The spectacular eruption of a volcano, the magnificent scenery of a rocky coast, and the destruction created by a hurricane are all subjects for an Earth scientist. The study of Earth science deals with many fascinating and practical questions about our environment. What forces produce mountains? Why is our daily weather variable? Is climate really changing? How old is Earth, and how is our planet related to the other planets in the solar system? What causes ocean tides? What was the Ice Age like? Will there be another? Can a successful well be located at a particular site?

The subject of this text is *Earth science*. To understand Earth is not an easy task because our planet is not a static and unchanging mass. Rather, it is a dynamic body with many interacting parts and a long and complex history.

1.1 WHAT IS EARTH SCIENCE? List and describe the sciences that collectively make up Earth science. Discuss the scales of space and time in Earth science.

Field

l and
l

pe-
h's
tant
logy.

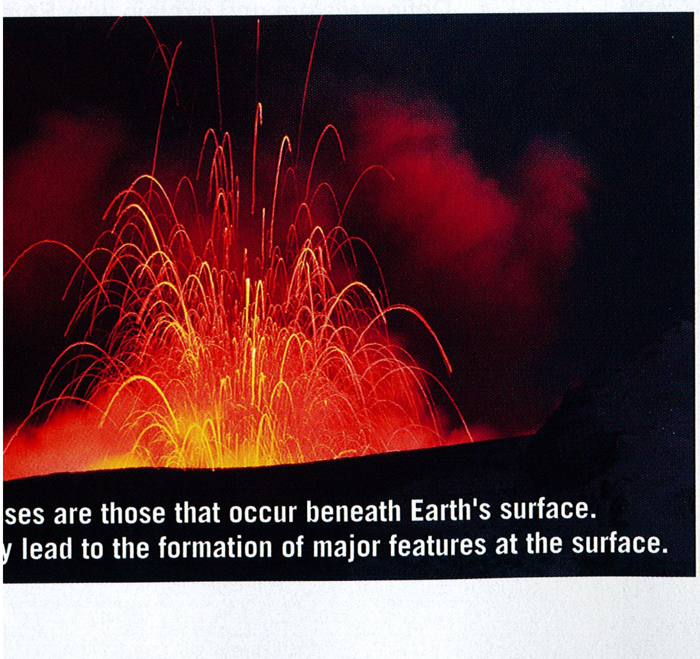
Earth science is the name for all the sciences that collectively seek to understand Earth and its neighbors in space. It includes geology, oceanography, meteorology, and astronomy. Understanding Earth science is challenging because our planet is a dynamic body with many interacting parts and a complex history. Throughout its long existence, Earth has been changing. In fact, it is changing as you read this page and will continue to do so into the foreseeable future. Sometimes the changes are rapid and violent, as when severe storms, landslides, and volcanic eruptions occur. Conversely, many changes take place so gradually that they go unnoticed during a lifetime. Scales of size and space also vary greatly among the phenomena studied in Earth science.

Earth science is often perceived as science that is performed in the out of doors, and rightly so. A great deal of an Earth scientist's study is based on observations and experiments conducted in the field. But Earth science is also conducted in the laboratory, where, for example, the study of various Earth materials provides insights into many basic processes, and the creation of complex computer models allows for the simulation of our planet's complicated climate system. Frequently, Earth scientists require an understanding and application of knowledge and principles from physics, chemistry, and biology. Geology, oceanography, meteorology, and astronomy are sciences that seek to expand our knowledge of the natural world and our place in it.

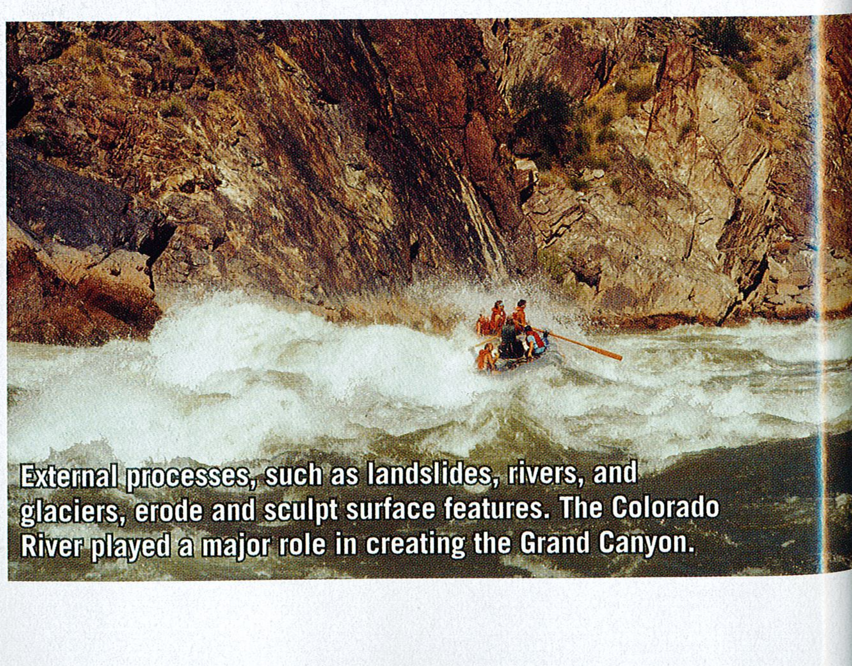
Geology

In this book, Units 1–4 focus on the science of **geology**, a word that literally means "study of Earth." Geology is traditionally divided into two broad areas: physical and historical.

Physical geology examines the materials composing Earth and seeks to understand the many processes that operate beneath and upon its surface (**FIGURE 1.1**). Earth is a dynamic, ever-changing planet. Internal forces create earthquakes, build mountains, and produce volcanic structures. At the surface, external processes break rock apart and sculpt a broad array of landforms. The erosional



ses are those that occur beneath Earth's surface.
y lead to the formation of major features at the surface.



External processes, such as landslides, rivers, and glaciers, erode and sculpt surface features. The Colorado River played a major role in creating the Grand Canyon.

effects of water, wind, and ice result in a great diversity of landscapes. Because rocks and minerals form in response to Earth's internal and external processes, their interpretation is basic to an understanding of our planet.

In contrast to physical geology, the aim of *historical geology* is to understand the origin of Earth and the development of the planet through its 4.6-billion-year history. It strives to establish an orderly chronological arrangement of the multitude of physical and biological changes that have occurred in the geologic past. The study of physical geology logically precedes the study of Earth history because we must first understand how Earth works before we attempt to unravel its past.

Oceanography

Earth is often called the "water planet" or the "blue planet." Such terms relate to the fact that more than 70 percent of Earth's surface is covered by the global ocean. If we are to understand Earth, we must learn about its oceans. Unit 5, *The Global Ocean*, is devoted to **oceanography**. Oceanography is actually not a separate and distinct science. Rather, it involves the application of all sciences in a comprehensive and interrelated study of the oceans in all their aspects and relationships. Oceanography integrates chemistry, physics, geology, and biology. It includes the study of the composition and movements of seawater, as well as coastal processes, seafloor topography, and marine life.

Meteorology

The continents and oceans are surrounded by an atmosphere. Unit 6, *Earth's Dynamic Atmosphere*, examines the mixture of gases that is held to the planet by gravity and thins rapidly with altitude. Acted on by the combined effects of Earth's motions and energy from the Sun, and influenced by Earth's land and sea surface, the formless and invisible atmosphere reacts by producing an infinite variety of weather, which in turn creates the basic pattern of global climates. **Meteorology** is the study of the atmosphere and the processes that produce weather and climate. Like oceanography, meteorology involves the application of other sciences in an integrated study of the thin layer of air that surrounds Earth.

Astronomy

Unit 7, *Earth's Place in the Universe*, demonstrates that an understanding of Earth requires that we relate our planet to the larger universe. Because Earth is related to all the other objects in space, the science of **astronomy**—the study of the universe—is very useful in probing the origins of our own environment. Because we are so closely acquainted with the planet on which we live, it is easy to forget that Earth is just a tiny object in a vast universe. Indeed, Earth is subject to the same physical laws that govern the many other objects populating the great expanses of space. Thus, to understand explanations of our planet's origin, it is useful to learn something about the other members of our solar system. Moreover, it is helpful to view the solar system as a part of the great assemblage of stars that comprise our galaxy, which is but one of many galaxies.

Earth Science Is Environmental Science

Earth science is an environmental science that explores many important relationships between people and the natural environment. Many of the problems and issues addressed by Earth science are of practical value to people.

Natural Hazards Natural hazards are a part of living on Earth. Every day they adversely affect literally millions of people worldwide and are responsible for staggering damages. Among the hazardous Earth processes studied by Earth scientists are volcanoes, floods, tsunami, earthquakes, landslides, and hurricanes. Of course, these hazards are *natural* processes. They become hazards only when people try to live where these processes occur.

For most of history, most people lived in rural areas. According to the United Nations, that changed in 2008, and today more people live in cities than in rural areas. This global trend toward urbanization concentrates millions of people into megacities, many of which are vulnerable to natural hazards (**FIGURE 1.2**). Coastal sites are becoming more vulnerable because development often destroys

FIGURE 1 Sandy A
Jersey sh
this huge
October 2
especially
cause it st
a high pop
and exten
Shifting sh
the desire
cupy these
in conflict.
Mike Groll)

opper mine at Morenci, Arizona, ucer. When demand for copper ine operates nonstop, processing f rock each day and producing unds of copper per year.

per Mine Resources represent an important link between people and Earth sci-
el Collier)

natural defenses such as wetlands and sand dunes. In addition, there is a growing threat associated with human influences on the Earth system such as sea level rise that is linked to global climate change.[1] Other megacities are exposed to seismic (earthquake) and volcanic hazards where inappropriate land use and poor construction practices, coupled with rapid population growth, are increasing vulnerability.

Resources Resources represent another important focus that is of great practical value to people. They include water and soil, a great variety of metallic and nonmetallic minerals, and energy (**FIGURE 1.3**). Together they form the very foundation of modern civilization. Earth science deals with the formation and occurrence of these vital resources and also with maintaining supplies and with the environmental impact of their extraction and use.

People Influence Earth Processes Not only do Earth processes have an impact on people, but we humans can dramatically influence Earth processes as well. Human activities alter the composition of the atmosphere that trigger air pollution episodes and cause global climate change (**FIGURE 1.4**). River flooding is natural, but the magnitude and frequency of flooding can be changed significantly by human activities such as clearing forests, building cities, and constructing dams. Unfortunately, natural systems do not always adjust to artificial changes in ways that we can anticipate. Thus, an alteration to the environment that was intended to benefit society often has the opposite effect.

At various places throughout this book, you will have opportunities to examine different aspects of our relationship with the physical environment. It will be rare to find

[1]The idea of the Earth system is explored later in the chapter. Global climate change and its effects are a focus of Chapter 20.

n Air
e air
Beijing,
, 2008.
factories,
notor
high
llutants.
ors
pollutants
ne city or
o by AP

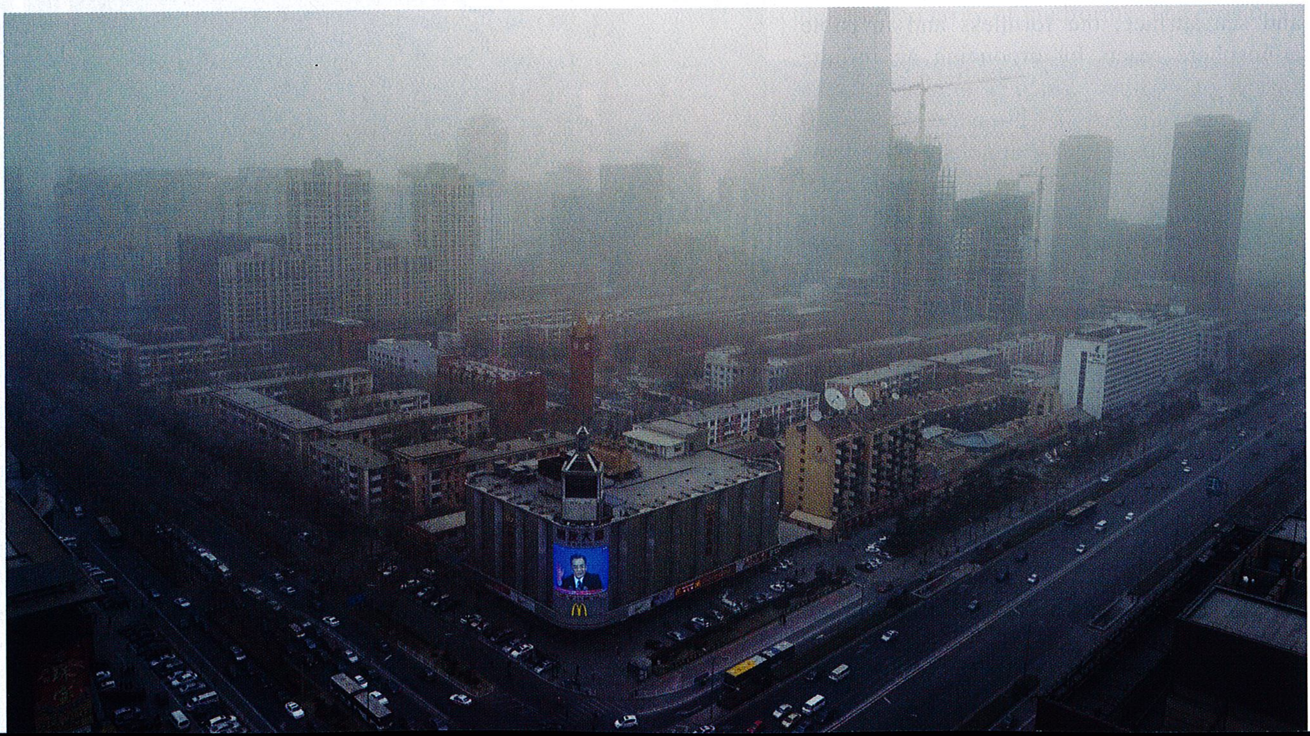


FIGURE 1.
to Galaxie
studies phe
different sc

a chapter that does not address some aspect of natural hazards, environmental issues, or resources. Significant parts of some chapters provide the basic knowledge and principles needed to understand environmental problems.

Scales of Space and Time in Earth Science

When we study Earth, we must contend with a broad array of space and time scales (**FIGURE 1.5**). Some phenomena are relatively easy for us to imagine, such as the size and duration of an afternoon thunderstorm or the dimensions of a sand dune. Other phenomena are so vast or so small that they are difficult to imagine. The number of stars and distances in our galaxy (and beyond!) or the internal arrangement of atoms in a mineral crystal are examples of such phenomena.

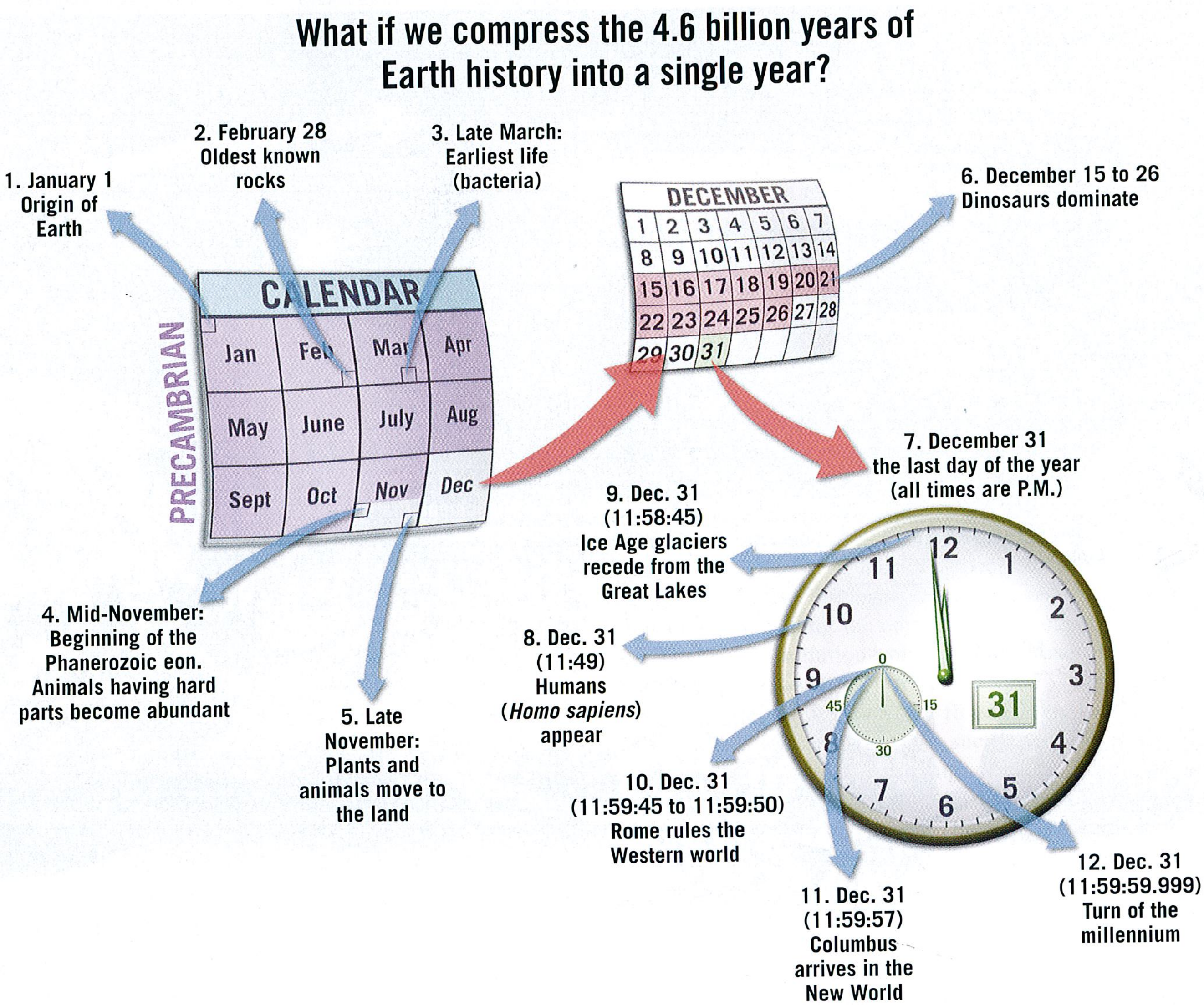
Some of the events we study occur in fractions of a second. Lightning is an example. Other processes extend over spans of tens or hundreds of millions of years. For example, the lofty Himalaya Mountains began forming nearly 50 million years ago, and they continue to develop today.

The concept of **geologic time**, the span of time since the formation of Earth, is new to many nonscientists. People are accustomed to dealing with increments of time that are measured in hours, days, weeks, and years. Our history books often examine events over spans of centuries, but even a century is difficult to appreciate fully. For most of us, someone or something that is 90 years old is *very old*, and a 1000-year-old artifact is *ancient*.

