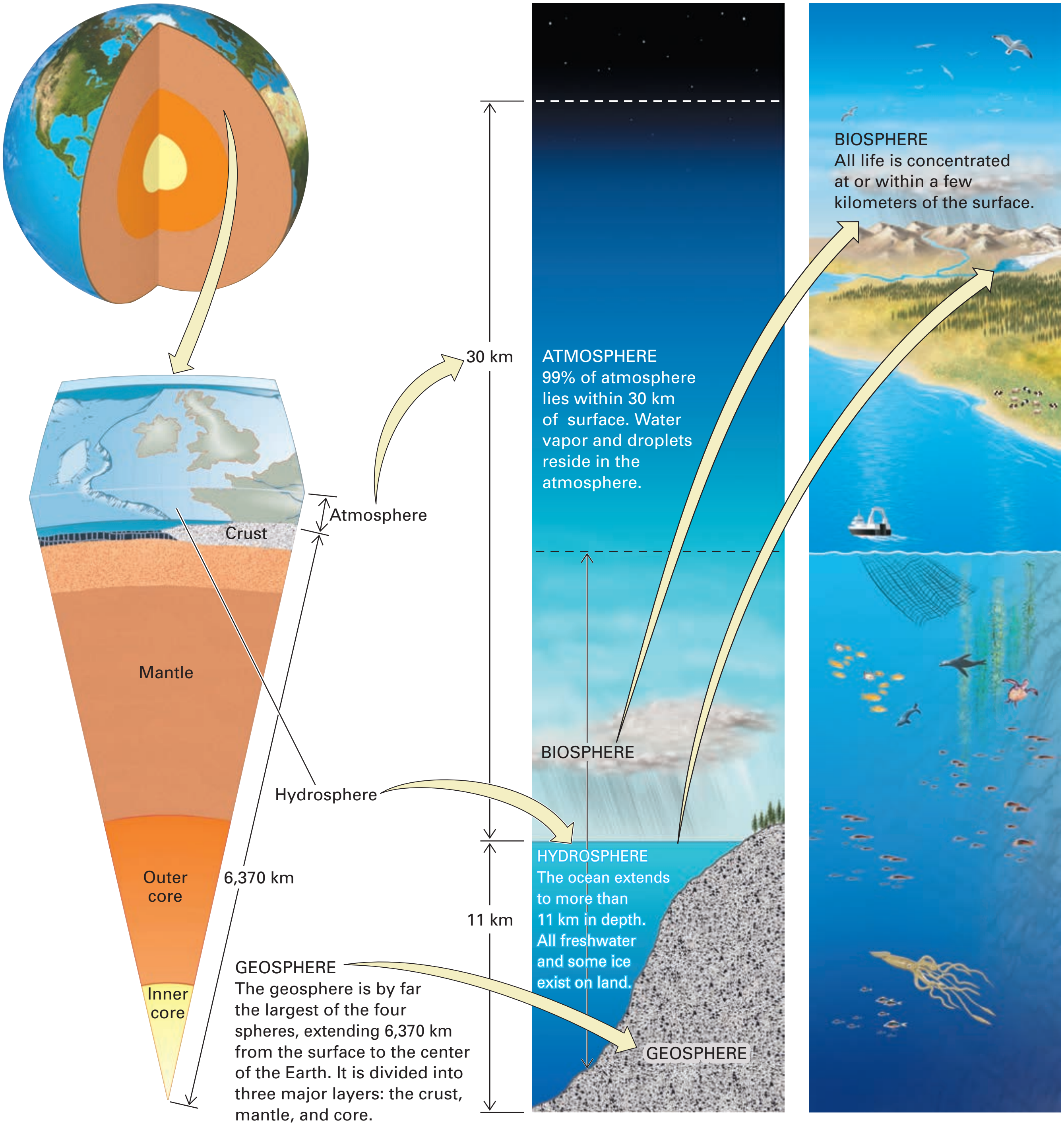
