HENDRIX / THOMPSON

# EARTH 2

STUDENT EDITION

## WHAT'S INSIDE:

*A Student-Tested, Faculty-Approved Approach to Learning* **EARTH SCIENCE**

Study Smarter with tear-out Review Cards

*Apply Your Skills with Virtual Field Trips*

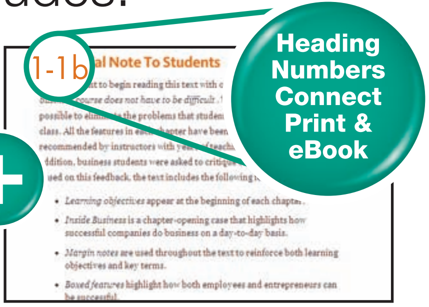
* **PLUS** *
**CourseMate Delivers** an Interactive eBook, Flashcards, Auto-Graded Quizzes, Interactive Games, and More!

**$84.95 US** Suggested Retail Price
ISBN-13: 978-1-285-44226-6
ISBN-10: 1-285-44226-1
90000
9 781285 442266

STUDENT TESTED, FACULTY APPROVED

# THE EARTH SOLUTION

## Every 4LTR Press solution includes:



al Note To Students

…nt to begin reading this text with c…
…course does not have to be difficult…
possible to elim… the problems that studen…
class. All the features in ea… chapter have been…
recommended by instructors with years of teachi…
…ddition, business students were asked to critique…
…sed on this feedback, the text includes the following…

- *Learning objectives* appear at the beginning of each chapter.
- *Inside Business* is a chapter-opening case that highlights how successful companies do business on a day-to-day basis.
- *Margin notes* are used throughout the text to reinforce both learning objectives and key terms.
- *Boxed features* highlight how both employees and entrepreneurs can be successful.

**Visually Engaging Textbook**

**Online Study Tools**

**Tear-out Review Cards**

**Interactive eBook**

## STUDENT RESOURCES:

- Interactive eBook
- Auto-Graded Quizzes
- Flashcards
- Virtual Field Trips
- Video Exercises
- Student Review Cards

Students sign in at **www.cengagebrain.com**

## INSTRUCTOR RESOURCES:

- All Student Resources
- Engagement Tracker
- Instructor's Manual
- Test Bank
- PowerPoint® Slides
- Instructor Prep Cards

Instructors sign in at **www.cengage.com/login**

> "Useful and fun. It helped spark my learning, and when I did not feel like studying, it would help me get motivated." – **David Robinson**, Student, *Baton Rouge Community College*

JULY 2010

4LTR Press adds eBooks in response to a 10% uptick in digital learning preferences.

AUGUST 2010

Engagement Tracker launches, giving faculty a window into student usage of digital tools.

1 out of every 3 (1,400) schools has adopted a 4LTR Press solution.

750,000 students are IN.

NOVEMBER 2010

Third party research confirms that 4LTR Press digital solutions improve retention and outcomes.

IN 2011

60 unique solutions across multiple course areas validates the 4LTR Press concept.

IN 2011

CourseMate

Students access the 4LTR Press website at 4x's the industry average.

APRIL 2011

1 out of every 2 (2,000) schools has a 4LTR Press adoption.

2,000

AUGUST 2011

Over 1 million students are IN.

2013 AND BEYOND

We're always evolving. Join the 4LTR Press In-Crowd on Facebook at www.facebook.com/4ltrpress

CENGAGE
Learning®

***EARTH*, Second Edition**
**Hendrix, Thompson, Turk**

Product Director: Yolanda Cossio

Product Manager: Aileen Berg

Content Developer: Jake Warde

Content Coordinator: Kellie Petruzzelli

Product Assistant: Victor Luu

Media Developer: Stefanie Beeck

Marketing Manager: Lindsy Lettre

Content Project Manager: Tanya Nigh

Art Director: Pam Galbreath

Manufacturing Planner: Rebecca Cross

Rights Acquisitions Specialist:
Don Schlotman

Production Service and Compositor: Integra

Photo and Text Researchers:
PreMedia Global

Text and Cover Designer:
Red Hanger Design, LLC

Cover Images: Shutterstock/Spirit of America and Shutterstock/Anton Gvozdikov

Inside Front Cover: © iStockphoto.com/sdominick; © iStockphoto.com/alexsl; © iStockphoto.com/A-Digit