Those who study Earth science must routinely deal with vast time periods—millions or billions (thousands of millions) of years. When viewed in the context of Earth's 4.6-billion-year history, an event that occurred 100 million years ago may be characterized as "recent" by a geologist, and a rock sample that has been dated at 10 million years may be called "young."

An appreciation for the magnitude of geologic time is important in the study of our planet because many processes are so gradual that vast spans of time are needed before significant changes occur. How long is 4.6 billion years? If you were to begin counting at the rate of one number per second and continued 24 hours a day, seven

1.6
ogic



days a week and never stopped, it would take about two lifetimes (150 years) to reach 4.6 billion!

The preceding analogy is just one of many that have been conceived in an attempt to convey the magnitude of geologic time. Although helpful, all of them, no matter how clever, only begin to help us comprehend the vast expanse of Earth history. **FIGURE 1.6** provides another interesting way of viewing the age of Earth.

Over the past 200 years or so, Earth scientists have developed the *geologic time scale* of Earth history. It divides the 4.6-billion-year history of Earth into many different units and provides a meaningful time frame within which the events of the geologic past are arranged (see Figure 11.24, page 364). The principles used to develop the geologic time scale are examined in some detail in Chapter 11.

1.1 CONCEPT CHECKS

1. List and briefly describe the sciences that collectively make up Earth science.
2. Name the two broad subdivisions of geology and distinguish between them.
3. List at least four different natural hazards.
4. Aside from natural hazards, describe another important connection between people and Earth science.
5. List two examples of size/space scales in Earth science that are at opposite ends of the spectrum.
6. How old is Earth?
7. If you compress geologic time into a single year, how much time has elapsed since Columbus arrived in the New World?

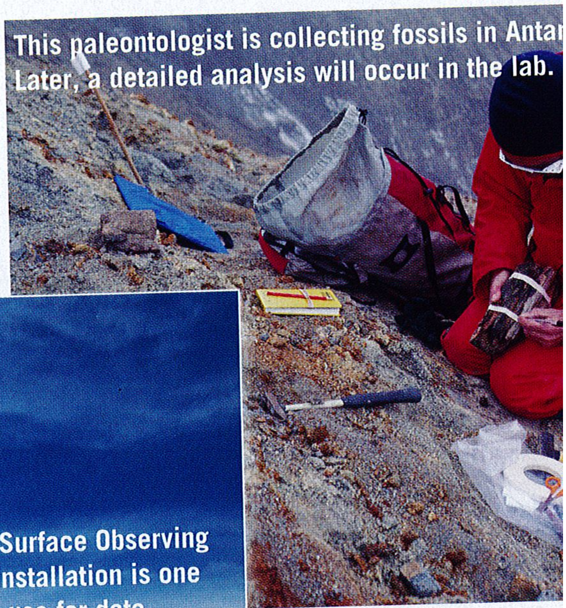
1.2 THE NATURE OF SCIENTIFIC INQUIRY

Discuss the nature of scientific inquiry and distinguish between a hypothesis and a theory.

As members of a modern society, we are constantly reminded of the benefits derived from science. But what exactly is the nature of scientific inquiry? Developing an understanding of how science is done and how scientists work is another important theme that appears throughout this book. You will explore the difficulties in gathering data and some of the ingenious methods that have been developed to overcome these difficulties. You will also see many examples of how hypotheses are formulated and tested, as well as learn about the evolution and development of some major scientific theories.

All science is based on the assumption that the natural world behaves in a consistent and predictable manner that is comprehensible through careful, systematic study. The overall goal of science is to discover the underlying patterns in nature and then to use this knowledge to make predictions about what should or should not be expected, given certain facts or circumstances. For example, by understanding the processes that produce certain cloud types, meteorologists are often able to predict the approximate time and place of their formation.

The development of new scientific knowledge involves some basic logical processes that are universally accepted. To determine what is occurring in the natural world, scientists collect scientific facts through observation and measurement (**FIGURE 1.7**). The types of facts or data that are collected generally seek to answer a well-defined question about the natural world. Because some error is inevitable, the accuracy of a particular measurement or observation is always open to question. Nevertheless, these data are essential to science and serve as the springboard for the development of scientific hypotheses and theories.



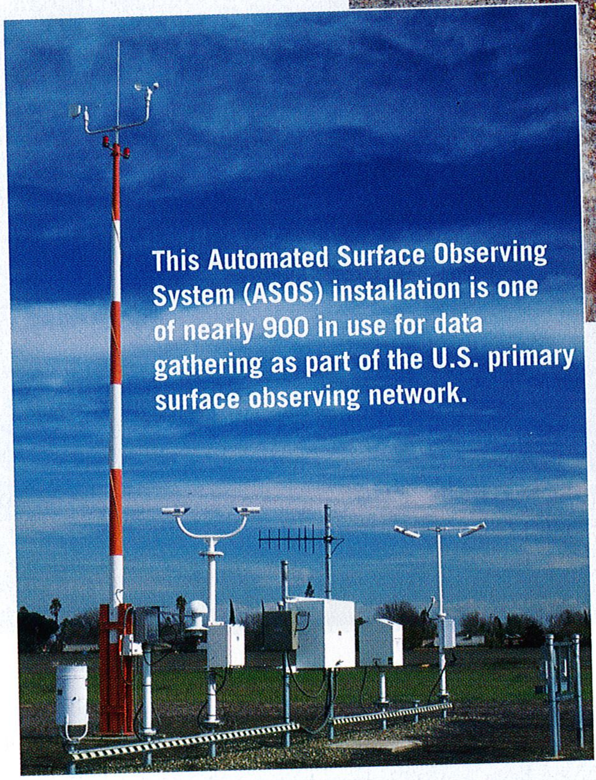


FIGURE 1.7 Observation an ment Gathering data and mak vations are basic parts of scien (Instrument photo by Bobbé Christoph photo by British Antarctic Survey/Scie

Hypothesis

Once facts have been gathered and principles have been formulated to describe a natural phenomenon, investigators try to explain how or why things happened in the manner observed. They often do this by constructing a tentative (or untested) explanation, which is called a scientific **hypothesis**. It is best if an investigator can formulate more than one hypothesis to explain a given set of observations. If an individual scientist is unable to devise multiple hypotheses, others in the scientific community will almost always develop alternative explanations. A spirited debate frequently ensues. As a result, extensive research is conducted by proponents of opposing hypotheses, and the results are made available to the wider scientific community in scientific journals.

Before a hypothesis can become an accepted part of scientific knowledge, it must pass objective testing and analysis. If a hypothesis cannot be tested, it is not scientifically useful, no matter how interesting it might seem. The verification process requires that *predictions* be made based on the hypothesis being considered and that the predictions be tested by comparing them against objective observations of nature. Put another way, hypotheses must fit observations other than those used to formulate them in the first place. Hypotheses that fail rigorous testing are ultimately discarded. The history of science is littered with discarded hypotheses. One of the best known is the Earth-centered model of the universe—a proposal that was supported by the apparent daily motion of the Sun, Moon, and stars around Earth. As the mathematician Jacob Bronowski so ably stated, "Science is a great many things, but in the end they all return to this: Science is the acceptance of what works and the rejection of what does not."

GEOGRAPHICS

World Population Passes 7 BILLION

Complicating all environmental issues is rapid world population growth and everyone's aspiration to a better standard of living. There is a ballooning demand for resources and a growing pressure for people to live in environments having significant geologic hazards.

This composite satellite image of Earth's city lights helps us appreciate the intensity of human occupation in many parts of the world. In the year 1800, only about 3 percent of the world's people were urban. Today about 51 percent are classified as urban.

Theory

When a hypothesis has survived extensive scrutiny and when competing hypotheses have been eliminated, it may be elevated to the status of a scientific **theory**. In everyday language, we might say, "That's only a theory." But a scientific theory is a well-tested and widely accepted view that the scientific community agrees best explains certain observable facts.

Some theories that are extensively documented and extremely well supported are comprehensive in scope. For example, the theory of plate tectonics provides the framework for understanding the origin of mountains, earthquakes, and volcanic activity. In addition, plate tectonics explains the evolution of the continents and the ocean basins through time—ideas that are explored in some detail in Chapters 7 through 10.

Scientific Methods

The process just described, in which researchers gather facts through observations and formulate scientific hypotheses and theories, is called the *scientific method*. Contrary to popular belief, the scientific method is not a standard recipe that scientists apply in a routine manner to unravel the secrets of our natural world. Rather, it is an endeavor that involves creativity and insight. Rutherford and Ahlgren put it this way: "Inventing hypotheses or theories to imagine how the world works and then figuring out how they can be put to the test of reality is as creative as writing poetry, composing music, or designing skyscrapers."[2]

There is not a fixed path that scientists can always follow unerringly to scientific knowledge. However, many scientific investigations involve the following processes:

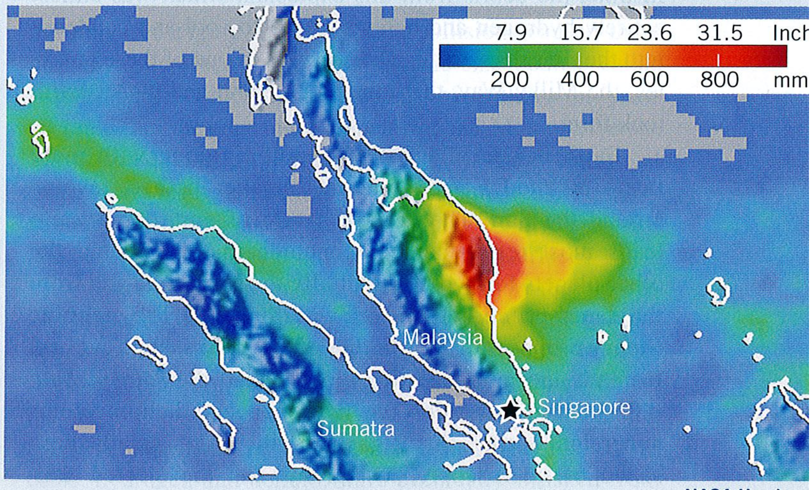
- A question is raised about the natural world.
- Scientific data that relate to the question are collected.
- Questions that relate to the data are posed, and one or more working hypotheses are developed that may answer these questions.
- Observations and experiments are developed to test the hypotheses.

[2]F. James Rutherford and Andrew Ahlgren, *Science for All Americans* (New York: Oxford University Press, 1990), p. 7.

EYE ON EARTH

This image shows rainfall data for December 7–13, 2004, in Malaysia. More than 800 millimeters (32 inches) of rain fell along the east coast of the peninsula (darkest red area). The extraordinary rains caused extensive flooding. The data for this image are from NASA's *Tropical Rainfall Measuring Mission* (*TRMM*). This is just one of hundreds of satellites that provide scientists with all kinds of data about our planet.

QUESTION 1 *Gathering data is a basic part of scientific inquiry. Suggest some advantages that satellites provide scientists as a way of gaining information about Earth.*



NASA Headqua

- The hypotheses are accepted, modified, or rejected, based on extensive testing.
- Data and results are shared with the scientific community for critical examination and further testing.

Some scientific discoveries may result from purely theoretical ideas, which stand up to extensive examination. Some researchers use high-speed computers to simulate what is happening in the "real" world. These models are useful when dealing with natural processes that occur on very long time scales or that take place in extreme or inaccessible locations. Still other scientific advancements are made when a totally unexpected happening occurs during an experiment. These serendipitous discoveries are more than pure luck, for as Louis Pasteur said, "In the field of observation, chance favors only the prepared mind."

Scientific knowledge is acquired through several avenues, so it might be best to describe the nature of scientific inquiry as the *methods of science* rather than as the *scientific method*. In addition, it should always be remembered that even the most compelling scientific theories are still simplified explanations of the natural world.

In this book, you will discover the results of centuries of scientific work. You will see the end product of millions of observations, thousands of hypotheses, and hundreds of theories. We have distilled all of this to give you a "briefing" on Earth science.

But realize that our knowledge of Earth is changing daily, as thousands of scientists worldwide make satellite observations, analyze drill cores from the seafloor, measure earthquakes, develop computer models to predict climate, examine the genetic codes of organisms, and discover new facts about our planet's long history. This new knowledge often updates hypotheses and theories. Expect to see many new discoveries and changes in scientific thinking in your lifetime.

1.2 CONCEPT CHECKS

1 How is a scientific hypothesis different from a scientific theory?
2 Summarize the basic steps followed in many scientific investigations.

1.3 EARLY EVOLUTION OF EARTH

Outline the stages in the formation of our solar system.

This section describes the most widely accepted views on the origin of our solar system. The theory summarized here represents the most consistent set of ideas available to explain what we know about our solar system today.

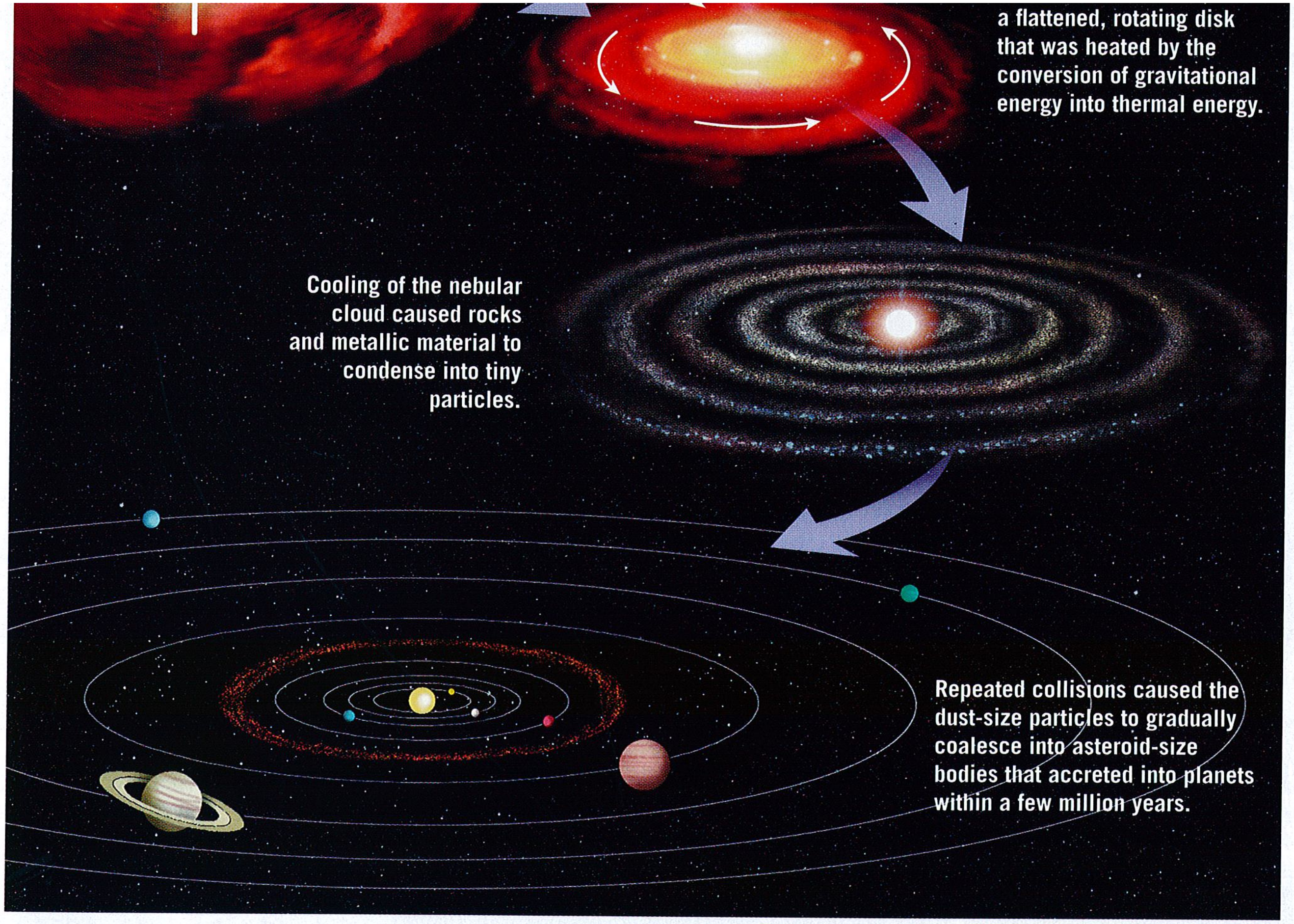
Origin of Planet Earth

Our story begins about 13.7 billion years ago, with the *Big Bang*, an incomprehensibly large explosion that sent all matter of the universe flying outward at incredible speeds. In time, the debris from this explosion, which was almost entirely hydrogen and helium, began to cool and condense into the first stars and galaxies. It was in one of these galaxies, the Milky Way, that our solar system and planet Earth took form.

Earth is one of eight planets that, along with more than 160 moons and numerous smaller bodies, revolve around the Sun. The orderly nature of our solar system leads most researchers to conclude that Earth and the other planets formed at essentially the same time and from the same primordial material as the Sun. The **nebular theory** proposes that the bodies of our solar system evolved from an enormous rotating cloud called the *solar nebula* (**FIGURE 1.8**). Besides the hydrogen and helium atoms generated during the Big Bang, the solar nebula consisted of microscopic dust grains and the ejected matter of long-dead stars. (Nuclear fusion in stars converts hydrogen and helium into the other elements found in the universe.)

Nearly 5 billion years ago, this huge cloud of gases and minute grains of heavier elements began to slowly contract due to the gravitational interactions among its particles (see Figure 1.8). Some external influence, such as a shock wave traveling from a catastrophic explosion (*supernova*), may have triggered the collapse. As this slowly spiraling nebula contracted, it rotated faster and faster, much as spinning ice skaters do when they draw their arms toward their bodies. Eventually the inward pull of gravity came into balance with the outward force caused by the rotational motion of the nebula (see Figure 1.8). By this time, the once-vast cloud had assumed a flat disk shape with a large concentration of material at its center called the *protosun* (pre-Sun). Astronomers are fairly confident that the nebular cloud formed a disk because similar structures have been detected around other stars.

During the collapse, gravitational energy was converted to thermal energy (heat), causing the temperature of the inner portion of the nebula to dramatically rise. At these high temperatures, the dust grains broke up into molecules and extremely energetic atomic particles. However, at distances beyond the orbit of Mars, the temperatures probably remained quite low. At –200°C (–328°F), the tiny particles in the outer portion of the nebula were likely covered with a thick layer of ices made of frozen water, carbon dioxide, ammonia, and methane. (Some of this material still resides



in the outermost reaches of the solar system, in a region called the *Oort cloud*.) The disk-shaped cloud also contained appreciable amounts of the lighter gases hydrogen and helium.