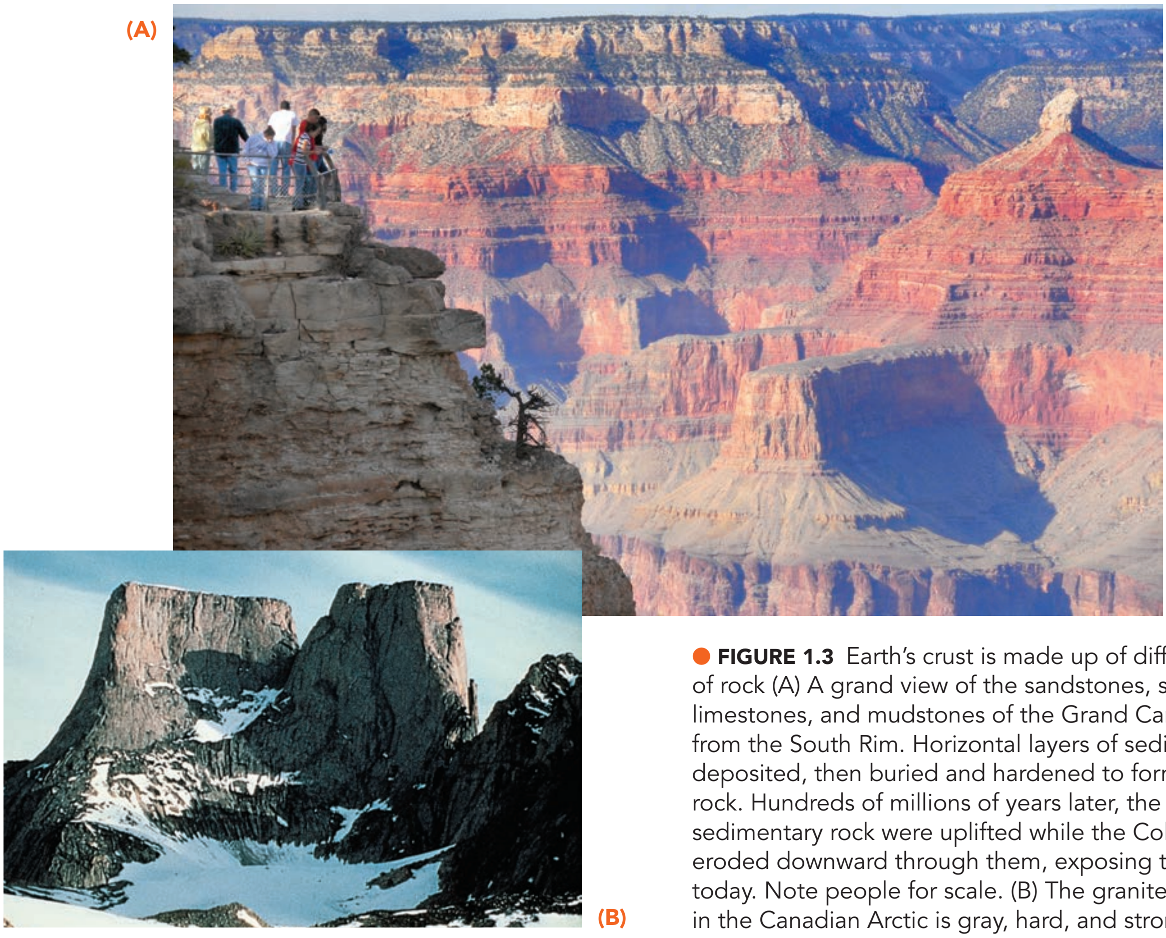