Page i: © iStockphoto.com/CostinT; © iStockphoto.com/photovideostock; © iStockphoto.com/Leontura

Back Cover: © iStockphoto.com/René Mansi

Digging Deeper: schankz/Shutterstock.com; Pinkyone/Shutterstock.com

Virtual Field Trip: Brooke Becker/Shutterstock.com; mmello/iStockphoto.com; U.P.images/Shutterstock.com; HKPNC/iStockphoto.com

For product information and technology assistance, contact us at
**Cengage Learning Customer & Sales Support, 1-800-354-9706**.

For permission to use material from this text or product,
submit all requests online at **www.cengage.com/permissions**.
Further permissions questions can be e-mailed to
**permissionrequest@cengage.com**.

Library of Congress Control Number: 2013952108

ISBN-13: 978-1-285-44226-6

ISBN-10: 1-285-44226-1

**Cengage Learning**
200 First Stamford Place, 4th Floor
Stamford, CT 06902
USA

Cengage Learning is a leading provider of customized learning solutions with office locations around the globe, including Singapore, the United Kingdom, Australia, Mexico, Brazil, and Japan. Locate your local office at **www.cengage.com/global**.

Cengage Learning products are represented in Canada by
Nelson Education, Ltd.

To learn more about Cengage Learning Solutions, visit **www.cengage.com.**

Purchase any of our products at your local college store or at our preferred online store **www.cengagebrain.com**.