The Inner Planets Form

The formation of the Sun marked the end of the period of contraction and thus the end of gravitational heating. Temperatures in the region where the inner planets now reside began to decline. The decrease in temperature caused substances with high melting points to condense into tiny particles that began to coalesce (that is, join together). Materials such as iron and nickel and the elements of which the rock-forming minerals are composed—silicon, calcium, sodium, and so forth—formed metallic and rocky clumps that orbited the Sun (see Figure 1.8). Repeated collisions caused these masses to coalesce into larger asteroid-size bodies, called *planetesimals*, which in a few tens of millions of years accreted into the four inner planets we call Mercury, Venus, Earth, and Mars (**FIGURE 1.9**). Not all of these clumps of matter were incorporated into the planetesimals. Those rocky and metallic pieces that remained in orbit are called asteroids and become *meteorites* if they impact Earth's surface.

As more and more material was swept up by these growing planetary bodies, the high-velocity impact of nebular debris caused their temperatures to rise. Because of their relatively high temperatures and weak gravitational fields, the inner planets were unable to accumulate much of the lighter components of the nebular cloud. The lightest of these, hydrogen and helium, were eventually whisked from the inner solar system by the solar wind.

emnant
s image
tia was
l cameras
space-
10. Space-
nowed
nitive
) left over
r system
esy of ESA)

The Outer Planets Develop

At the same time that the inner planets were forming, the larger, outer planets (Jupiter, Saturn, Uranus, and Neptune), along with their extensive satellite systems, were also developing. Because of low temperatures far from the Sun, the material from which these planets formed contained a high percentage of ices—water, carbon dioxide, ammonia, and methane—as well as rocky and metallic debris. The accumulation of ices accounts in part for the large size and low density of the outer planets. The two most massive planets, Jupiter and Saturn, had a surface gravity sufficient to attract and hold large quantities of even the lightest elements—hydrogen and helium.

1.3 CONCEPT CHECKS

1. Name and briefly outline the theory that describes the formation of our solar system.
2. List the inner planets and the outer planets. Describe basic differences in size and composition.

1.4 EARTH'S SPHERES

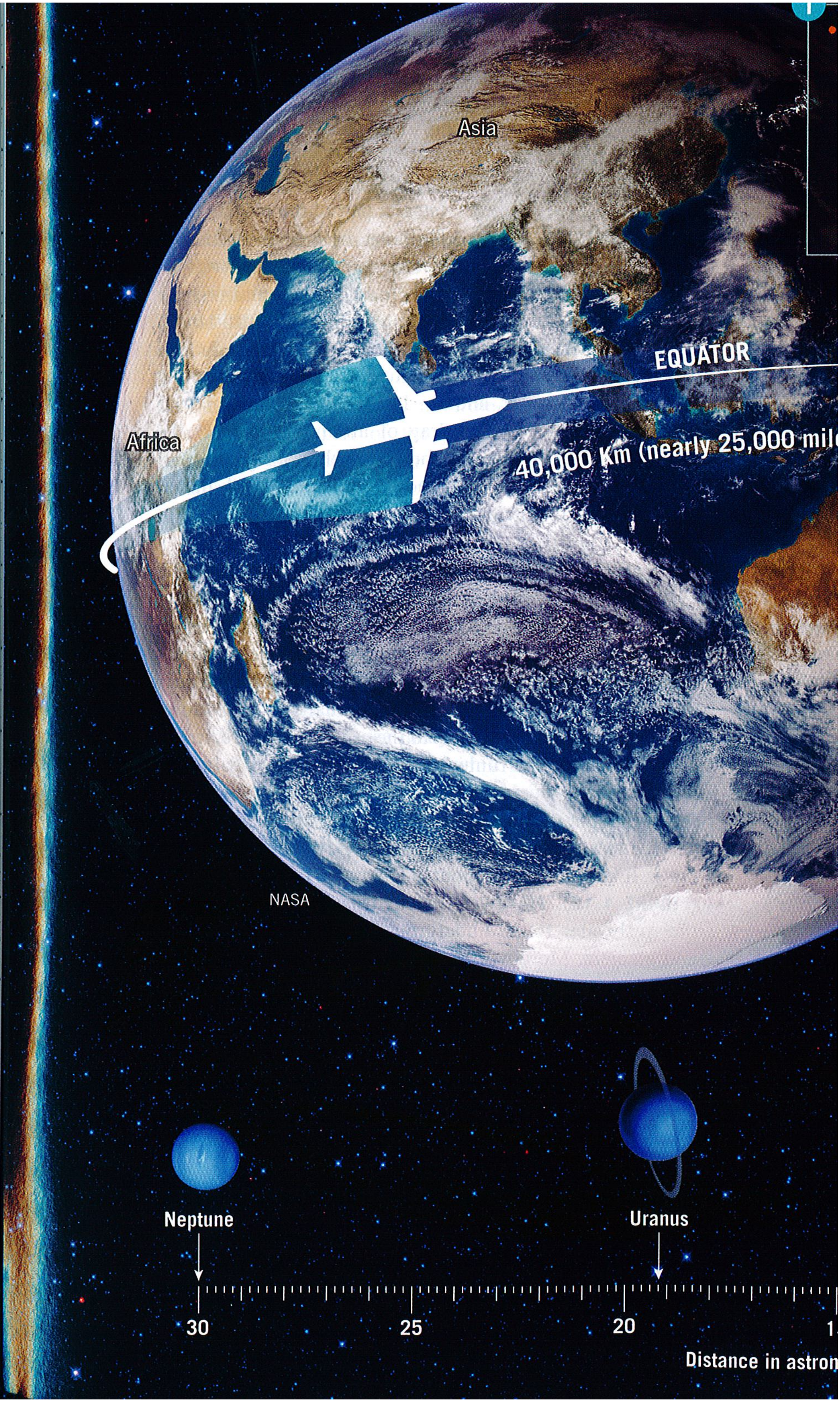
List and describe Earth's four major spheres.

The images in **FIGURE 1.10** are considered to be classics because they let humanity see Earth differently than ever before. These early views profoundly altered our conceptualizations of Earth and remain powerful images decades after they were first viewed. Seen from space, Earth is breathtaking in its beauty and startling in its solitude. The photos remind us that our home is, after all, a planet—small, self-contained, and in some ways even fragile.

lled "Earthrise" that greeted astronauts as their spacecraft from behind the Moon in er 1968. This classic image le see Earth differently than ore.

This image taken from *Apollo 17* in December 1972 is perhaps the first to be called "The Blue Marble." The dark blue ocean and swirling cloud patterns remind us of the importance of the oceans and atmosphere.

0 Two Classic Views of Earth from Space. (Photo on left courtesy of NASA Headquarters; photo on right courtesy of NASA/Johnson Space Center)


Asia
EQUATOR
Africa
40,000 Km (nearly 25,000 mil
NASA
Neptune
Uranus
30
25
20
Distance in astron

iterac-
th's
oreline is
erface—a
y where
a system
ene, ocean
ere) that
he force
iosphere)
ocky shore
llier)

Bill Anders, the *Apollo 8* astronaut who took the "Earthrise" photo, expressed it this way: "We came all this way to explore the Moon, and the most important thing is that we discovered the Earth."

As we look closely at our planet from space, it becomes apparent that Earth is much more than rock and soil. In fact, the most conspicuous features in Figure 1.10 are not continents but swirling clouds suspended above the surface of the vast global ocean. These features emphasize the importance of water on our planet.

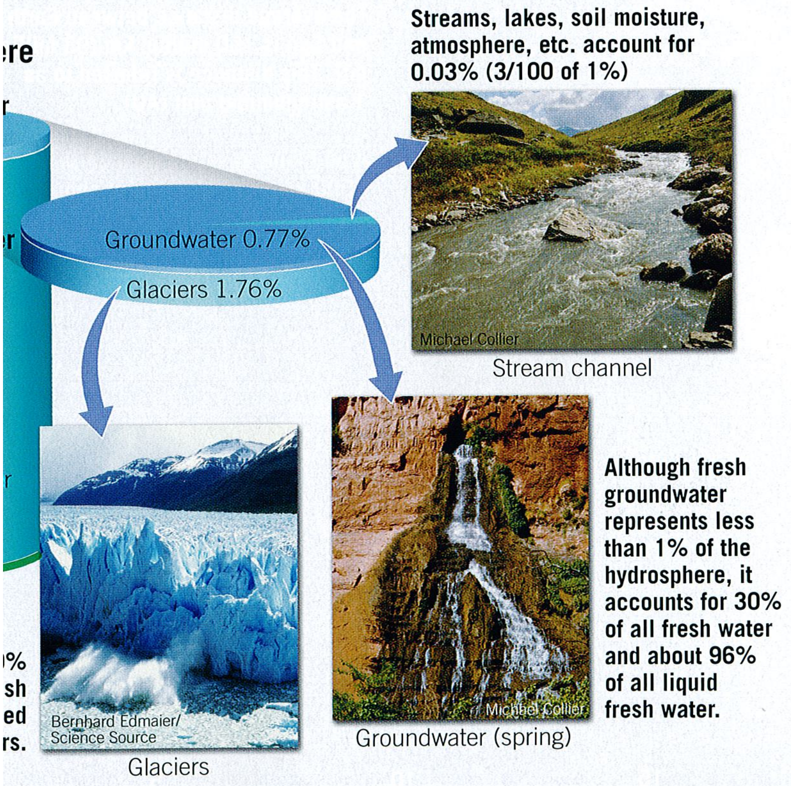
The closer view of Earth from space shown in Figure 1.10 helps us appreciate why the physical environment is traditionally divided into three major spheres: the water portion of our planet, the hydrosphere; Earth's gaseous envelope, the atmosphere; and, of course, the solid Earth, or geosphere.

It should be emphasized that our environment is highly integrated and is not dominated by rock, water, or air alone. It is instead characterized by continuous interactions as air comes in contact with rock, rock with water, and water with air. Moreover, the biosphere, the totality of life-forms on our planet, extends into each of the three physical realms and is an equally integral part of the planet. Thus, Earth can be thought of as consisting of four major spheres: the hydrosphere, atmosphere, geosphere, and biosphere.

The interactions among the spheres of Earth's environment are incalculable. **FIGURE 1.11** provides an easy-to-visualize example. The shoreline is an obvious meeting place for rock, water, and air. In this scene, ocean waves that were created by the drag of air moving across the water are breaking against the rocky shore. The force of the water can be powerful, and the erosional work that is accomplished can be great.

he Water
on of water
e.

ere



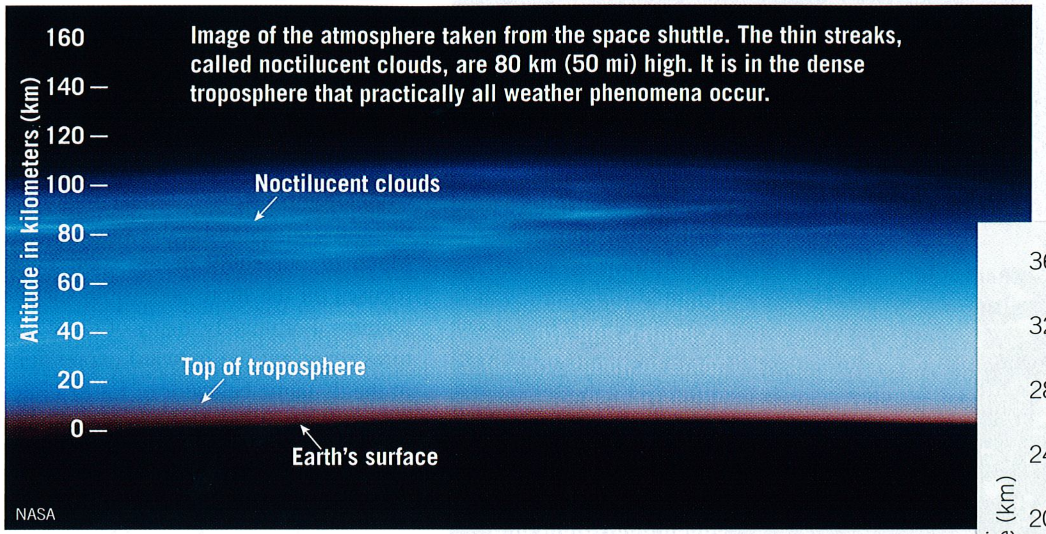
Hydrosphere

Earth is sometimes called the *blue planet* or, as we saw in Figure 1.10, "The Blue Marble." Water more than anything else makes Earth unique. The **hydrosphere** is a dynamic mass of water that is continually on the move, evaporating from the oceans to the atmosphere, precipitating to the land, and running back to the ocean again. The global ocean is certainly the most prominent feature of the hydrosphere, blanketing nearly 71 percent of Earth's surface to an average depth of about 3800 meters (12,500 feet). It accounts for about 97 percent of Earth's water (**FIGURE 1.12**). However, the hydrosphere also includes the freshwater found underground and in streams, lakes, and glaciers. Moreover, water is an important component of all living things.

Although these latter sources constitute just a tiny fraction of the total, they are much more important than their meager percentages indicate. In addition to providing the freshwater that is so vital to life on land, streams, glaciers, and groundwater are responsible for sculpturing and creating many of our planet's varied landforms.

Atmosphere

Earth is surrounded by a life-giving gaseous envelope called the **atmosphere** (**FIGURE 1.13**). When we watch a high-flying jet plane cross the sky, it seems that the atmosphere



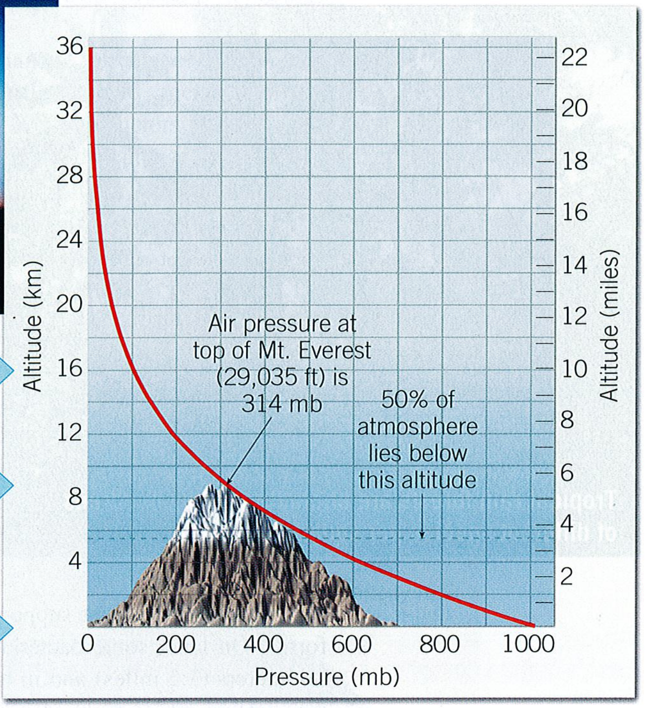


FIGURE 1.13 A Shallow Layer The atmosphere is an integral part of the planet. (NASA)

extends upward for a great distance. However, when compared to the thickness (radius) of the solid Earth (about 6400 kilometers [4000 miles]), the atmosphere is a very shallow layer. Despite its modest dimensions, this thin blanket of air is nevertheless an integral part of the planet. It not only provides the air that we breathe but also protects us from the Sun's dangerous ultraviolet radiation. The energy exchanges that continually occur between the atmosphere and Earth's surface and between the atmosphere and space produce the effects we call *weather* and *climate*. Climate has a strong influence on the nature and intensity of Earth's surface processes. When climate changes, these processes respond.

If, like the Moon, Earth had no atmosphere, our planet would be lifeless because many of the processes and interactions that make the surface such a dynamic place could not operate. Without weathering and erosion, the face of our planet might more closely resemble the lunar surface, which has not changed appreciably in nearly 3 billion years.

Biosphere

The **biosphere** includes all life on Earth (**FIGURE 1.14**). Ocean life is concentrated in the sunlit surface waters of the sea. Most life on land is also concentrated near the surface, with tree roots and burrowing animals reaching a few meters underground and flying insects and birds reaching a kilometer or so above the surface. A surprising variety of life-forms are also adapted to extreme environments. For example, on the ocean floor, where pressures are extreme and no light penetrates, there are places where vents spew hot,

EYE ON EARTH

This jet is cruising at an altitude of 10 kilometers (6.2 miles).

QUESTION 1 *Refer to the graph in Figure 1.13. What is the approximate air pressure at the altitude where the jet is flying?*

QUESTION 2 *About what percentage of the atmosphere is below the jet (assuming that the pressure at the surface is 1000 millibars)?*

1

bio-
; four
ife.
Leniuk/
photo by
k)

The ocean contains a significant portion of Earth's biosphere. Modern coral reefs are unique and complex examples and are home to about 25% of all marine species. Because of this diversity, they are sometimes referred to as the ocean equivalent of a rain forest.

sts are characterized by hundreds
es per square kilometer.

mineral-rich fluids that support communities of exotic life-forms. On land, some bacteria thrive in rocks as deep as 4 kilometers (2.5 miles) and in boiling hot springs. Moreover, air currents can carry microorganisms many kilometers into the atmosphere. But even when we consider these extremes, life still must be thought of as being confined to a narrow band very near Earth's surface.

Plants and animals depend on the physical environment for the basics of life. However, organisms do more than just respond to their physical environment. Through countless interactions, life-forms help maintain and alter their physical environment. Without life, the makeup and nature of the geosphere, hydrosphere, and atmosphere would be very different than they are.

Geosphere

Lying beneath the atmosphere and the ocean is the solid Earth, or **geosphere**. The geosphere extends from the surface to the center of the planet, a depth of 6400 kilometers [4000 miles], making it by far the largest of Earth's four spheres. Much of our study of the solid Earth focuses on the more accessible surface features. Fortunately, many of these features represent the outward expressions of the dynamic behavior of Earth's interior. By examining the most prominent surface features and their global extent, we can obtain clues to the dynamic processes that have shaped our planet. The next section of this chapter takes a first look at the structure of Earth's interior and at the major surface features of the geosphere.

Soil, the thin veneer of material at Earth's surface that supports the growth of plants, may be thought of as part of all four spheres. The solid portion is a mixture of weathered rock debris (geosphere) and organic matter from decayed plant and animal life (biosphere). The decomposed and disintegrated rock debris is the product of weathering processes that require air (atmosphere) and water (hydrosphere). Air and water also occupy the open spaces between the solid particles.

1.4 CONCEPT CHECKS

1. List Earth's four spheres.
2. Compare the height of the atmosphere to the thickness of the geosphere.
3. How much of Earth's surface do oceans cover? How much of the planet's total water supply do oceans represent?
4. To which sphere does soil belong?