FIGURE 1.2 The geosphere is the largest component of Earth. It is surrounded by the hydrosphere, the biosphere, and the atmosphere.

The mantle surrounds the core and lies beneath the crust. The physical characteristics of the mantle vary with depth. From its upper surface to a depth of about 100 kilometers, the outermost mantle is relatively cool, strong, and hard. However, below a depth of 100 kilometers, rock making up the mantle is so hot that it is weak, soft, *plastic* (a solid that will deform permanently), and flows slowly—like cold honey. Even deeper in the mantle, pressure overwhelms temperature, and the rock becomes strong again.

The crust is the outermost layer of rock extending from the ground surface or bottom of the ocean to the top of the mantle. The crust ranges from as little as 4 kilometers thick beneath the oceans to as much as 75 kilometers thick beneath the continents. Even a casual observer sees that the crust includes many different rock types: some are soft, others hard, and they come in many colors, as you can see in ●**FIGURE 1.3**.

The relatively cool, hard, and strong rock of the uppermost mantle is similar to that of the crust. Together



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Courtesy of Graham R. Thompson/Jonathan Turk

● **FIGURE 1.3** Earth's crust is made up of different kinds of rock (A) A grand view of the sandstones, siltstones, limestones, and mudstones of the Grand Canyon, as seen from the South Rim. Horizontal layers of sediment were deposited, then buried and hardened to form sedimentary rock. Hundreds of millions of years later, the layers of sedimentary rock were uplifted while the Colorado River eroded downward through them, exposing the view we see today. Note people for scale. (B) The granite of Baffin Island in the Canadian Arctic is gray, hard, and strong.

these layers make up the **lithosphere**, which averages about 100 kilometers thick.

According to the theory of plate tectonics, developed in the 1960s, the lithosphere is divided into seven major and eight smaller segments called **tectonic plates**. These tectonic plates float on the relatively hot, weak, plastic mantle rock beneath and move horizontally with respect to each other (●**FIGURE 1.4**). For example, North and South America are currently moving west relative to Eurasia and Africa about as fast as your fingernails grow. These continental movements are causing the Atlantic Ocean to grow larger and the Pacific Ocean to shrink. 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, completely collapsing the Pacific Ocean and crumpling the leading edges of the continents together into a giant mountain range. In later chapters, we will learn how the theory of plate tectonics explains earthquakes, volcanic eruptions, and the formation of mountain ranges, as well as many other processes and events that have created our modern Earth and its environment.

Scientific awareness, much less scientific understanding, of plate tectonics did not occur until after World War II and it was not widely accepted among scientists until the late 1960s. Since then, advances in modern technology have accelerated, and so have the tools available for scientists to probe Earth's interior and study its dynamics. Similarly, accelerating computational capacity and new tools are constantly being developed and deployed to explore Earth's oceans and atmosphere. In aggregate, these new tools have generated immense volume of new data available for scientific exploration of Earth's systems. Electronic accessibility to peer-reviewed scientific publications describing the results and analysis of that scientific exploration broadens the global community of scientists and educated nonscientists alike. All in all, it is a marvelous time to study Earth Sciences. Earth is dynamic, and we are just beginning to appreciate how much so that is.

The Hydrosphere

The hydrosphere includes all of Earth's water, which circulates among oceans, continents, glaciers, and the atmosphere. ●**FIGURE 1.5** shows the proportion of water in each of these areas. Oceans cover 71 percent of Earth and contain 97.5 percent of its water. Ocean currents transport heat across vast distances, altering global climate.

lithosphere The cool, rigid, outer part of Earth, which includes the crust and the uppermost mantle, is about 100 kilometers thick and makes up Earth's tectonic plates.

tectonic plates The segments of Earth's outermost, cool, rigid shell, comprising the lithosphere. Tectonic plates float on the weak, plastic rock of the asthenosphere beneath.