Printed in the United States of America
1 2 3 4 5 6 7 17 16 15 14 13

ANAKEN2012/ SHUTTERSTOCK.COM

# Brief Contents

© ISTOCKPHOTO.COM

ANAKEN2012/
SHUTTERSTOCK.COM

# Contents

## UNIT 1
## EARTH MATERIALS AND TIME

COPYRIGHT AND PHOTOGRAPH BY
DR. PARVINDER S. SETHI

COPYRIGHT AND PHOTOGRAPH BY DR. PARVINDER S. SETHI/
SMITHSONIAN MUSEUM OF NATURAL HISTORY

UNIT 2
## INTERNAL PROCESSES

COPYRIGHT AND PHOTOGRAPH BY DR. PARVINDER S. SETHI

USGS

© STEVEN PEPPLE/SHUTTERSTOCK

## UNIT 3
## SURFACE PROCESSES

## Chapter 10
## Weathering, Soil, and Erosion 184

COURTESY OF GRAHAM R. THOMPSON/JONATHAN TURK

## Chapter 11
## Freshwater: Streams, Lakes, Wetlands, and Groundwater 212

## Chapter 12
## Water Resources 240

UNIT 4
**THE OCEANS**

© CARLOS AMEGLIO/SHUTTERSTOCK

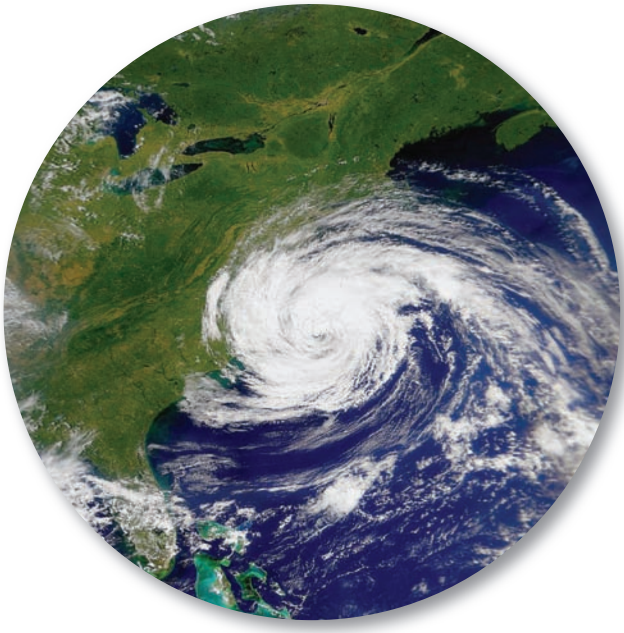
© ANTON FOLTIN/SHUTTERSTOCK

## Chapter 16
## Oceans and Coastlines 328

## UNIT 5
## THE ATMOSPHERE: EVOLUTION AND COMPOSITION

## Chapter 17
## The Atmosphere 354

## Chapter 18
## Energy Balance in the Atmosphere 370



COPYRIGHT AND PHOTOGRAPH BY DR. PARVINDER S. SETHI

# UNIT 6 (ONLINE ONLY)
# ASTRONOMY

© AUSTRALIAN ASTRONOMICAL OBSERVATORY

# Virtual Field Trips of our EARTH: Let's Go!

## GOALS OF THE TRIP

1. Improve student understanding of difficult geological concepts
2. Get students into the field
3. Deliver a more meaningful experience to today's technology

## GET INTO THE FIELD

With access to the complete set of Virtual Field Trips in Geology, EARTH 2 makes it easier that ever to engage students while educating them on the geologic concepts they need to succeed. Virtual Field Trips provide dynamic panoramas, high-definition videos and photos, key concepts, critical thinking questions, and more to serve diverse learning styles. Now available with all 15 Virtual Field Trips, EARTH 2 enables students to explore famous national parks throughout the United States while being guided by a virtual instructor!

**Instructors:** To learn more about Virtual Field Trips, see a video demo, or get access, please visit **www.cengage.com/earthscience/community** and click on the Virtual Field Trips page.

**Students:** To access Virtual Field Trips, sign in with your access code at **www.cengagebrain.com**

ALL PHOTOGRAPHS: COPYRIGHT AND PHOTOGRAPH BY DR. PARVINDER S. SETHI

▲ **Plate Tectonics**
Mount St. Helens and Sideling Hill Syncline

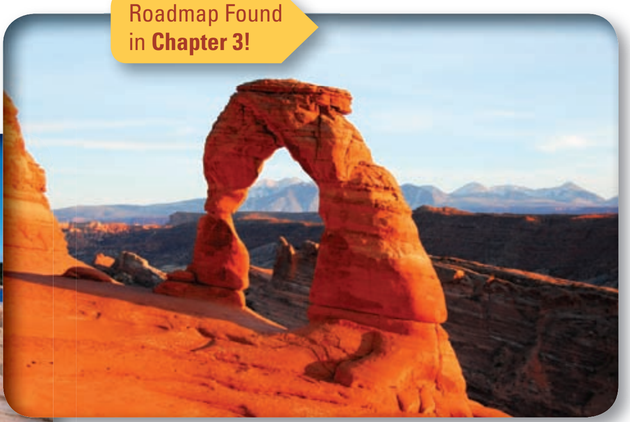
**Mineral Resources** ▶
Bingham Canyon Mine

◀ **Volcano Types**
Hawaii Volcanoes National Park and Mount St. Helens

◀ **Igneous Rocks**
Hawaii Volcanoes and Yosemite National Parks

▼ **Sedimentary Rocks**
Arches and Capitol Reef National Parks

Roadmap Found in **Chapter 3!**



**Metamorphic Rocks** ▶
Acadia National Park

▲ **Earthquakes and Seismicity**
Los Trancos Open Space Preserve
and Pt. Reyes National Seashore

Roadmap Found
in **Chapter 11!**

▲ **Running Water**
Zion National Park

▲ **Mass Wasting**
Arches and Yosemite
National Parks

▼ **Groundwater**
Mammoth Cave National Park

Roadmap Found
in **Chapter 4!**

▲ **Geologic Time**
Grand Canyon and Capitol Reef National parks

◀ **Hydrothermal Activity**
Yellowstone National Park

Roadmap Found
in **Chapter 8!**

▲ **Glaciers and Glaciation**
Kenai Fjords National Park
and Prince William Sound