1.5 A CLOSER LOOK AT THE GEOSPHERE

Label a diagram that shows Earth's internal structure. Briefly explain why the geosphere can be described as being mobile.

In this section and the next, we make a preliminary examination of the solid Earth. You will become more familiar with the internal and external "anatomy" of our planet and begin to understand that the geosphere is truly dynamic. The diagrams should help a great deal as you begin to develop a mental image of the geosphere's internal structure and major surface features, so study the figures carefully. We begin with a look at Earth's interior—its structure and mobility. Then we conduct a brief survey of the surface of the solid Earth. Although portions of the surface, such as mountains and river valleys, are familiar to most of us, areas that are out of sight on the floor of the ocean are not so familiar.

Earth's Internal Structure

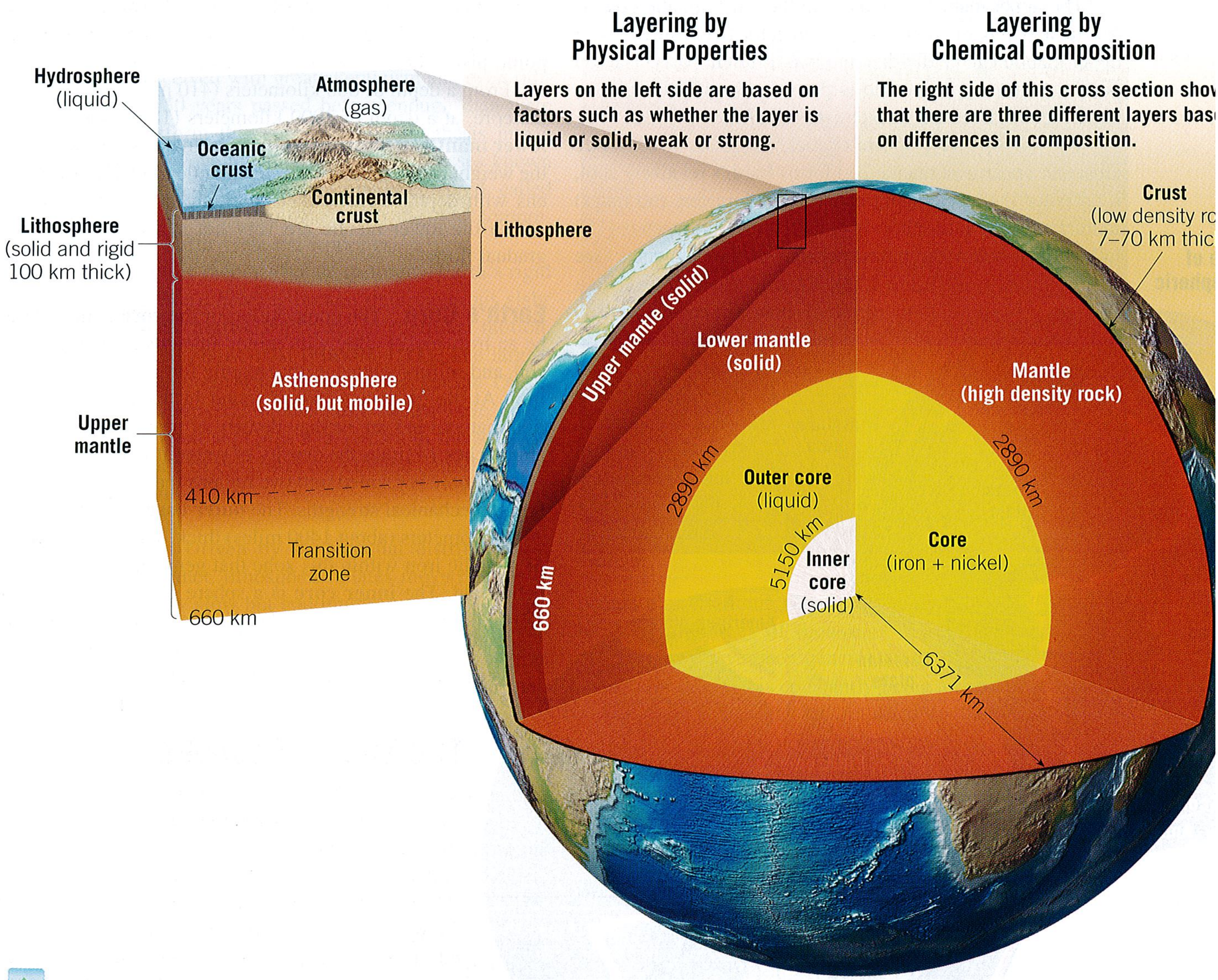
Early in Earth's history, when the planet was very hot, the sorting of material by compositional (density) differences resulted in the formation of three layers—the crust, mantle, and core. In addition to these compositionally distinct layers, Earth is also divided into layers based on *physical properties*. The physical properties that define these zones include whether the layer is solid or liquid and how weak or strong it is. Knowledge of both types of layers is essential to an understanding of our planet. **FIGURE 1.15** summarizes the two types of layers that characterize Earth's interior.

Earth's Crust The **crust**, Earth's relatively thin, rocky outer skin, is of two different types—*continental crust* and *oceanic crust*. Both share the word *crust*, but the similarity ends there. The oceanic crust is roughly 7 kilometers (5 miles) thick and composed of the dark igneous rock *basalt*. By contrast, the continental crust averages about 35 kilometers (22 miles) thick but may exceed 70 kilometers (40 miles) in some mountainous regions, such as the Rockies and Himalayas. Unlike the oceanic crust, which has a relatively homogeneous chemical composition, the continental crust consists of many rock types. Although the upper crust has an average composition of a *granitic rock* called *granodiorite*, it varies considerably from place to place.

Continental rocks have an average density of about 2.7 g/cm^3, and some have been discovered that are more than 4 billion years old. The rocks of the oceanic crust are younger (180 million years or less) and denser (about 3.0 g/cm^3) than continental rocks.[3]

Earth's Mantle More than 82 percent of Earth's volume is contained in the **mantle**, a solid, rocky shell that extends to a depth of nearly 2900 kilometers (1800 miles). The boundary between the crust and mantle is the site of a marked change in chemical composition. The dominant rock

[3] Liquid water has a density of 1 g/cm^3; therefore, the density of basalt is three times that of water.



SmartFigure 1.15 Earth's Layers Structure of Earth's interior.

looked
rs ago.
rn con-
niliar
rm a
e call

type in the uppermost mantle is *peridotite*, which is richer in the metals magnesium and iron than the minerals found in either the continental or oceanic crust.

The upper mantle extends from the crust–mantle boundary to a depth of about 660 kilometers (410 miles). The upper mantle can be divided into two different parts. The top portion of the upper mantle is part of the stiff *lithosphere*, and beneath that is the weaker *asthenosphere*.

The **lithosphere** ("sphere of rock") consists of the entire crust and uppermost mantle and forms Earth's relatively cool, rigid outer shell. Averaging about 100 kilometers (60 miles) in thickness, the lithosphere is more than 250 kilometers (150 miles) thick below the oldest portions of the continents (see Figure 1.15). Beneath this stiff layer to a depth of about 350 kilometers (220 miles) lies a soft, comparatively weak layer known as the **asthenosphere** ("weak sphere"). The top portion of the asthenosphere has a temperature/pressure regime that results in a small amount of melting. Within this very weak zone, the lithosphere is mechanically detached from the layer below. The result is that the lithosphere is able to move independently of the asthenosphere, a fact we consider in more detail in Chapter 7.

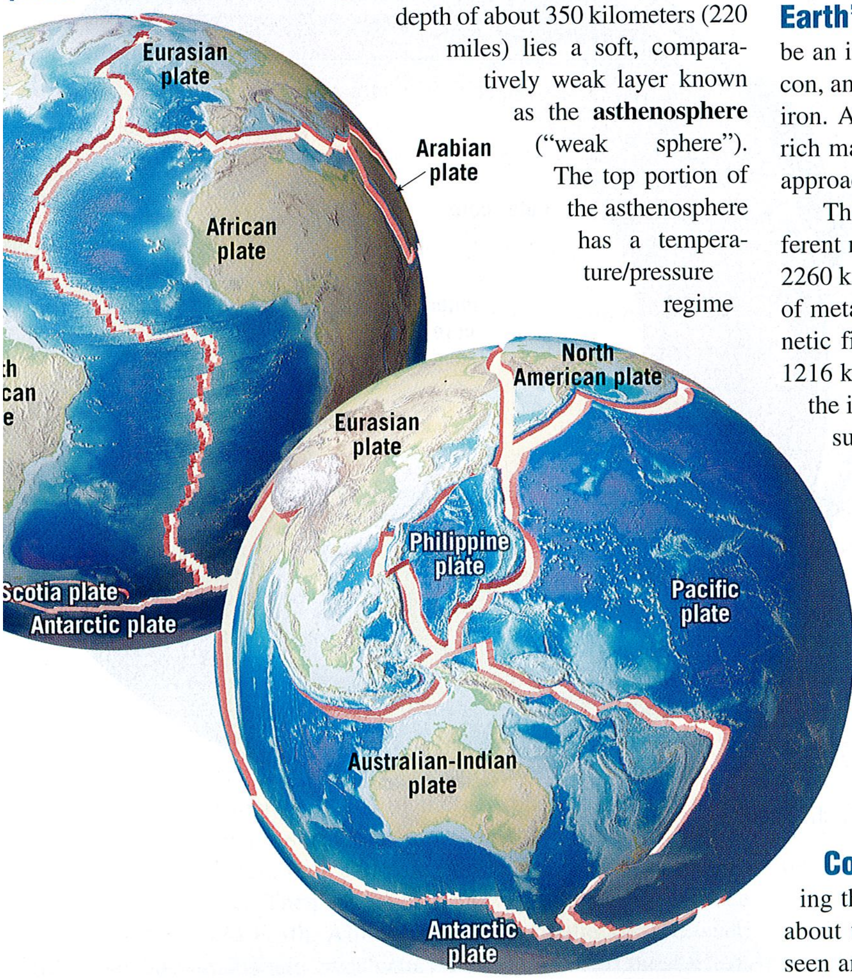
It is important to emphasize that the strength of various Earth materials is a function of both their composition and the temperature and pressure of their environment. You should not get the idea that the entire lithosphere behaves like a brittle solid similar to rocks found on the surface. Rather, the rocks of the lithosphere get progressively hotter and weaker (more easily deformed) with increasing depth. At the depth of the uppermost asthenosphere, the rocks are close enough to their melting temperature (some melting may actually occur) that they are very easily deformed. Thus, the uppermost asthenosphere is weak because it is near its melting point, just as hot wax is weaker than cold wax.

From a depth of 660 kilometers (410 miles) to the top of the core, at a depth of 2900 kilometers (1800 miles), is the **lower mantle**. Because of an increase in pressure (caused by the weight of the rock above), the mantle gradually strengthens with depth. Despite their strength, however, the rocks within the lower mantle are very hot and capable of very gradual flow.

Earth's Core The composition of the **core** is thought to be an iron–nickel alloy with minor amounts of oxygen, silicon, and sulfur—elements that readily form compounds with iron. At the extreme pressure found in the core, this iron-rich material has an average density of nearly 11 g/cm^3 and approaches 14 times the density of water at Earth's center.

The core is divided into two regions that exhibit very different mechanical strengths. The **outer core** is a *liquid layer* 2260 kilometers (about 1400 miles) thick. It is the movement of metallic iron within this zone that generates Earth's magnetic field. The **inner core** is a sphere that has a radius of 1216 kilometers (754 miles). Despite its higher temperature, the iron in the inner core is *solid* due to the immense pressures that exist in the center of the planet.

e of
spheric

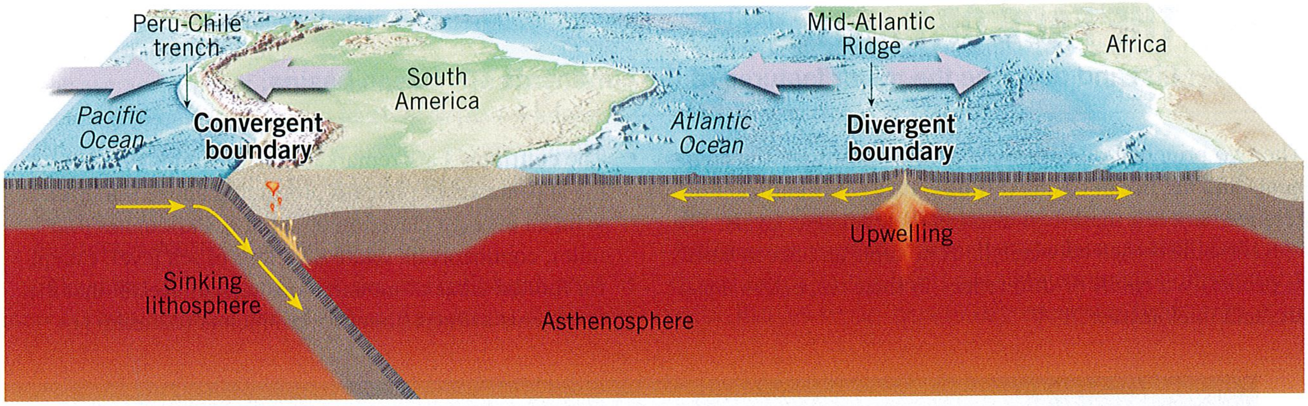


h
can
e

The Mobile Geosphere

Earth is a dynamic planet! If we could go back in time a few hundred million years, we would find the face of our planet dramatically different from what we see today. There would be no Mount St. Helens, Rocky Mountains, or Gulf of Mexico. Moreover, we would find continents having different sizes and shapes and located in different positions than today's landmasses (**FIGURE 1.16**).

Continental Drift and Plate Tectonics During the past several decades, a great deal has been learned about the workings of our dynamic planet. This period has seen an unequaled revolution in our understanding of Earth.



FIGU
and D
ries
occur
plates
along
South
gram.
occur
move
The M
such

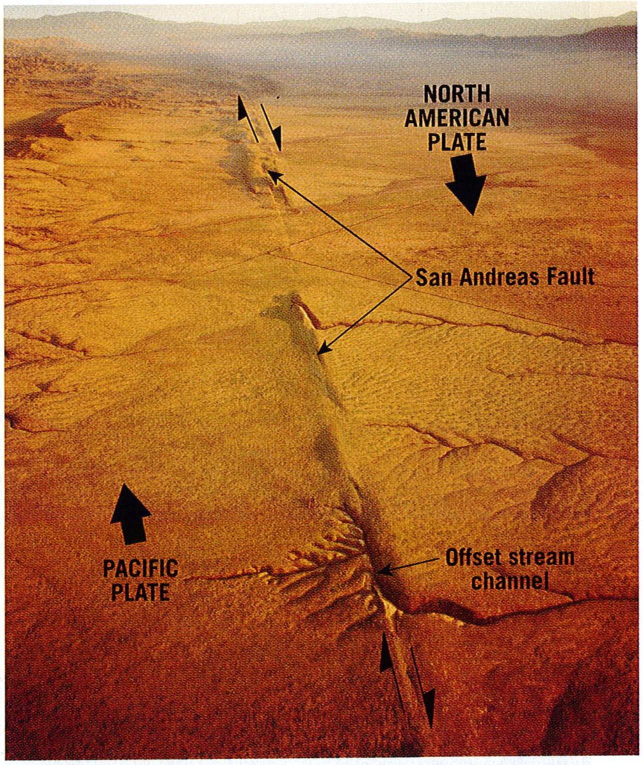
The revolution began in the early part of the twentieth century with the radical proposal of *continental drift*—the idea that the continents move about the face of the planet. This proposal contradicted the established view that the continents and ocean basins are permanent and stationary features on the face of Earth. For that reason, the notion of drifting continents was received with great skepticism and even ridicule. More than 50 years passed before enough data were gathered to transform this controversial hypothesis into a sound theory that wove together the basic processes known to operate on Earth. The theory that finally emerged, called **plate tectonics**, provided geologists with the first comprehensive model of Earth's internal workings.

According to the theory of plate tectonics, Earth's rigid outer shell (the *lithosphere*) is broken into numerous slabs called **lithospheric plates**, which are in continual motion. More than a dozen plates exist (**FIGURE 1.17**). The largest is the Pacific plate, covering much of the Pacific Ocean basin. Notice that several of the large lithospheric plates include an entire continent plus a large area of the seafloor. Note also that none of the plates are defined entirely by the margins of a continent.

Plate Motion Driven by the unequal distribution of heat within our planet, lithospheric plates move relative to each other at a very slow but continuous rate that averages about 5 centimeters (2 inches) per year—about as fast as your fingernails grow. Because plates move as coherent units relative to all other plates, they interact along their margins. Where two plates move together, called a *convergent boundary*, one of the plates plunges beneath the other and descends into the mantle (**FIGURE 1.18**). The lithospheric plates that sink into the mantle are those that are capped with relatively dense oceanic crust.

Any portion of a plate that is capped by continental crust is too buoyant to be carried into the mantle. As a result, when two plates carrying continental crust converge, a collision of the two continental margins occurs. The result is the formation of a major mountain belt, as exemplified by the Himalayas.

Divergent boundaries are located where plates pull apart (see Figure 1.18). Here the fractures created as the plates separate are filled with molten rock that wells up from the mantle. This hot material slowly cools to form solid rock, producing new slivers of seafloor. This process



FIGU
Fault
San A
exam
bounc
plates
(Photo

occurs along oceanic ridges where, over spans of millions of years, hundreds of thousands of square kilometers of new seafloor have been generated (see Figure 1.18). Thus, while new seafloor is constantly being added at the oceanic ridges, equal amounts are returned to the mantle along boundaries where two plates converge.

At other sites, plates do not push together or pull apart. Instead, they slide past one another, so that seafloor is neither created nor destroyed. These zones are called *transform fault boundaries*. California's San Andreas Fault is a well-known example (**FIGURE 1.19**).

1.5 CONCEPT CHECKS

1. List and briefly describe Earth's compositional layers.
2. Contrast the lithosphere and the asthenosphere.
3. What are lithospheric plates? List the three types of boundaries that separate plates.

1.6 THE FACE OF EARTH

List and describe the major features of the continents and ocean basins.