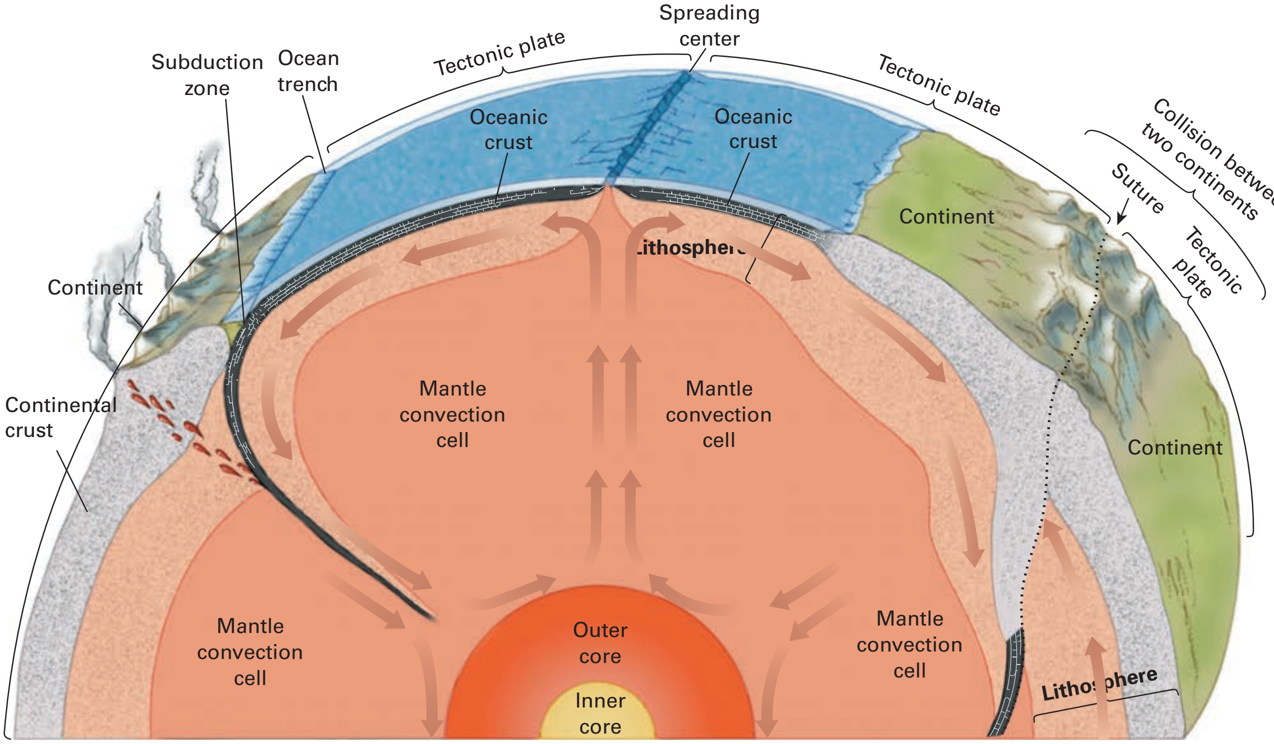

FIGURE 1.4 The lithosphere is composed of the crust and the uppermost mantle. It is a 100-kilometer-thick layer of strong rock that floats on the underlying plastic mantle. The lithosphere is broken into seven major segments, called tectonic plates, that glide horizontally over the plastic mantle at rates of a few centimeters per year. In the drawing, the thickness of the mantle and the lithosphere are exaggerated to show detail.

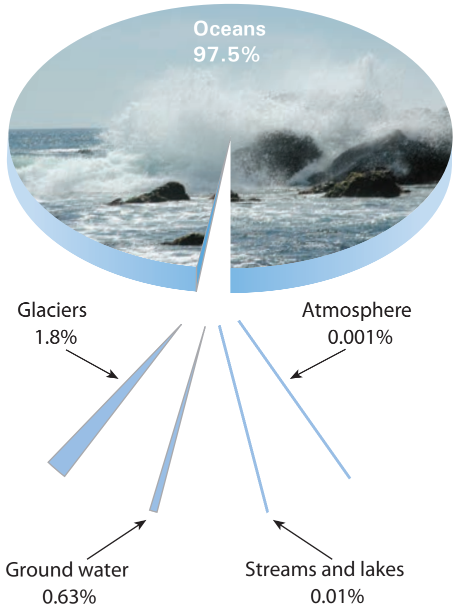

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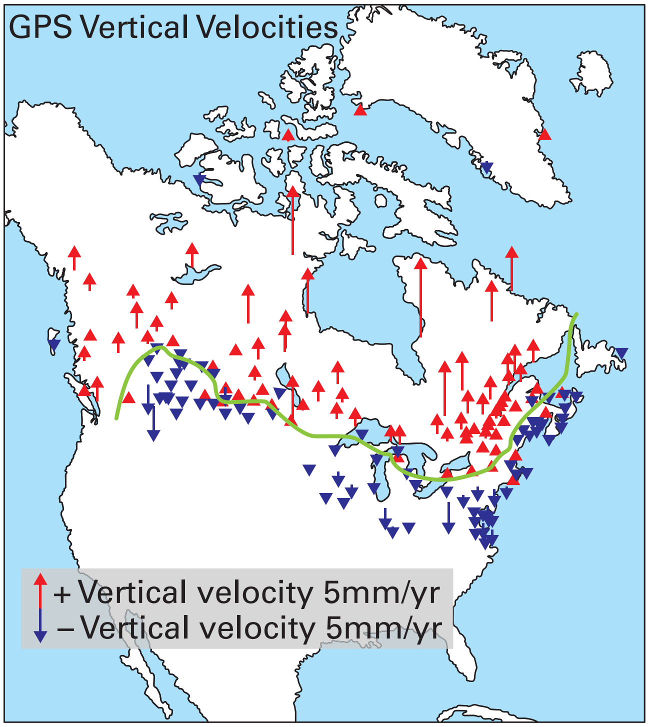
FIGURE 1.5 The oceans contain most of Earth's surface water. Most freshwater is frozen into glaciers. Most available freshwater is stored underground as groundwater.