**Shorelines and**
**Shoreline Processes** ▶
Bandon Beach

◀ **Desert Environments**
Death Valley National Park

Roadmap Found
in **Chapter 14!**

ALL PHOTOGRAPHS: COPYRIGHT AND
PHOTOGRAPH BY DR. PARVINDER S. SETHI

# 1

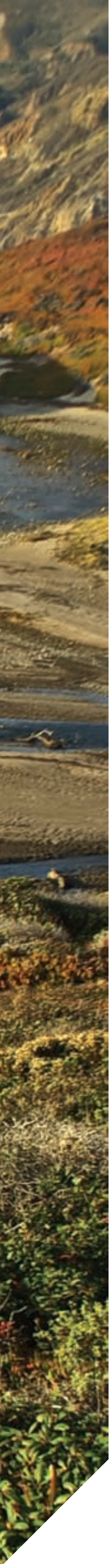
# Earth Systems

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

## SECTIONS

VISIT 4LTRPRESS.CENGAGE.COM

GO TO PAGE 15 FOR STUDY TOOLS



COURTESY OF MATTHEW P MCARDLE

> ***When we try to pick out anything by itself, we find it hitched to everything else in the Universe.***
>
> *John Muir*

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.

## 1-1 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.

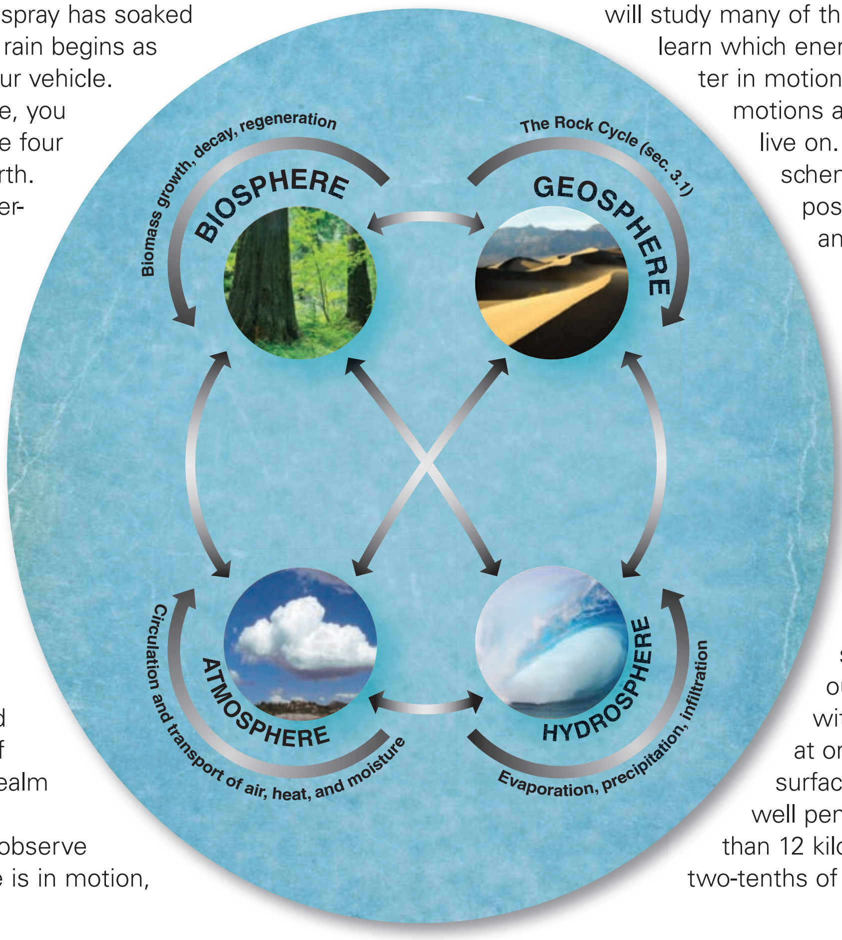


**FIGURE 1.1** All of Earth's cycles and spheres are interconnected.

COPYRIGHT AND PHOTOGRAPHS BY DR. PARVINDER S. SETHI; HYDROSPHERE: RENIW-IMAGERY/ISTOCKPHOTO.COM
BLUE BACKGROUND: © BILL NOLL/ISTOCKPHOTO.COM