The two principal divisions of Earth's surface are the continents and the ocean basins (**FIGURE 1.20**). A significant difference between these two areas is their relative levels. The elevation difference between the continents and ocean basins is primarily a result of differences in their respective densities and thicknesses:

- The **continents** are remarkably flat features that have the appearance of plateaus protruding above sea level. With an average elevation of about 0.8 kilometer (0.5 mile), continents lie relatively close to sea level, except for limited areas of mountainous terrain. Recall that the continents average about 35 kilometers (22 miles) in

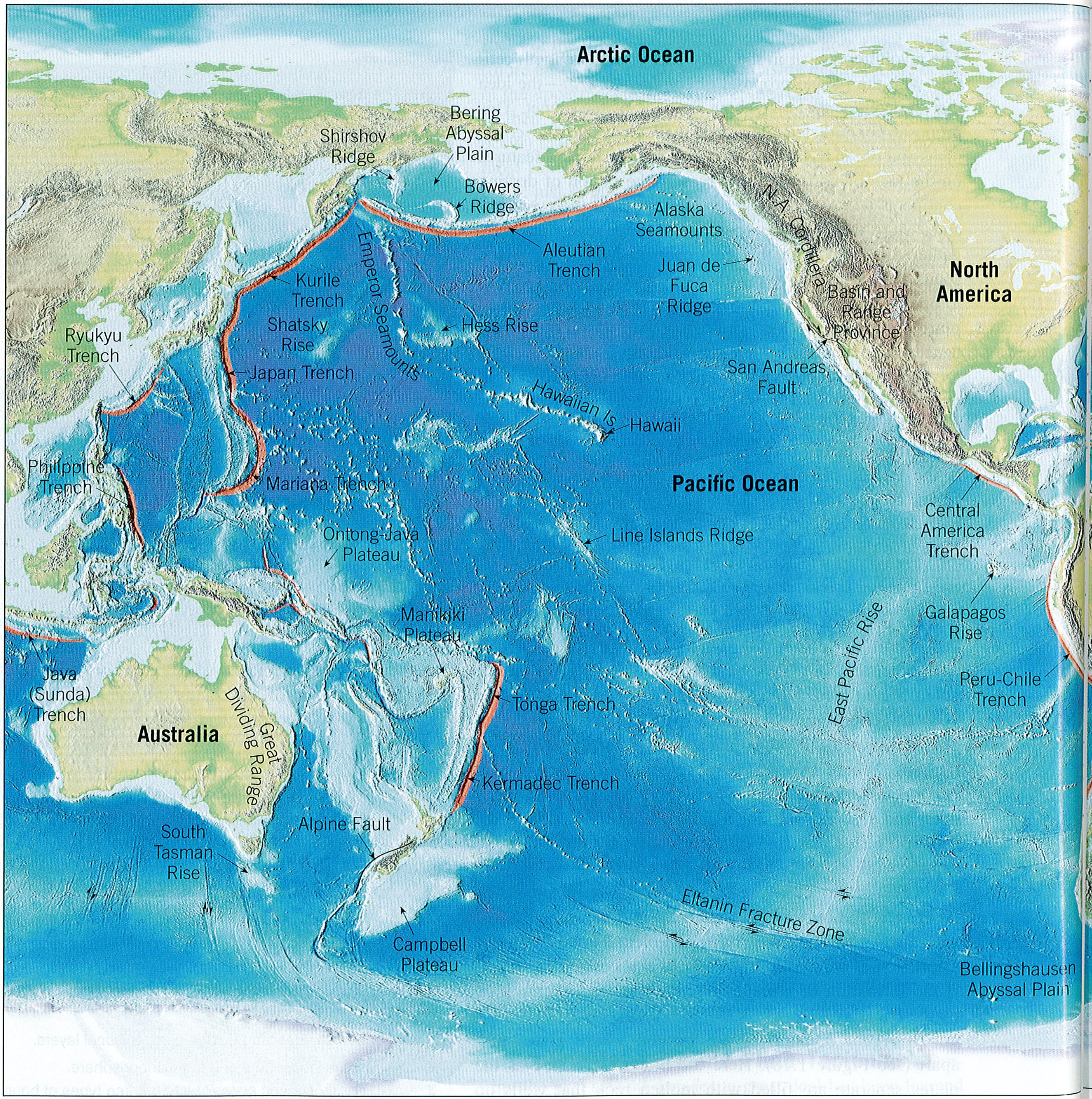


FIGURE 1.20 The Face of Earth Major surface features of the geosphere.

thickness and are composed of granitic rocks that have a density of about 2.7 g/cm^3.

- The average depth of the **ocean basin** is about 3.8 kilometers (2.4 miles) below sea level, or about 4.5 kilometers (2.8 miles) lower than the average elevation of the continents. The basaltic rocks that comprise the oceanic crust average only 7 kilometers (5 miles) thick and have an average density of about 3.0 g/cm^3.

Thus, the thicker and less dense continental crust is more buoyant than the oceanic crust. As a result, continental crust floats on top of the deformable rocks of the mantle at a higher level than oceanic crust for the same reason that a large, empty (less dense) cargo ship rides higher than a small, loaded (more dense) one.

Major Features of the Continents

The largest features of the continents can be grouped into two distinct categories: extensive, flat, stable areas that have been eroded nearly to sea level, and uplifted regions of deformed rocks that make up present-day mountain belts. Notice in

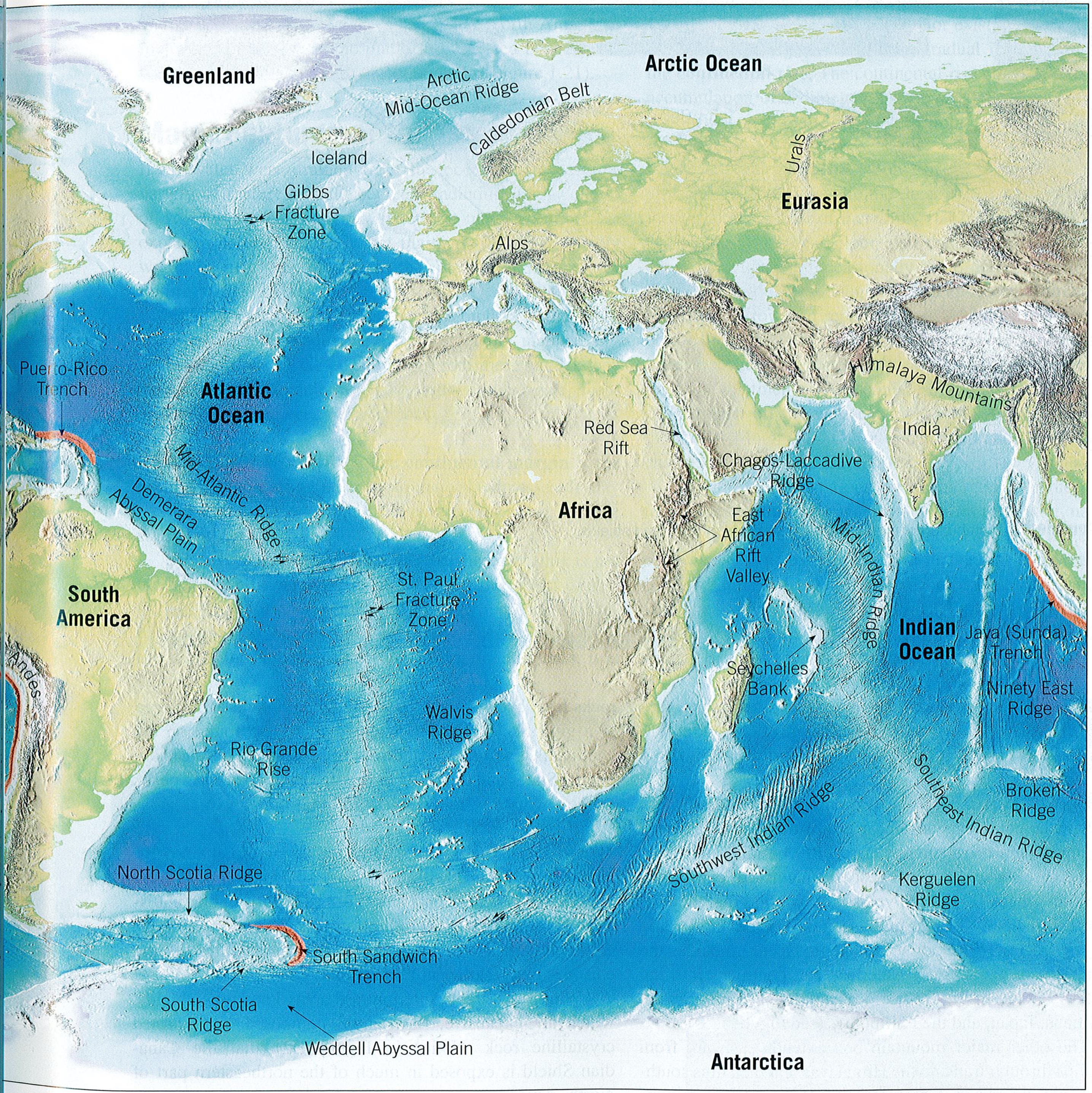
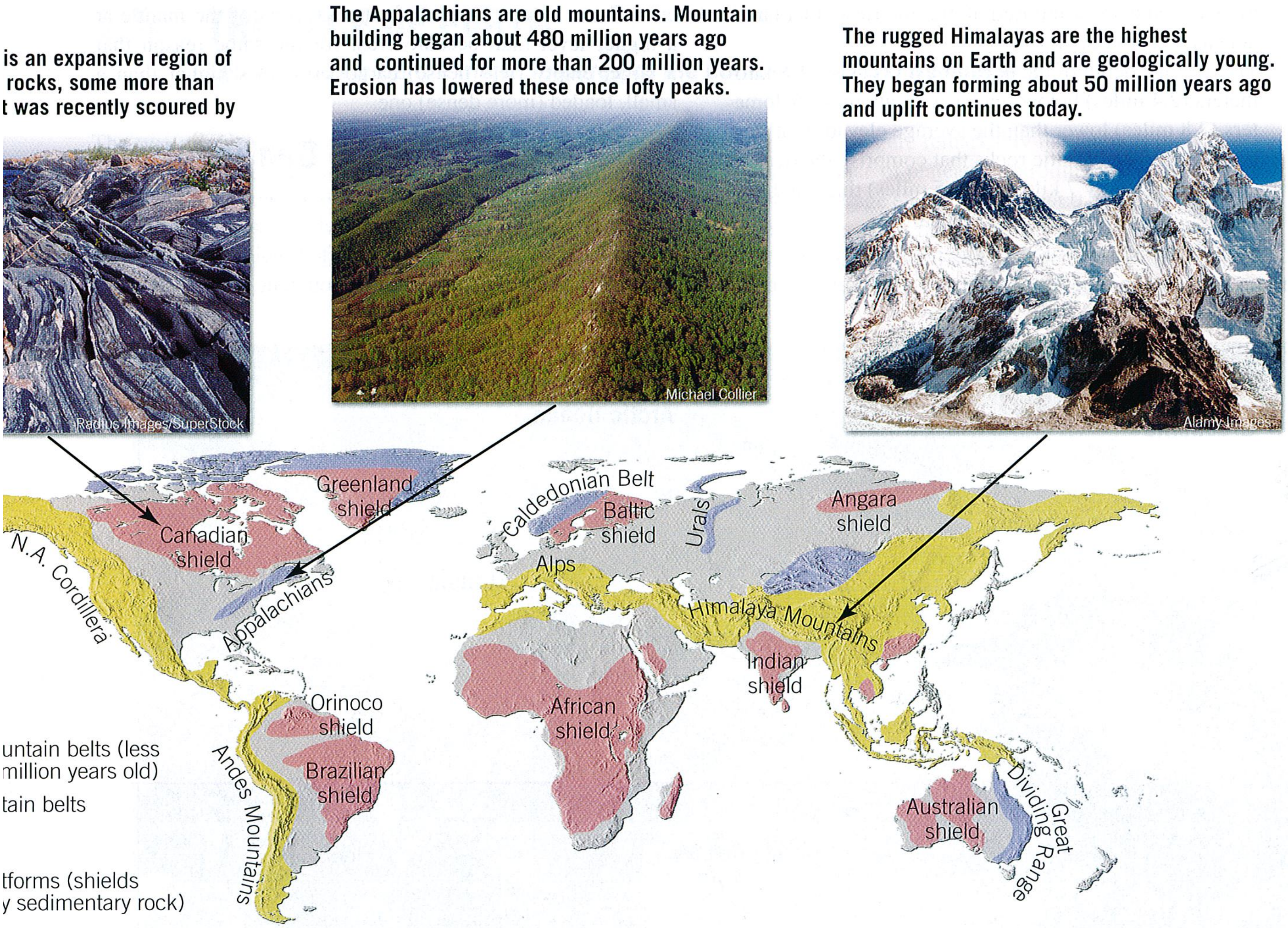


FIGURE 1.20 (Continued)



re 1.21 The Continents Distribution of mountain belts, stable platforms, and shields.

FIGURE 1.21 that young mountain belts tend to be long, narrow features at the margins of continents and that the flat, stable areas are typically located in the interior of continents.

Mountain Belts The most prominent topographic features of the continents are linear **mountain belts**. Although the distribution of mountains appears to be random, this is not the case. When the youngest mountains are considered (those less than 100 million years old), we find that they are located principally in two major zones. The circum-Pacific belt (the region surrounding the Pacific Ocean) includes the mountains of the western Americas and continues into the western Pacific in the form of volcanic islands such as the Aleutians, Japan, and the Philippines (see Figure 1.20).

The other major mountain belt extends eastward from the Alps through Iran and the Himalayas and then dips southward into Indonesia. Careful examination of mountainous terrains reveals that most are places where thick sequences of rocks have been squeezed and highly deformed, as if placed in a gigantic vise. Older mountains are also found on the continents. Examples include the Appalachians in the eastern United States and the Urals in Russia. Their once lofty peaks are now worn low, as a result of millions of years of erosion.

The Stable Interior Unlike the young mountain belts, which have formed within the past 100 million years, the interiors of the continents have been relatively stable (undisturbed) for the past 600 million years or even longer. Typically, these regions were involved in mountain-building episodes much earlier in Earth's history.

Within the stable interiors are areas known as **shields**, which are expansive, flat regions composed of deformed crystalline rock. Notice in Figure 1.21 that the Canadian Shield is exposed in much of the northeastern part of North America. Age determinations for various shields have shown that they are truly ancient regions. All contain

Precambrian-age rocks that are over 1 billion years old, with some samples approaching 4 billion years in age. These oldest-known rocks exhibit evidence of enormous forces that have folded and faulted them and altered them with great heat and pressure. Thus, we conclude that these rocks were once part of an ancient mountain system that has since been eroded away to produce these expansive, flat regions.

Other flat areas of the stable interior exist in which highly deformed rocks, like those found in the shields, are covered by a relatively thin veneer of sedimentary rocks. These areas are called **stable platforms**. The sedimentary rocks in stable platforms are nearly horizontal except where they have been warped to form large basins or domes. In North America a major portion of the stable platform is located between the Canadian Shield and the Rocky Mountains (Figure 1.21).

Major Features of the Ocean Basins

If all water were drained from the ocean basins, a great variety of features would be seen, including linear chains of volcanoes, deep canyons, extensive plateaus, and large expanses of monotonously flat plains. In fact, the scenery would be nearly as diverse as that on the continents (see Figure 1.20).

During the past 70 years, oceanographers using modern depth-sounding equipment have gradually mapped significant portions of the ocean floor. From these studies they have defined three major regions: *continental margins*, *deep-ocean basins*, and *oceanic (mid-ocean) ridges*.

Continental Margins

The **continental margin** is the portion of the seafloor adjacent to major landmasses. It may include the *continental shelf*, the *continental slope*, and the *continental rise*.

Although land and sea meet at the shoreline, this is not the boundary between the continents and the ocean basins. Rather, along most coasts a gently sloping platform of material, called the **continental shelf**, extends seaward from the shore. Because it is underlain by continental crust, it is considered a flooded extension of the continents. A glance at Figure 1.20 shows that the width of the continental shelf is variable. For example, it is broad along the East and Gulf coasts of the United States but relatively narrow along the Pacific margin of the continent.

The boundary between the continents and the deep-ocean basins lies along the **continental slope**, which is a relatively steep dropoff that extends from the outer edge of the continental shelf to the floor of the deep ocean (see Figure 1.20). Using this as the dividing line, we find that about 60 percent of Earth's surface is represented by ocean basins and the remaining 40 percent by continents.

In regions where trenches do not exist, the steep continental slope merges into a more gradual incline known as the **continental rise**. The continental rise consists of a thick accumulation of sediments that moved downslope from the continental shelf to the deep-ocean floor.

Deep-Ocean Basins

Between the continental margins and oceanic ridges lie the **deep-ocean basins**. Parts of these regions consist of incredibly flat features called **abyssal plains**. The ocean floor also contains extremely deep depressions that are occasionally more than 11,000 meters (36,000 feet) deep. Although these **deep-ocean trenches** are relatively narrow and represent only a small fraction of the ocean floor, they are nevertheless very significant features. Some trenches are located adjacent to young mountains that flank the continents. For example, in Figure 1.20 the Peru–Chile trench off the west coast of South America parallels the Andes Mountains. Other trenches parallel linear island chains called *volcanic island arcs*.

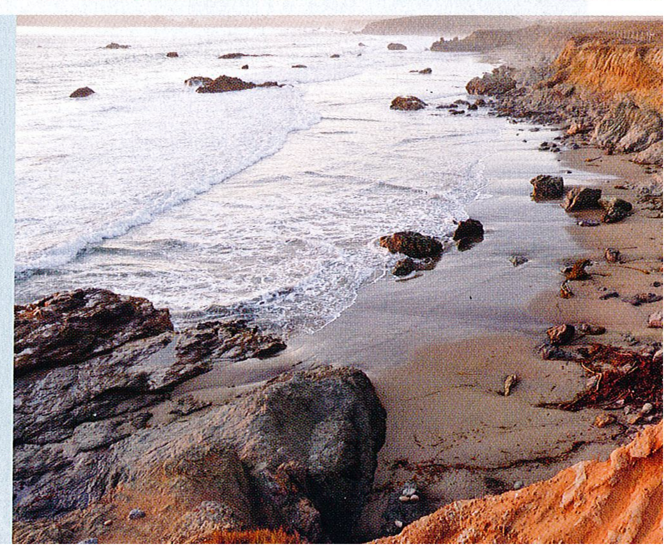
Dotting the ocean floor are submerged volcanic structures called **seamounts**, which sometimes form long, narrow chains. Volcanic activity has also produced several large *lava plateaus*, such as the Ontong Java Plateau located northeast of New Guinea. In addition, some submerged plateaus are composed of continental-type crust. Examples include the Campbell Plateau southeast of New Zealand and the Seychelles Bank northeast of Madagascar.

EYE ON EARTH

This photo shows the picturesque coastal bluffs and rocky shoreline along a portion of the California coast south of San Simeon State Park.