About 1.8 percent of Earth's water is frozen in glaciers. Although glaciers cover about 10 percent of Earth's land surface today, they covered much greater portions of the globe as recently as 18,000 years ago. During this glacial period, nearly all of Canada, the British Isles, and Scandinavia were covered with ice that was locally up to 4 kilometers thick. In North America, the ice was so massive that it caused the underlying lithosphere to sag beneath its weight. Hudson Bay in Canada exists because the glacial ice melted faster than the lithosphere was able to bounce back. Today, parts of the Hudsons Bay region are undergoing over 10 cm of uplift per year as the lithosphere continues to recover from the weight of the ice. As shown on **FIGURE 1.6**, upward velocity rates of the ground surface decrease south of Hudson Bay to zero in the Great Lakes region. South of the Great Lakes, the ground surface is slowly subsiding downward. The boundary between upward-rebounding and slowly subsiding regions (green line in Figure 1.6) corresponds very roughly to the maximum advance of continental glaciers during the Last Glacial Maximum about 18,000 years ago.

Only about 0.64 percent of Earth's total water exists on the continents as a liquid. Although this is a small proportion, freshwater 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 Earth's water. In contrast, **groundwater**—which occurs in pores, spaces within soil and rock of the upper few kilometers of the geosphere—is much more voluminous and accounts for 0.63 percent of Earth's water. Only a minuscule amount of water, 0.001 percent, exists in the atmosphere, but



● **FIGURE 1.6** Map showing vertical velocities of the ground surface in North America. Each blue arrow shows downward movement of the ground surface, with the length of the arrow proportional to the velocity measurement as shown in the key. Each red arrow shows upward movement of the ground surface, with the length of each arrow similarly proportional to the velocity magnitude. The green line demarcates the boundary between upward and downward moving regions and is approximately coincident with the southernmost advance of continental ice sheets during the Last Glacial Maximum, approximately 18,000 years ago.

because it is so mobile, this atmospheric water profoundly affects both the weather and the climate of our planet.

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 Earth by gravity and thins rapidly with altitude. Ninety-nine percent is concentrated in the first 30 kilometers, but traces of atmospheric gas occur as far as 10,000 kilometers above 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 serves as both a blanket and a filter, 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.

The Biosphere

The biosphere is the zone that life inhabits. 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 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 under glacial ice and in rock to depths of as great as 4 kilometers. Some organisms live on the ocean floor, including entire thriving ecosystems based off mineral-rich, super-heated water spewing from vents along the mid-ocean ridges. A few windblown microorganisms drift at heights of 10 kilometers or more. Despite these extremes, the biosphere is a very thin layer at Earth's surface.

Plants and animals are clearly affected by 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. But plants and animals also alter the atmosphere through respiration and contribute organic matter to the geosphere when they die.

EARTH SYSTEMS

A **system** is any assemblage or combination of interacting components that forms a complex whole. For example, the human body is a system composed of bones, nerves, muscles, and a variety of specialized organs. Each organ is discrete, yet all the organs interact to produce a living human. For example, blood nurtures the stomach, and the stomach helps provide energy to maintain the blood.

Systems are driven by the flow of matter and energy. Thus, a person ingests food, which contains both matter and chemical energy, and inhales oxygen. Waste products are released through urine, feces, sweat, and exhaled breath. Some energy is used for respiration and motion, and the remainder is released as heat or stored as fat.

A single system may be composed of many smaller ones. For instance, the human body contains hundreds of millions of bacteria, each of which is its own system. Many of these bacteria are essential to the functioning of human metabolic processes such as digestion.

In addition, humans are part of their local **ecosystem**, which is defined as a complex community of organisms and their environment functioning as an ecological unit in nature. Therefore, to understand the human body system, we must study smaller systems (e.g., bacteria) that exist within the body, while also exploring how humans interact with their larger ecosystems.