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 drift, 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 we live on. 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

**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.

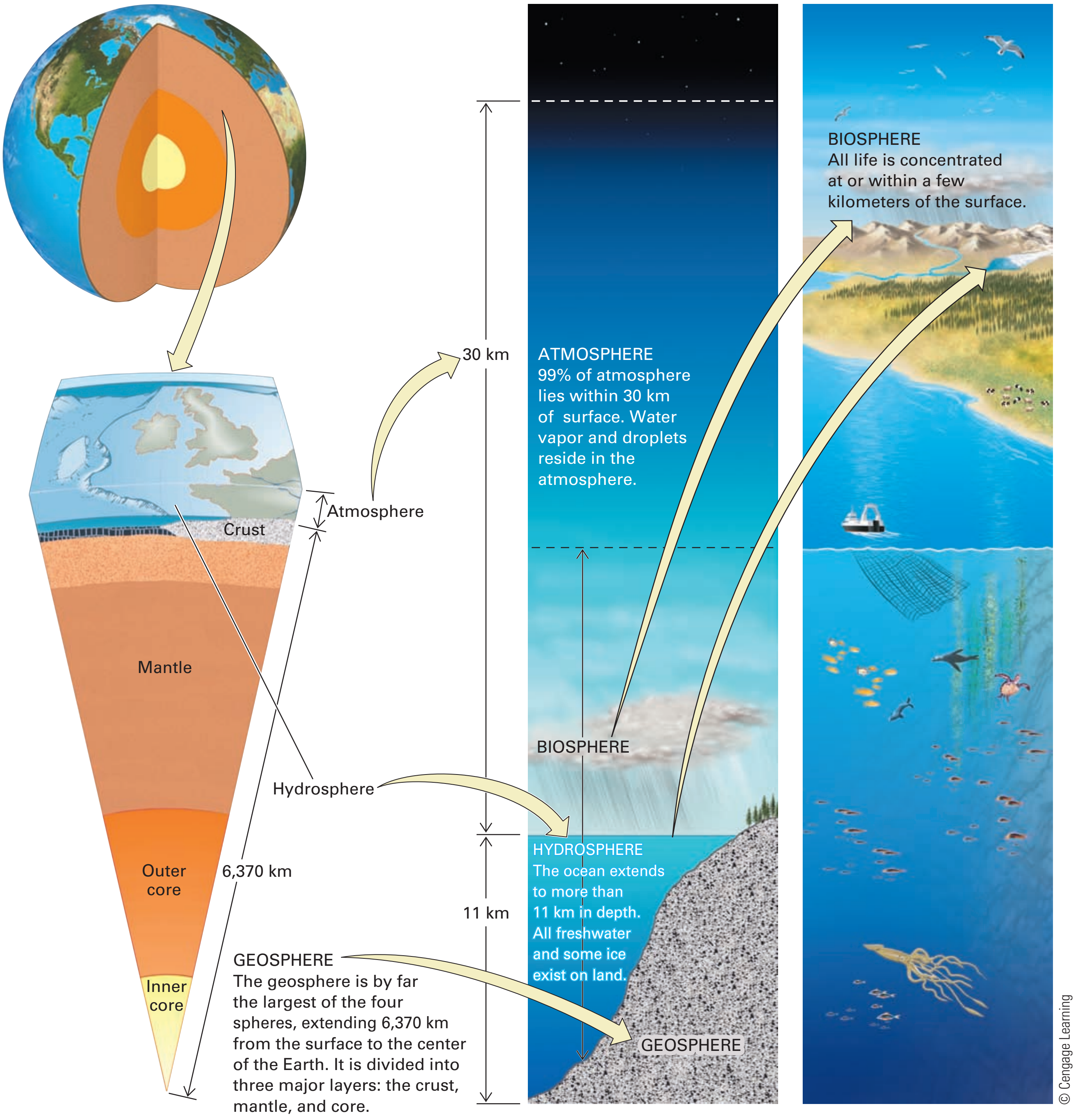


**FIGURE 1.2** The geosphere is the largest component of Earth. It is surrounded by the hydrosphere, the biosphere, and the atmosphere.