QUESTION 1 *This area, like other shorelines, is described as an interface. What does that mean?*

QUESTION 2 *Does the shoreline represent the boundary between the continent and ocean basin? Explain.*



Oceanic Ridges The most prominent feature on the ocean floor is the **oceanic ridge**, or **mid-ocean ridge**. As shown in Figure 1.20, the Mid-Atlantic Ridge and the East Pacific Rise are parts of this system. This broad elevated feature forms a continuous belt that winds for more than 70,000 kilometers (43,000 miles) around the globe in a manner similar to the seam of a baseball. Rather than consisting of highly deformed rock, such as most of the mountains on the continents, the oceanic ridge system consists of layer upon layer of igneous rock that has been fractured and uplifted.

Understanding the topographic features that comprise the face of Earth is critical to our understanding of the mechanisms that have shaped our planet. What is the significance of the enormous ridge system that extends through all the world's oceans? What is the connection, if any, between young, active mountain belts and deep-ocean trenches? What forces crumple rocks to produce majestic mountain ranges? These are questions that are addressed in some of the coming chapters, as we investigate the dynamic processes that shaped our planet in the geologic past and will continue to shape it in the future.

1.6 CONCEPT CHECKS

1. Contrast continents and ocean basins.
2. Describe the general distribution of Earth's youngest mountains.
3. What is the difference between shields and stable platforms?
4. What are the three major regions of the ocean floor and some features associated with each region?

1.7 EARTH AS A SYSTEM

Define *system* and explain why Earth is considered to be a system.

Anyone who studies Earth soon learns that our planet is a dynamic body with many separate but interacting parts, or *spheres*. The hydrosphere, atmosphere, biosphere, and geosphere and all of their components can be studied separately. However, the parts are not isolated. Each is related in some way to the others, and together they produce a complex and continuously interacting whole that we call the *Earth system*.

Earth System Science

A simple example of the interactions among different parts of the Earth system occurs every winter, as moisture evaporates from the Pacific Ocean and subsequently falls as rain in the hills and mountains of southern California, triggering destructive debris flows (**FIGURE 1.22**). The processes that move water from the hydrosphere to the atmosphere and then to the solid Earth have a profound impact on the plants and animals (including humans) that inhabit the affected regions.

Scientists have recognized that in order to more fully understand our planet, they must learn how its individual components (land, water, air, and life-forms) are interconnected. This endeavor, called **Earth system science**, aims to study Earth as a *system* composed of numerous interacting parts, or *subsystems*. Rather than looking through the limited lens of only one of the traditional sciences—geology, atmospheric science, chemistry, biology, and so on—Earth system science attempts to integrate the knowledge of several academic fields. Using an interdisciplinary approach, those engaged in Earth system science attempt to achieve the level of understanding necessary to comprehend and solve many of our global environmental problems.

A **system** is a group of interacting, or interdependent, parts that form a complex whole. Most of us hear and use the term *system* frequently. We may service our car's cooling *system*, make use of the city's transportation *system*, and be a participant in the political *system*. A news report might inform us of an approaching weather *system*. Further, we know that Earth is just a small part of a larger system known as the *solar system*, which in turn is a subsystem of an even larger system called the Milky Way Galaxy.

The Earth System

The Earth system has a nearly endless array of subsystems in which matter is recycled over and over. One familiar loop, or subsystem, is the *hydrologic cycle.* It represents the unending circulation of Earth's water among the hydrosphere, atmosphere, biosphere, and geosphere. Water enters the atmosphere through evaporation from Earth's surface and transpiration from plants. Water vapor condenses in the atmosphere to form clouds, which in turn produce precipitation that falls back to Earth's surface. Some of the rain that falls onto the land sinks in and then is taken up by plants or becomes groundwater, and some flows across the surface toward the ocean.

Viewed over long time spans, the rocks of the geosphere are constantly forming, changing, and re-forming. The loop that involves the processes by which one rock changes to another is called the *rock cycle* and is discussed at some length in Chapter 3. The cycles of the Earth system are not independent of one another. To the contrary, there are many places where the cycles come in contact and interact.

The Parts Are Linked The parts of the Earth system are linked so that a change in one part can produce changes in any or all of the other parts. For example, when a volcano erupts, lava from Earth's interior may flow out at the surface and block a nearby valley. This new obstruction influences the region's drainage system by creating a lake or causing streams to change course. The large quantities of volcanic ash and gases that can be emitted during an eruption might be blown high into the atmosphere and influence the amount of solar energy that can reach Earth's surface. The result could be a drop in air temperatures over the entire hemisphere.

Where the surface is covered by lava flows or a thick layer of volcanic ash, existing soils are buried. This causes the soil-forming processes to begin anew to transform the new surface material into soil (**FIGURE 1.23**). The soil that eventually forms will reflect the interactions among many parts of the Earth system—the volcanic parent material, the climate, and the impact of biological activity. Of course, there would also be significant changes in the biosphere. Some organisms and their habitats would be eliminated by the lava and ash, and new settings for life, such as a lake formed by a lava dam, would be created. The potential climate change could also impact sensitive life-forms.

Time and Space Scales The Earth system is characterized by processes that vary on spatial scales from fractions of millimeters to thousands of kilometers. Time scales for Earth's processes range from milliseconds to billions of years. As we learn about Earth, it becomes increasingly clear that despite significant separations in distance or time, many processes are connected, and a change in one component can influence the entire system.

Energy for the Earth System The Earth system is powered by energy from two sources. The Sun drives external processes that occur in the atmosphere, in the hydrosphere, and at Earth's surface. Weather and climate, ocean circulation, and erosional processes are driven by energy from the Sun. Earth's interior is the second source of energy. Heat remaining from when our planet formed and heat that is continuously generated by radioactive decay power the internal processes that produce volcanoes, earthquakes, and mountains.

FIGURE 1.23 Change Is a Constant When Mount St. Helens erupted in
shown here was buried by a volcanic mudflow. Now plants are reestablished
(Photo by Terry Donnelly/Alamy Images)

People and the Earth System Humans are *part of* the Earth system, a system in which the living and nonliving components are entwined and interconnected. Therefore, our actions produce changes in all the other parts. When we burn gasoline and coal, dispose of our wastes, and clear the land, we cause other parts of the system to respond, often in unforeseen ways. Throughout this book, you will learn about many of Earth's subsystems, including the hydrologic system, the tectonic (mountain-building) system, the rock cycle, and the climate system. Remember that these components *and we humans* are all part of the complex interacting whole we call the Earth system.

The organization of this text involves traditional groupings of chapters that focus on closely related topics. Nevertheless, the theme of *Earth as a system* keeps recurring through *all* major units of *Earth Science*. It is a thread that weaves through the chapters and helps tie them together. At the end of each chapter is a section titled "Examining the Earth System." The questions and problems found there will help you develop an awareness and appreciation for some of the Earth system's important interrelationships.

1.7 CONCEPT CHECKS

1. What is a system? List three examples of systems.
2. What are the two sources of energy for the Earth system?
3. Predict how a change in the hydrologic cycle, such as increased rainfall in an area, might influence the biosphere and geosphere in that area.

ONCEPTS
N REVIEW

Introduction to Earth Science

IS EARTH SCIENCE?

escribe the sciences that collectively make up Earth science.
ie scales of space and time in Earth science.

science, geology, oceanography, meteorology, astronomy, geologic time

ıcludes geology, oceanography, meteorology, and astronomy.
road subdivisions of geology. Physical geology studies Earth materials
and external processes that create and shape Earth's landscape. Histori-
mines Earth history.
sciences seek to understand the oceans, the atmosphere's weather and
rth's place in the universe.
onships between people and the environment include the quest for re-
act of people on the natural environment, and the effects of natural hazards.
ust deal with processes and phenomena that vary from the subatomic
o the nearly infinite scale of the universe. The time scales of phenomena
science range from tiny fractions of a second to many billions of years.
the span of time since the formation of Earth, is about 4.6 billion years.

1.2 THE NATURE OF SCIENTIFIC INQUIRY

Discuss the nature of scientific inquiry and distinguish between a hypothesis and a theory.

KEY TERMS: hypothesis, theory

- Scientists make careful observations, construct tentative explanations for those observations (hypotheses), and then test those hypotheses with field investigations and laboratory work. In science, a theory is a well-tested and widely accepted explanation that the scientific community agrees best fits certain observable facts.
- As failed hypotheses are discarded, scientific knowledge moves closer to a correct understanding, but we can never be fully confident that we know all the answers. Scientists must always be open to new information that forces change in our model of the world.

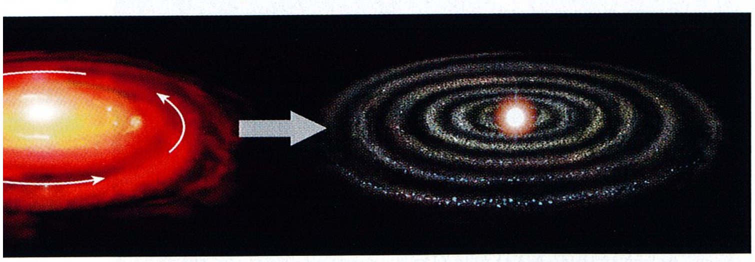
EVOLUTION OF EARTH

e stages in the formation of our solar system.

theory

ory describes the formation of the solar system. The planets and Sun
about 5 billion years ago from a large cloud of dust and gases.
ntracted, it began to rotate and assume a disk shape. Material that was
pulled toward the center became the protosun. Within the rotating disk,
alled planetesimals, swept up more and more of the cloud's debris.
r high temperatures and weak gravitational fields, the inner planets were
ulate and retain many of the lighter components. Because of the very
es existing far from the Sun, the large outer planets consist of huge
ter materials. These gaseous substances account for the comparatively
low densities of the outer planets.

4.6 billion years old. If all the planets in our solar system formed at e time, how old would you expect Mars to be? Jupiter? The Sun?



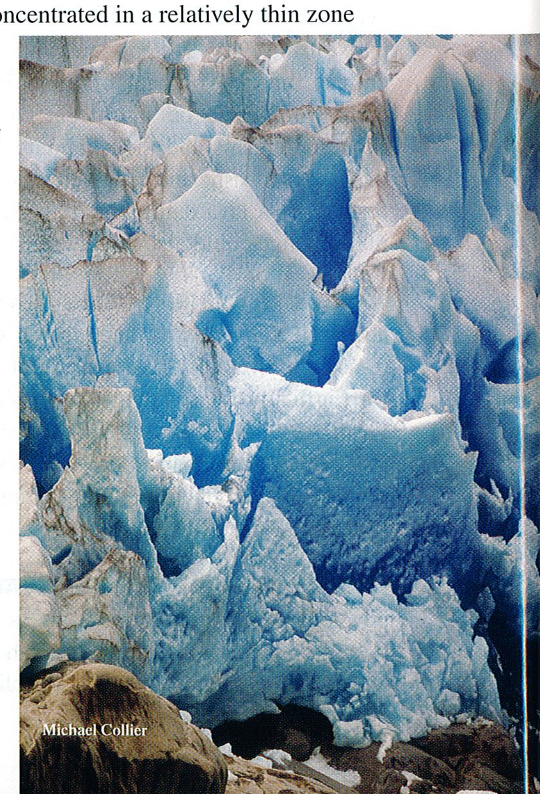
1.4 EARTH'S SPHERES

List and describe Earth's four major spheres.

KEY TERMS: hydrosphere, atmosphere, biosphere, geosphere

- Earth's physical environment is traditionally divided into three major parts: the solid Earth, called the geosphere; the water portion of our planet, called the hydrosphere; and Earth's gaseous envelope, called the atmosphere.
- A fourth Earth sphere is the biosphere, the totality of life on Earth. It is concentrated in a relatively thin zone that extends a few kilometers into the hydrosphere and geosphere and a few kilometers up into the atmosphere.
- Of all the water on Earth, more than 96 percent is in the oceans, which cover nearly 71 percent of the planet's surface.

Q Is glacial ice part of the geosphere, or does it belong to the hydrosphere? Explain your answer.



Michael Collier

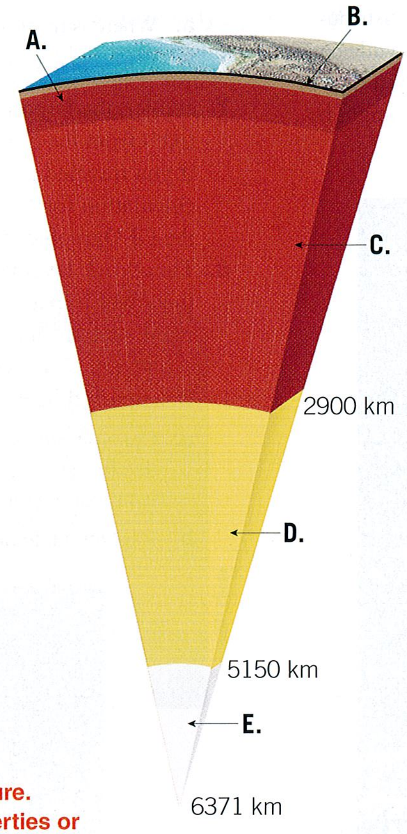
1.5 A CLOSER LOOK AT THE GEOSPHERE

Label a diagram that shows Earth's internal structure. Briefly explain why the geosphere can be described as being mobile.

KEY TERMS: crust, mantle, lithosphere, asthenosphere, lower mantle, core, outer core, inner core, plate tectonics, lithospheric plate

- Compositionally, the solid Earth has three layers: core, mantle, and crust. The core is most dense, and the crust is least dense.
- Earth's interior can also be divided into layers based on physical properties. The crust and upper mantle make a two-part layer called the lithosphere, which is broken into the plates of plate tectonics. Beneath that is the "weak" asthenosphere. The lower mantle is stronger than the asthenosphere and overlies the molten outer core. This liquid is made of the same iron–nickel alloy as the inner core, but the extremely high pressure of Earth's center compacts the inner core into a solid form.

Q The diagram represents Earth's layered structure. Does it show layering based on physical properties or layering based on composition? Identify the lettered layers.



1.6 THE FACE OF EART

List and describe the major fea nents and ocean basins.

KEY TERMS: continent, ocean basin, moun stable platform, continental margin, conti nental slope, continental rise, deep-ocean l deep-ocean trench, seamount, oceanic ridg

- Two principal divisions of Earth's surf nents and ocean basins. A significant c relative levels. The elevation differenc nents and ocean basins is primarily the ences in their respective densities and
- The largest features of the continents c two categories: mountain belts and the ocean floor is divided into three major continental margin, deep-ocean basin, ocean) ridge.

Q Put these features of the ocean floor shallowest to deepest: continental s trench, continental shelf, abyssal pla rise.

1.7 EARTH AS A SYSTEM

Define *system* and explain why Earth is considered to be a system.

KEY TERMS: Earth system science, system

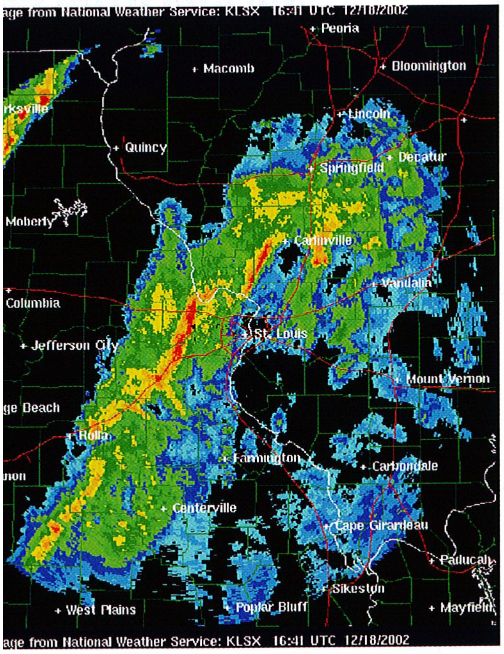
- Although each of Earth's four spheres can be studied separately, they are all related in a complex and continuously interacting whole tl Earth system.
- Earth system science uses an interdisciplinary approach to integrate the knowledge of several academic fields in the study of our plane environmental problems.
- The two sources of energy that power the Earth system are (1) the Sun, which drives the external processes that occur in the atmospher and at Earth's surface, and (2) heat from Earth's interior that powers the internal processes that produce volcanoes, earthquakes, and m

Q Give a specific example of how humans are affected by the Earth system and another example of how humans affect the Earth s

GIVE IT SOME THOUGHT

1. After entering a dark room, you turn on a wall switch, but the light does not come on. Suggest at least three hypotheses that might explain this observation. How would you determine which one of your hypotheses (if any) is correct?
2. Each of the following statements may either be a hypothesis (H), a theory (T), or an observation (O). Use one of these letters to identify each statement. Briefly explain each choice.
   - **a.** A scientist proposes that a recently discovered large ring-shaped structure on the Canadian Shield is the remains of an ancient meteorite crater.
   - **b.** The Redwall Formation in the Grand Canyon is composed primarily of limestone.
   - **c.** The outer part of Earth consists of several large plates that move and interact with each other.
   - **d.** Since 1885, the terminus of Canada's Athabasca Glacier has receded 1.5 kilometers.

: measurements and observations is a basic part of sci-
'he accompanying radar image, showing the distribu-
y of precipitation associated with a storm, provides one
y another image in this chapter that illustrates a way in
data are gathered. Suggest an advantage that might be
:he example you select.



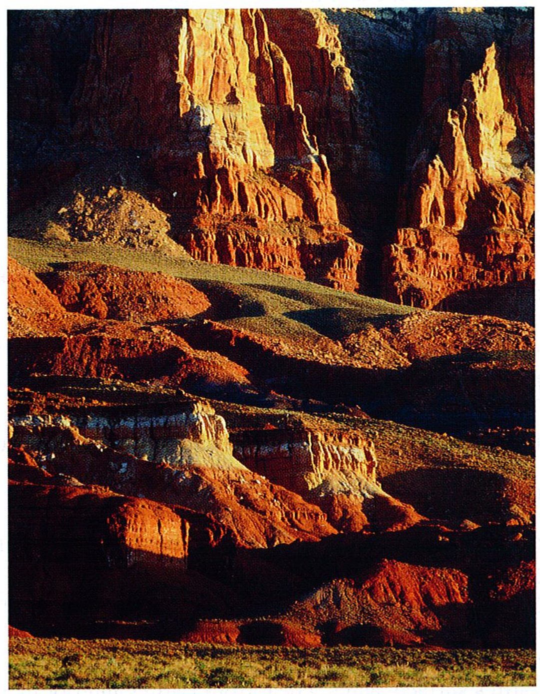
National Weather Service

corded history for humankind is about 5000 years.
ople view this span as being very long. How does it
ength of geologic time? Calculate the percentage or
ɔgic time that is represented by recorded history. To
ıs easier, round the age of Earth to the nearest billion.
ɔh in Figure 1.13 to answer the following questions.