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groundwater Subsurface water contained in the soil and bedrock of the upper few kilometers of the geosphere, comprising about 0.63 percent of all water in the hydrosphere.

system Any combination of interacting components that form a complex whole.

ecosystem A complex community of individual organisms interacting with each other and with their physical environment and functioning as an ecological unit in nature.

But we're not finished yet. Individual ecosystems interact with climate systems, ocean currents, and other Earth systems. Thus:

- The size of systems varies dramatically.
- Large systems contain numerous smaller systems.
- Systems interact with one another in complex ways.

As we have learned, Earth is composed of four major systems: geosphere, hydrosphere, atmosphere, and biosphere. Each of these large systems is subdivided into a great many interacting smaller ones. For example, a single volcanic eruption is part of a system. Energy from deep within Earth melts rock, forming magma. Some of this magma escapes during the eruption, along with volcanic gases that react chemically with surface materials. But this volcanic eruption is driven by the distribution and movement of heat within Earth's interior, which is also a system. Volcanic ash and certain gases spewed skyward during the eruption can affect local weather and cool Earth's climate, thereby becoming part of these systems. Heat from the eruption can also rapidly melt glaciers growing near the summit of the volcano, affecting the local hydrologic system. In this book, we will study systems of all sizes and illustrate many of the complex interactions among them.

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, and ocean currents move in response to wind or differences in water temperature or density. Luckily for us, Earth receives a continuous influx of solar energy, and it will continue to receive this energy for another 5 billion years or so.

In contrast, 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 of heat in later chapters.

Fundamental to our study of Earth systems are several energy and material cycles. A **cycle** is a sequential process or phenomenon that returns to its beginning and then repeats itself over and over. During the course of these cycles, matter and energy both are always conserved. They never simply disappear, although either may continuously change form. For example, water evaporates from the ocean into the atmosphere, falls to Earth as rain or snow, and eventually flows back to the oceans. Ultraviolet radiation that we cannot see enters Earth's atmosphere from the sun and heats up the surface which in turn emits heat. In this book, we will examine the rock cycle (Chapter 3), the hydrologic cycle or water cycle (Chapter 11), the carbon cycle (Chapter 17), and the nitrogen cycle (Chapter 17). We will also explore the critical role that energy and transformations of energy from one form to another play in Earth's oceans (Chapters 15 and 16) and atmospheric processes (Chapters 17–19).

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. Water, for example, is chemically bound into clays and other minerals as a component of the geosphere. It is the primary constituent of the hydrosphere and exists in the atmosphere as vapor and clouds. Water is also an essential part of all living organisms. Salt is another example. Thick layers of salt occur as chemical sedimentary rocks; large quantities of salt are dissolved in the oceans; salt aerosols are suspended in the atmosphere; and salt is an essential component of life. As we can see, all the spheres continuously exchange matter and energy. 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 1.1).

TIME AND RATES OF CHANGE 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. He also noted that rocks in the Scottish Highlands slowly decompose into sand and that streams carry sand into the Lowlands. He inferred that sandstone is composed of sand grains that originated from 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 streambeds. 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 had no way of measuring the magnitude of geologic time. However, modern geologists have learned that certain radioactive materials in rocks can be used as clocks to record the passage of time. Using these "clocks" and other clues embedded in Earth's crust, in the Moon, and in meteorites fallen from the Solar System, geologists estimate that Earth formed 4.6 billion years ago.

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

No one knows exactly when or how 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 542 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, or roughly only one-tenth of 1 percent of the planet's history.

In his book *Basin and Range*, John McPhee offers a metaphor for the magnitude of geologic time.[1] If the history of 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 1.7** summarizes Earth history in graphical form.

Geologists routinely talk about events that occurred millions or even billions of years ago. For example, about 1.7 billion years ago, the granite now forming Mount Rushmore cooled from a melt and crystallized. About a half billion years ago, the Appalachian Mountains began to form from tectonic crumpling of the eastern part of the North American plate. About 150 million years ago, a blanket of mud containing the remains of tiny plankton accumulated in deep water off the West Coast of North America. That sediment has since hardened to sedimentary rock that was subsequently added to the westernmost edge of North America by tectonic plate motions and today forms the bedrock on which the northern end of the Golden Gate Bridge rests. (●**FIGURE 1.8**).