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.

### 1-1a 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,

COURTESY OF GRAHAM R. THOMPSON/JONATHAN TURK

COPYRIGHT AND PHOTOGRAPH BY DR. PARVINDER S. SETHI

**FIGURE 1.3** Earth's crust is made up of different kinds of rock (A) A grand view of the sandstones, siltstones, limestones, and shales of the Grand Canyon, as seen from the South Rim. These sedimentary rocks are relatively soft and crumbly and show a marked horizontal layering. Note people for scale. (B) The granite of Baffin Island in the Canadian Arctic is gray, hard, and strong.

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.

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. Below a depth of 100 kilometers, however, 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 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

**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.

**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, consisting of the lithosphere. Tectonic plates float on the weak, plastic rock of the asthenosphere beneath.

**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 drifting 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.

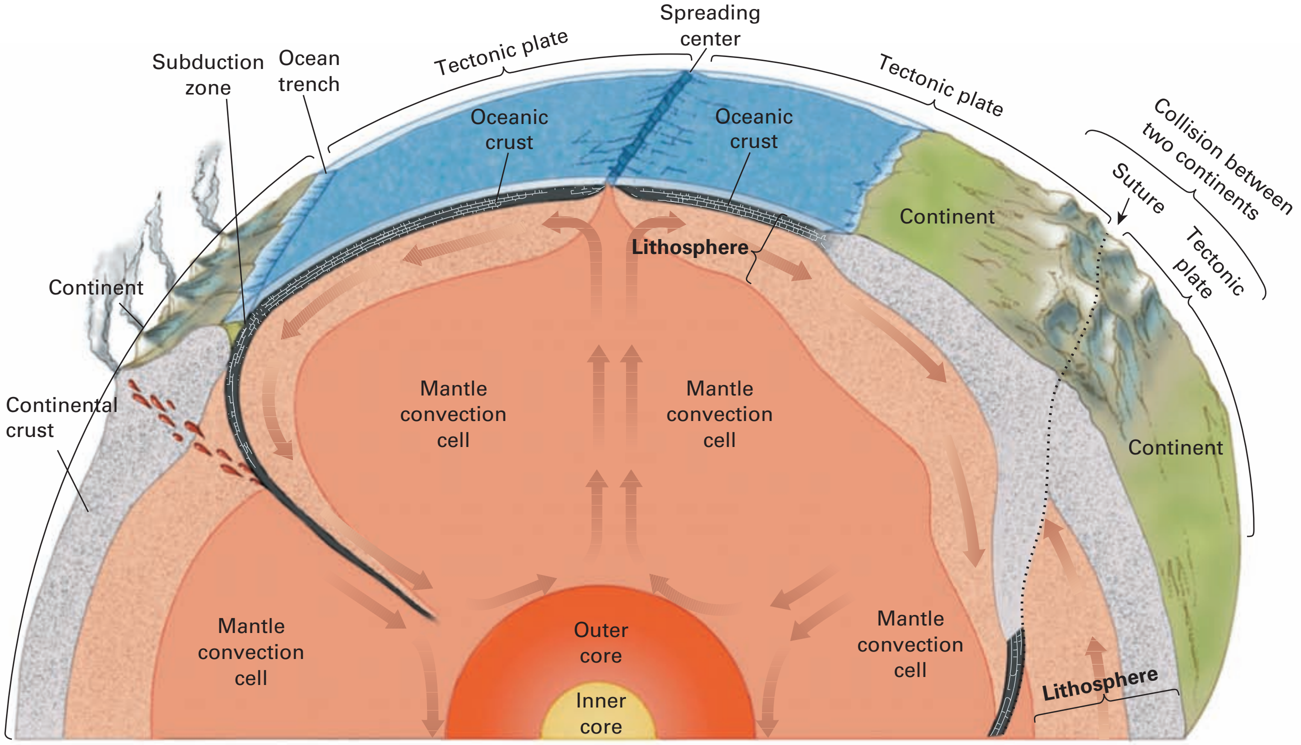
## 1-1b The Hydrosphere

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.