ɔ climb to the top of Mount Everest, how many breaths
you have to take at that altitude to equal one breath at sea

ing in a commercial jet at an altitude of 12 kilometers
) feet), about what percentage of the atmosphere's mass is

6. Examine Figure 1.12 to answer these questions.
   a. Where is most of Earth's freshwater stored?
   b. Where is most of Earth's liquid freshwater found?
7. Jupiter, the largest planet in our solar system, is 5.2 astronomical units (AU) from the Sun. How long would it take to go from Earth to Jupiter if you traveled as fast as a jet (1000 kilometers/hour)? Do the same calculation for Neptune, which is 30 AU from the Sun. Referring to the GEOgraphics feature on page 15 will be helpful.
8. These rock layers consist of materials such as sand, mud, and gravel that, over a span of millions of years, were deposited by rivers, waves, wind, and glaciers. Each layer was buried by subsequent deposits and eventually compacted and cemented into solid rock. Later, the region was uplifted, and erosion exposed the layers seen here.
   a. Can you establish a relative time scale for these rocks? That is, can you determine which one of the layers shown here is likely oldest and which is probably youngest?
   b. Explain the logic you used.



Michael Collier

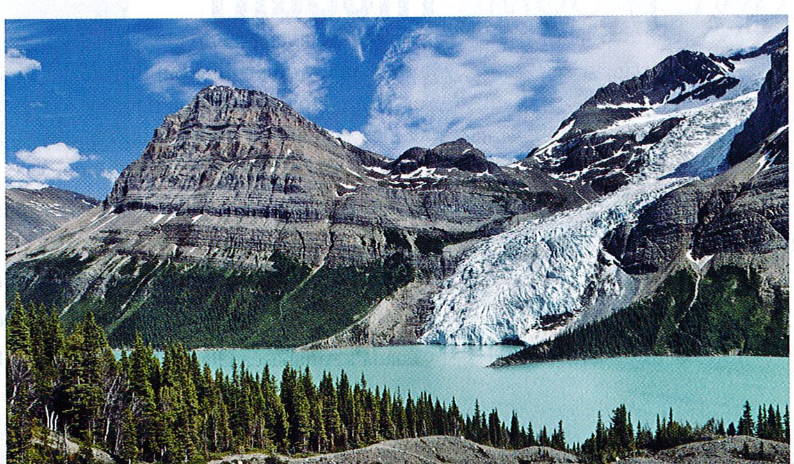
NG THE **EARTH SYSTEM**

British Columbia's Mount Robson Provincial Park.
ıed for the highest peak in the Canadian Rockies.

ɛxamples as possible of features associated with each of
pheres.

, of these features was created by internal processes? De-
ɛ of external processes in this scene.

ırt of the Earth system. List at least three examples of
icular, influence one or more of Earth's major spheres.

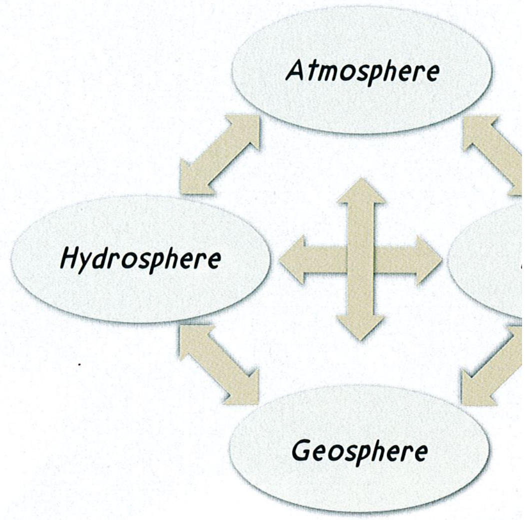


Michael Wheatley/AGE Fotostock

3. The accompanying photo provides an example of interactions among different parts of the Earth system. It is a view of a debris flow (popularly called a mudslide) that was triggered by extraordinary rains. Which of Earth's four spheres were involved in this natural disaster, which buried a small town on the Philippine island of Leyte? Describe how each contributed to or was influenced by the event.

Pat Roque/AP Photo

4. Examine the accompanying concept map that links the Earth system. All of the spheres are linked by a processes by which the spheres interact and influen each arrow list at least one process.



MasteringGeology™

Looking for additional review and test prep materials? Visit the Self Study area in **www.masteringgeology.com** to find practice quizzes, study tools, and multimedia that will aid in your understanding of this chapter's content. In **MasteringGeology™** you will find:

- GEODe: Earth Science: An interactive visual walkthrough of key concepts
- Geoscience Animation Library: More than 100 animations illuminating many difficult-to-understand Earth science concepts
- In The News RSS Feeds: Current Earth science eve are pulled into the site with assessment
- Pearson eText
- Optional Self Study Quizzes
- Web Links
- Glossary
- Flashcards

Earth's crust and oceans are home to a wide variety of useful and essential minerals. Most people are familiar with the common uses of many basic metals, including aluminum in beverage cans, copper in electrical wiring, and gold and silver in jewelry. But some people are not aware that pencil "lead" contains the greasy-feeling mineral graphite and that bath powders and many cosmetics contain the mineral talc. Moreover, many do not know that dentists use drill bits impregnated with diamonds to drill through tooth enamel or that the common mineral quartz is the source of silicon for computer chips. In fact, practically every manufactured product contains materials obtained from minerals.

In addition to rocks and minerals having economic uses, all the processes that geologists study are in some way dependent on the properties of these basic Earth materials. Events such as volcanic eruptions, mountain building, weathering and erosion, and even earthquakes involve rocks and minerals. Consequently, a basic knowledge of Earth materials is essential to understanding all geologic phenomena.

2.1 MINERALS: BUILDING BLOCKS OF ROCK

List the main characteristics that an Earth material must possess to be considered a mineral and describe each.

We begin our discussion of Earth materials with an overview of **mineralogy** (*mineral* = mineral, *ology* = the study of) because minerals are the building blocks of rocks. In addition, humans have used minerals for both practical and decorative purposes for thousands of years (**FIGURE 2.1**). Flint and chert were the first minerals to be mined; they were fashioned into weapons and cutting tools. Egyptians began mining gold, silver, and copper as early as 3700 B.C. By 2200 B.C., humans had discovered how to combine copper with tin to make bronze, a strong, hard alloy. Later, a process was developed to extract iron from minerals such as hematite—a discovery that marked the decline of the Bronze Age. During the Middle Ages, mining of a variety of minerals became common, and the impetus for the formal study of minerals was in place.

ırtz
eloped
nd near
ısas. (Photo
ɛ fotostock)

The term *mineral* is used in several different ways. For example, those concerned with health and fitness extol the benefits of vitamins and minerals. The mining industry typically uses the word to refer to anything taken out of the ground, such as coal, iron ore, or sand and gravel. The guessing game known as *Twenty Questions* usually begins with the question "Is it animal, vegetable, or mineral?" What criteria do geologists use to determine whether something is a mineral?

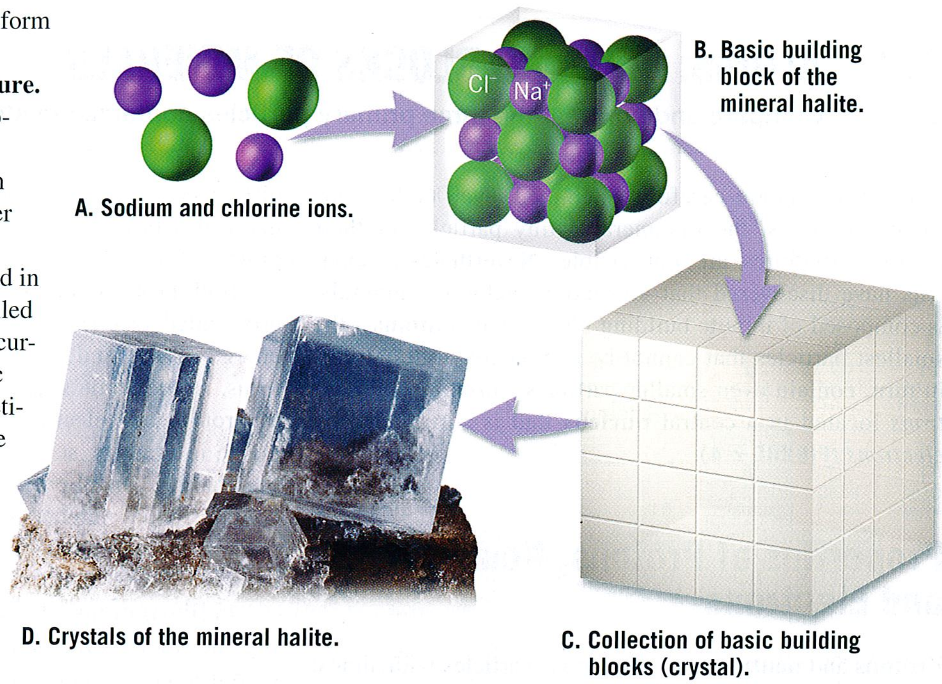
Defining a Mineral

Geologists define **mineral** as *any naturally occurring inorganic solid that possesses an orderly crystalline structure and a definite chemical composition that allows for some variation*. Thus, Earth materials that are classified as minerals exhibit the following characteristics:

1. **Naturally occurring.** Minerals form through natural geologic processes. Synthetic materials—meaning those produced in a laboratory or by human intervention—are not considered minerals.
2. **Generally inorganic.** Inorganic crystalline solids, such as ordinary table salt (halite), that are found naturally in the ground are considered minerals. (Organic compounds, on the other hand, are generally not. Sugar, a crystalline solid like salt but that comes from sugarcane or sugar beets, is a common example of such an organic compound.) Many marine animals secrete inorganic compounds, such as calcium carbonate (calcite), in the form of shells and coral reefs. If these materials are buried and become part of the rock record, geologists consider them minerals.
3. **Solid substance.** Only solid crystalline substances are considered minerals. Ice (frozen water) fits this criterion and is considered a mineral, whereas liquid water and water vapor do not. The exception is mercury,

which is found in its liquid form in nature.

4. **Orderly crystalline structure.** Minerals are crystalline substances, which means their atoms (ions) are arranged in an orderly, repetitive manner (**FIGURE 2.2**). This orderly packing of atoms is reflected in regularly shaped objects called *crystals*. Some naturally occurring solids, such as volcanic glass (obsidian), lack a repetitive atomic structure and are not considered minerals.
5. **Definite chemical composition that allows for some variation.** Minerals are chemical compounds having compositions that can be expressed by a chemical formula. For example, the common mineral quartz has the formula SiO_2, which indicates that quartz consists of silicon (Si) and oxygen (O) atoms, in a ratio of one-to-two. This proportion of silicon to oxygen is true for any sample of pure quartz, regardless of its origin. However, the compositions of some minerals vary *within specific, well-defined limits.* This occurs because certain elements can substitute for others of similar size without changing the mineral's internal structure.



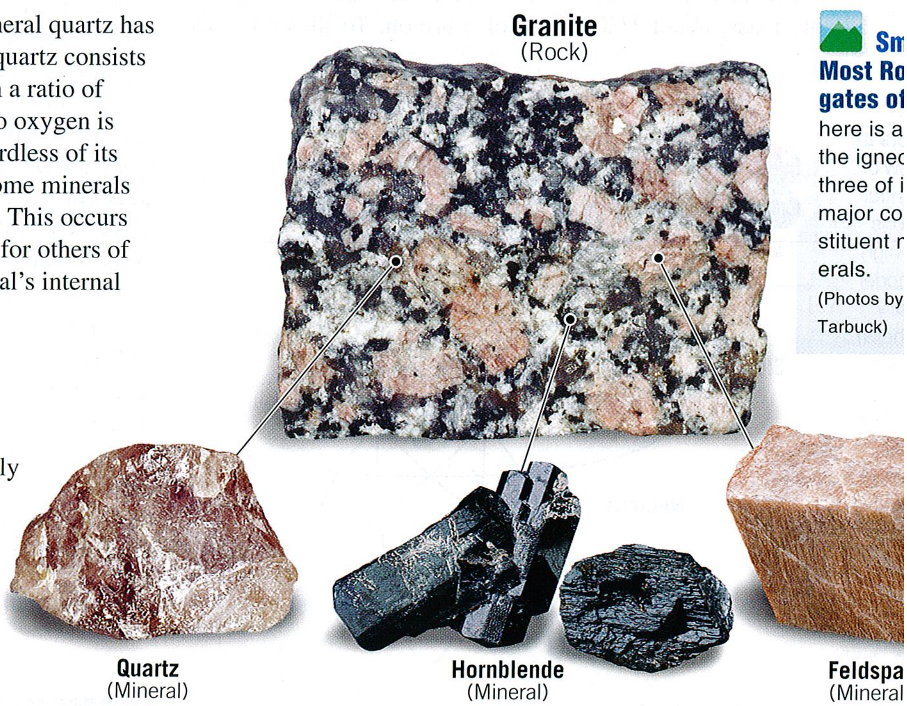
FIGU
of So
Ions
Halit
atom
ing b
shap
shap
(Photo

What Is a Rock?

In contrast to minerals, rocks are more loosely defined. Simply, a **rock** is any solid mass of mineral, or mineral-like, matter that occurs naturally as part of our planet. Most rocks, like the sample of granite shown in **FIGURE 2.3**, occur as aggregates of several different minerals. The term *aggregate* implies that the minerals are joined in such a way that their individual properties are retained. Note that the different minerals that make up granite can be easily identified. However, some rocks are composed almost entirely of one mineral. A common example is the sedimentary rock *limestone*, which is an impure mass of the mineral calcite.

In addition, some rocks are composed of nonmineral matter. These include the volcanic rocks *obsidian* and *pumice*, which are noncrystalline glassy substances, and *coal*, which consists of solid organic debris.

Although this chapter deals primarily with the nature of minerals, keep in mind that most rocks are aggregates of minerals. Because the properties of rocks are determined largely by the chemical composition and crystalline structure of the minerals contained within them, we will first consider these Earth materials.



Sm
Most Ro
gates of
here is a
the igneo
three of i
major co
stituent r
erals.
(Photos by
Tarbuck)

2.1 CONCEPT CHECKS

1. List five characteristics an Earth material must have in order to be considered a mineral.
2. Based on the definition of *mineral*, which of the following materials are not classified as minerals and why: gold, water, synthetic diamonds, ice, and wood?
3. Define the term *rock*. How do rocks differ from minerals?

2.2 ATOMS: BUILDING BLOCKS OF MINERALS

Compare and contrast the three primary particles contained in atoms.

When minerals are carefully examined, even under optical microscopes, the innumerable tiny particles of their internal structures are not visible. Nevertheless, scientists have discovered that all matter, including minerals, is composed of minute building blocks called **atoms**—the smallest particles that cannot be chemically split. Atoms, in turn, contain even smaller particles—*protons* and *neutrons* located in a central **nucleus** that is surrounded by *electrons* (**FIGURE 2.4**).

Properties of Protons, Neutrons, and Electrons

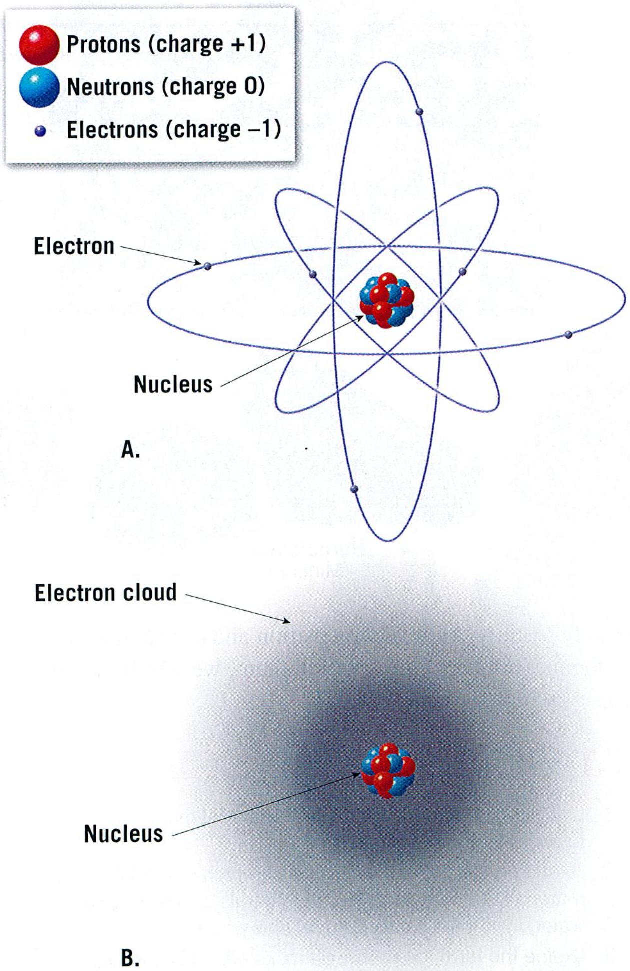
Protons and **neutrons** are very dense particles with almost identical masses. By contrast, **electrons** have a negligible mass, about 1/2000 that of a proton. To illustrate this difference, assume that on a scale where a proton has the mass of a baseball, an electron has the mass of a single grain of rice.

Both protons and electrons share a fundamental property called *electrical charge.* Protons have an electrical charge of +1, and electrons have a charge of −1. Neutrons, as the name suggests, have no charge. The charges of protons and electrons are equal in magnitude but opposite in polarity, so when these two particles are paired, the charges cancel each other out. Since matter typically contains equal numbers of positively charged protons and negatively charged electrons, most substances are electrically neutral.

In illustrations, electrons are sometimes shown orbiting the nucleus in a manner that resembles the planets of our solar system orbiting the Sun (see Figure 2.4A). However, electrons do not actually behave this way. A more realistic depiction shows electrons as a cloud of negative charges surrounding the nucleus (see Figure 2.4B). Studies of the arrangements of electrons show that they move about the nucleus in regions called *principal shells*, each with an associated energy level. In addition, each shell can hold a specific number of electrons, with the outermost shell generally containing **valence electrons** that interact with other atoms to form chemical bonds.

Most of the atoms in the universe (except hydrogen and helium) were created inside massive stars by nuclear fusion and released into interstellar space during hot, fiery supernova explosions. As this ejected material cooled, the newly formed nuclei attracted electrons to complete their atomic structure. At the temperatures found at Earth's surface, all free atoms (those not bonded to other atoms) have a full complement of electrons—one for each proton in the nucleus.

Models of
ied view of
of a central
of protons
ied by high-
This model
pherically
uds (shells)
al nucleus.
is virtually
e atom. The
m is the
negatively
The relative
nown are
.)