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

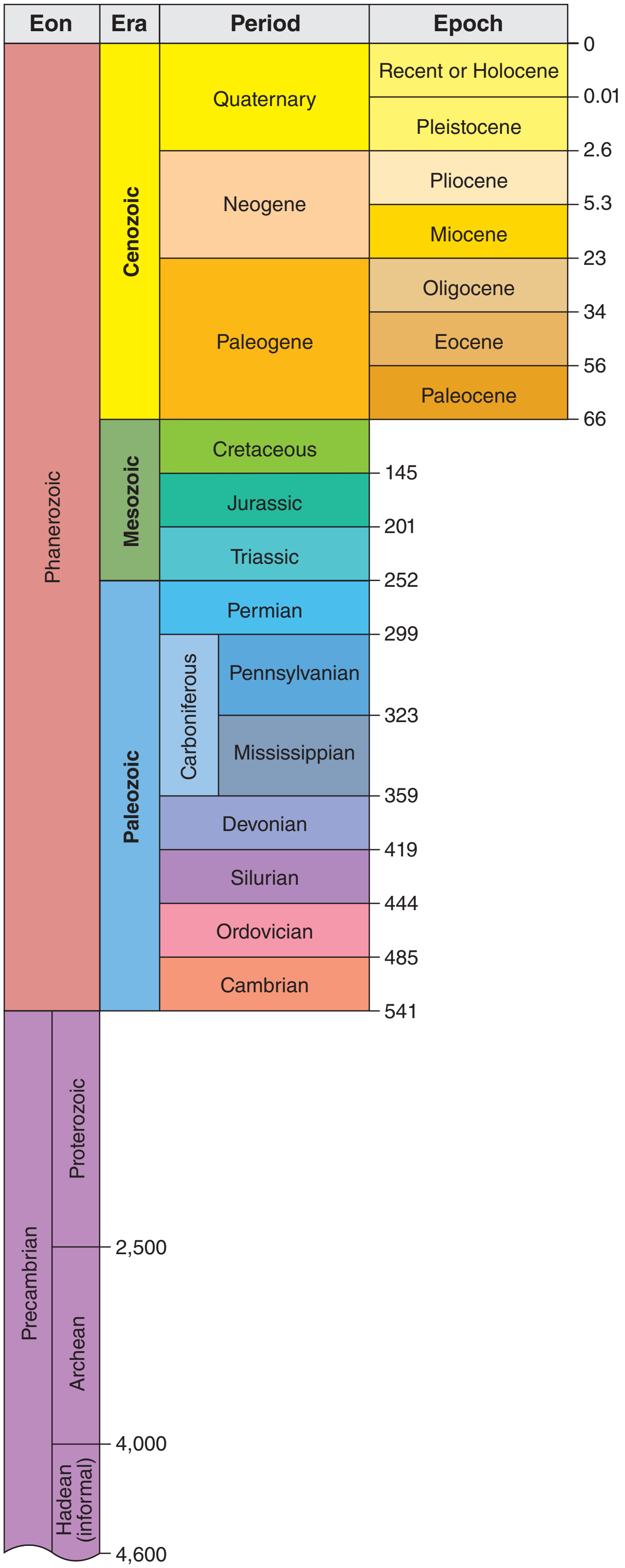
1. Events that occur slowly become significant. If a continent moves a few centimeters a year, the movement makes no noticeable alteration of Earth systems over decades or centuries. But over hundreds of millions of years, the effects are significant.
2. Improbable events occur regularly. The chances 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.

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 the principles now known as **gradualism** and **uniformitarianism**. The principle of gradualism states that geologic change occurs over long periods of time, by a sequence of almost-imperceptible events.

cycle A sequential process or phenomenon that returns to its beginning and then repeats itself over and over.

gradualism A principle stating that geological change occurs as a consequence of slow or gradual accumulation of small events, such as the slow erosion of mountains by wind and rain. More recently, scientists studying biological evolution use the term to describe a theory of evolution that proposes that species change gradually in small increments.

uniformitarianism A principle stating that the geologic processes operating today also operated in the past.



● **FIGURE 1.7** The geologic time scale. Note the great length of time before multicellular organisms became abundant about 541 million years ago.

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[1] John McPhee, *Basin and Range* (New York: Farrar, Straus & Giroux, 1982).