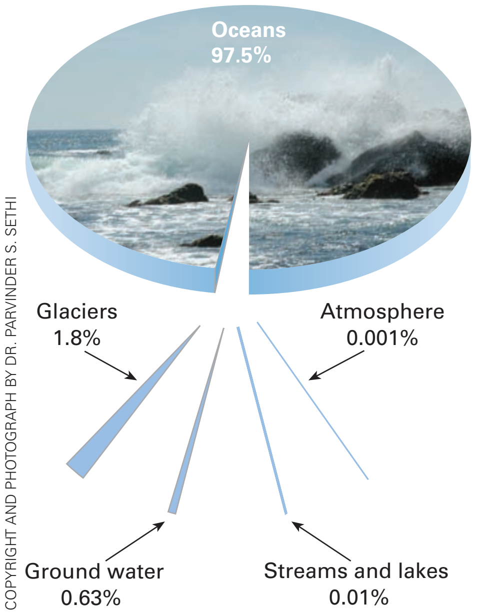
About 1.8 percent of Earth's water is frozen in glaciers. Although glaciers cover about 10 percent of Earth's land surface today, they covered much greater portions of the globe as recently as 18,000 years ago. During this glacial period, nearly all of Canada, the British Isles, and Scandinavia were 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, the Hudson Bay region is undergoing nearly one centimeter of uplift per year as the lithosphere continues to recover from the weight of the ice.

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.

**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.



© Cengage Learning 2015



COPYRIGHT AND PHOTOGRAPH BY DR. PARVINDER S. SETHI

**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.

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

### 1-1c 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.

### 1-1d 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, and 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.

**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.

## 1-2 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

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

(e.g., bacteria) that exist within the body, while also exploring how humans interact with their larger ecosystems.

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.

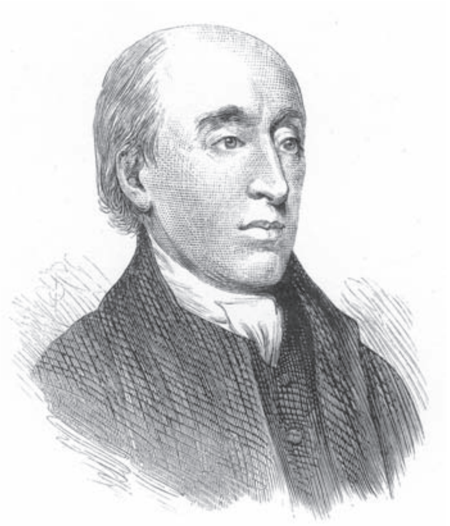
Earth's surface systems—the atmosphere, hydrosphere, and biosphere—are ultimately powered by the Sun. Wind is powered by uneven solar heating of the atmosphere, ocean waves are driven by the wind, and ocean currents move in response to wind or differences in water temperature or density. Luckily for 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 is always conserved. It never simply disappears, although it 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. 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).

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).

COURTESY OF MATTHEW P. McARDLE



©THE PRINT COLLECTOR/ALAMY

> *"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."*
>
> *James Hutton*[1]

## 1-3 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, 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 vastly 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, for only about 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.[2] 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 1.6 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 form one of the rock units on which the Golden Gate Bridge was built.

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.

---

[1] James Hutton, "Theory of the Earth; or an investigation of the laws observable in the composition, dissolution, and restoration of land upon the Globe." *Transactions of the Royal Society of Edinburgh 1* (1788): 209–304.

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