Elements: Defined by Their Number of Protons

The simplest atoms have only 1 proton in their nuclei, whereas others have more than 100. The number of protons in the nucleus of an atom, called the **atomic number**, determines its chemical nature. All atoms with the same number of protons have the same chemical and physical properties. Together, a group of the same kind of atoms is called an **element**. There are about 90 naturally occurring elements, and several more have been synthesized in the laboratory. You are probably familiar with the names of many elements, including carbon, nitrogen, and oxygen. All carbon atoms have six protons, whereas all nitrogen

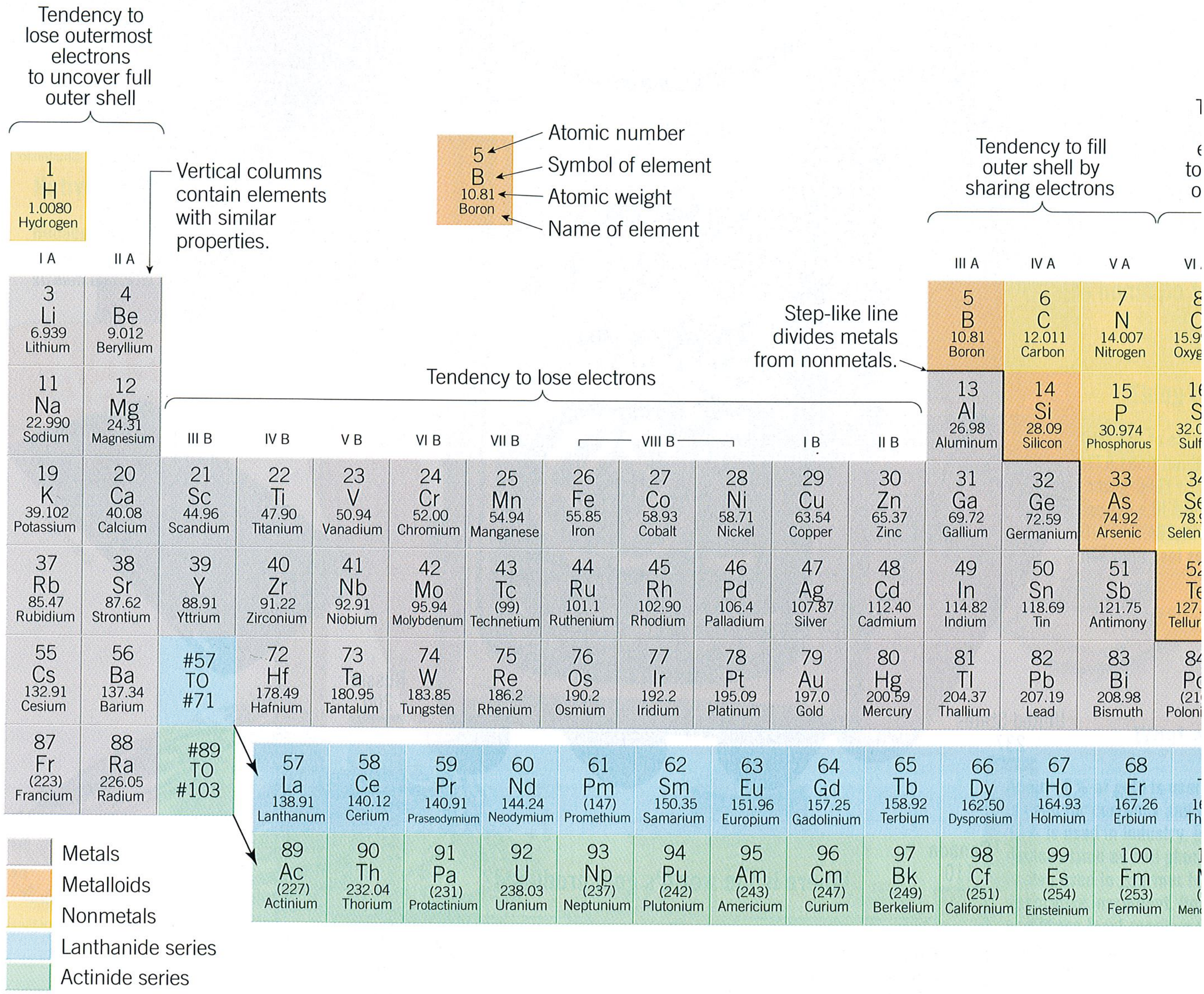


FIGURE 2.5 Periodic Table of the Elements

atoms have seven protons, and all oxygen atoms have eight protons.

Elements are organized so that those with similar properties line up in columns, referred to as groups. This arrangement, called the **periodic table**, is shown in **FIGURE 2.5**. Each element has been assigned a one- or two-letter symbol. The atomic numbers and masses for each element are also shown on the periodic table.

Atoms of the naturally occurring elements are the basic building blocks of Earth's minerals. Most elements join with atoms of other elements to form **chemical compounds**. Therefore, most minerals are chemical compounds composed of atoms of two or more elements. These include the minerals quartz (SiO_2), halite ($NaCl$), and calcite ($CaCO_3$). However, a few minerals, such as native copper, diamonds, sulfur, and gold, are made entirely of atoms of only one element (**FIGURE 2.6**).

A. Gold on quartz

B. Sulfur

FIGU amon That Singl

Dennis

2.2 CONCEPT CHECKS

1. List the three main particles of an atom and explain how they differ from one another.
2. Make a simple sketch of an atom and label its three main particles.
3. What is the significance of valence electrons?

ld

een treasured
; before recorded
r its beauty. Even
most common use
ry.

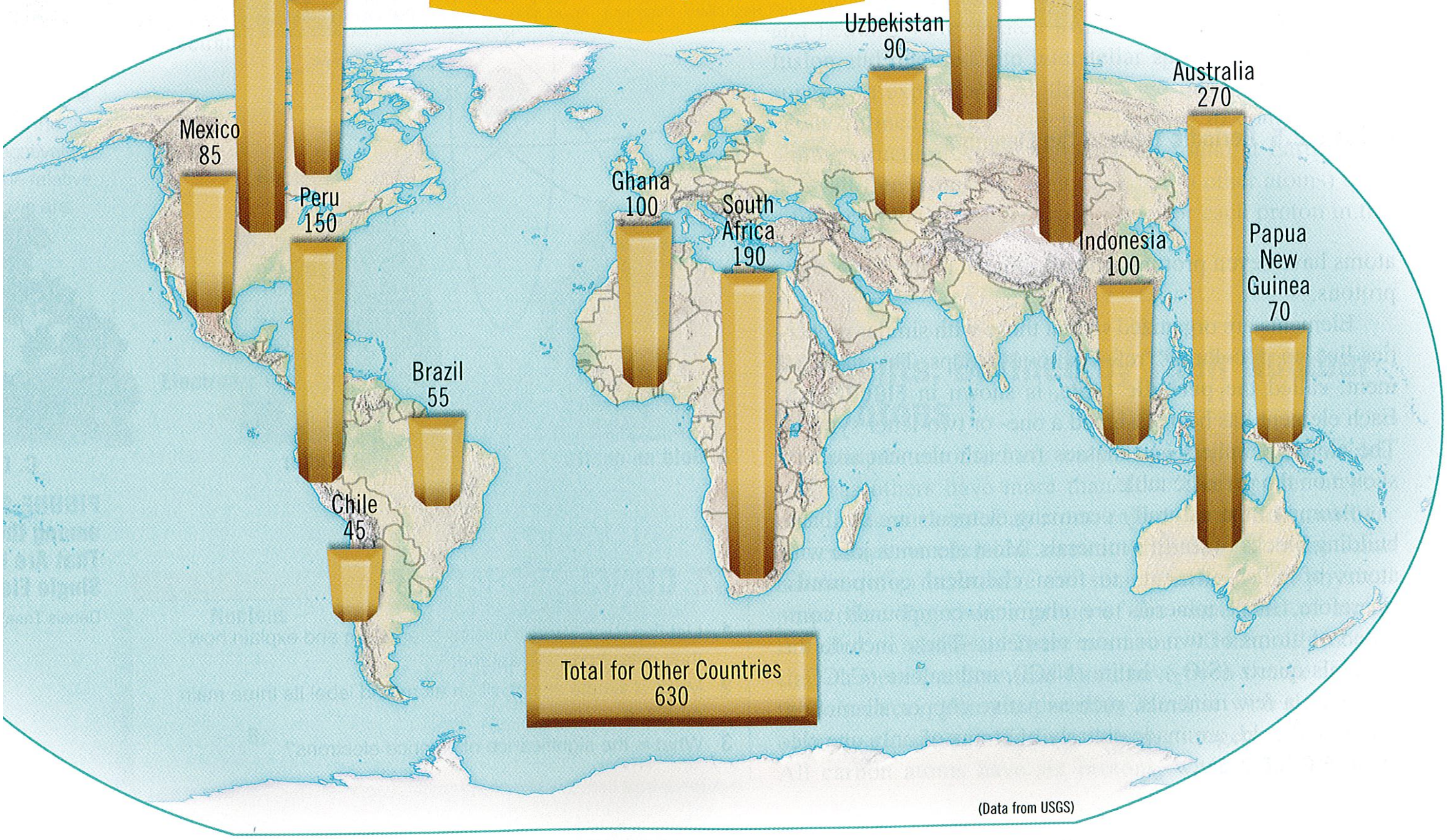
Shutterstock

ble is gold?

the value of one troy
was about US$1,677.
value, a 1000-gram
r of gold, like the one
orth $53,664. In 1970,
old was less than $40
e!

$53,664

Where is the world's gold produced?



Native gold

Because gold does not easily react with other elements, it often occurs as a native element in nuggets found in stream deposits or as grains in igneous rocks.

Shutterstock

Shutterstock

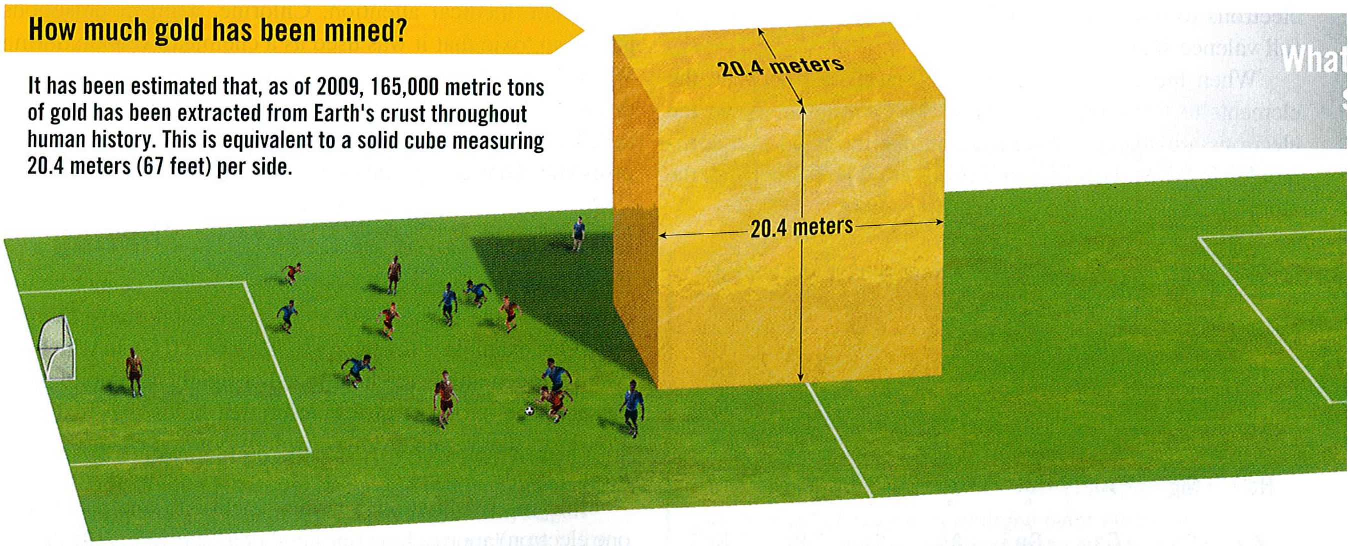
Shutterstock

Wha

About 50% of gold is
is used for currency a
10% is used in indust
devices such as cell p
is also used in gourm
decorative ingredient
one of the least react
provides no nutritiona
human body unaltere

How much gold has been mined?

It has been estimated that, as of 2009, 165,000 metric tons of gold has been extracted from Earth's crust throughout human history. This is equivalent to a solid cube measuring 20.4 meters (67 feet) per side.



What

2.3 WHY ATOMS BOND

Distinguish among ionic bonds, covalent bonds, and metallic bonds.

Except in a group of elements known as the noble gases, atoms bond to one another under the conditions (temperatures and pressures) that occur on Earth. Some atoms bond to form *ionic compounds*, some form *molecules*, and still others form *metallic substances*. Why does this happen? Experiments show that electrical forces hold atoms together and bond them to each other. These electrical attractions lower the total energy of the bonded atoms, which, in turn, generally makes them more stable. Consequently, atoms that are bonded in compounds tend to be more stable than atoms that are free (not bonded).

The Octet Rule and Chemical Bonds

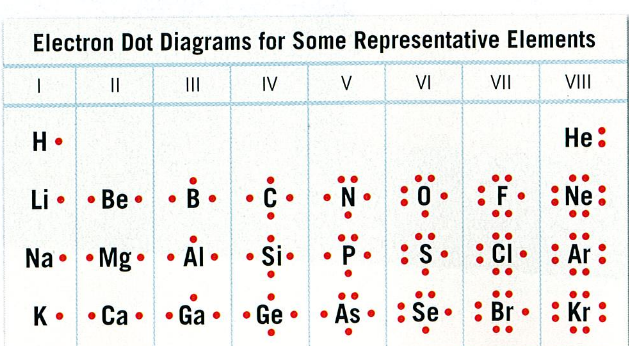
As was noted earlier, valence (outer shell) electrons are generally involved in chemical bonding. **FIGURE 2.7** shows a shorthand way of representing the number of valence electrons for selected elements in each group. Notice that the elements in Group I have one valence electron, those in Group II have two valence electrons, and so on, up to eight valence electrons in Group VIII.

The noble gases (except helium) have very stable electron arrangements with eight valence electrons and, therefore, tend to lack chemical reactivity. Many other atoms gain, lose, or share electrons during chemical reactions, ending up with electron arrangements of the noble gases. This observation led to a chemical guideline known as the **octet rule**: *Atoms tend to gain, lose, or share electrons until they are surrounded by eight valence electrons.* Although there are exceptions to the octet rule, it is a useful rule of thumb for understanding chemical bonding.

When an atom's outer shell does not contain eight electrons, it is likely to chemically bond to other atoms to fill its shell. A **chemical bond** is a transfer or sharing of electrons that allows each atom to attain a full valence shell of electrons. Some atoms do this by transferring all their valence electrons to other atoms so that an inner shell becomes the full valence shell.

When the valence electrons are transferred between the elements to form ions, the bond is an *ionic bond*. When the electrons are shared between the atoms, the bond is a *covalent bond*. When the valence electrons are shared among all the atoms in a substance, the bonding is *metallic*.

Diagrams
nts Each
ence elec-
ermost



Ionic Bonds: Electrons Transferred

Perhaps the easiest type of bond to visualize is the *ionic bond*, in which one atom gives up one or more of its valence electrons to another atom to form **ions**—*positively and negatively charged atoms*. The atom that loses electrons becomes a positive ion, and the atom that gains electrons becomes a negative ion. Oppositely charged ions are strongly attracted to one another and join to form ionic compounds.

Consider the ionic bonding that occurs between sodium (Na) and chlorine (Cl) to produce the solid ionic compound sodium chloride—the mineral halite (common table salt). Notice in **FIGURE 2.8A** that a sodium atom gives up its single valence electron to chlorine and, as a result, becomes a positively charged sodium ion. Chlorine, on the other hand, gains one electron and becomes a negatively charged chloride ion. We know that ions having unlike charges attract. Thus, an **ionic bond** is an attraction of oppositely charged ions to one another, producing an electrically neutral ionic compound.

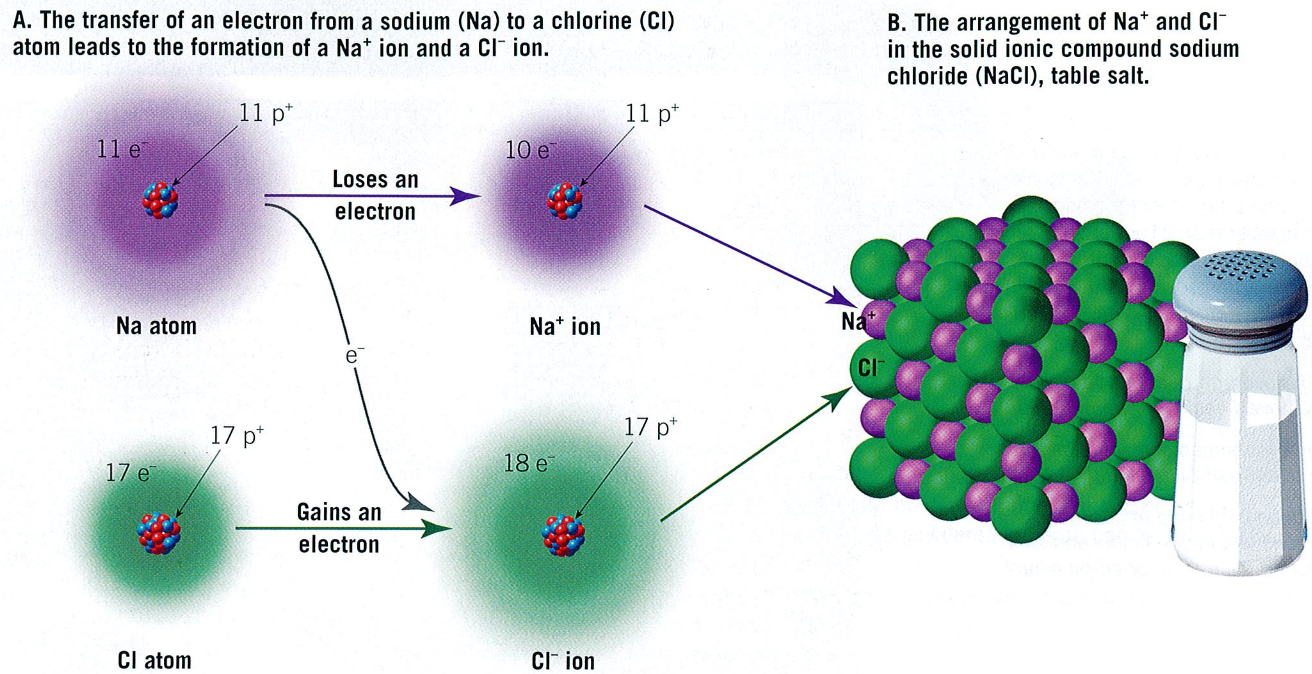
FIGURE 2.8B illustrates the arrangement of sodium and chlorine ions in ordinary table salt. Notice that salt consists of alternating sodium and chlorine ions, positioned in such a manner that each positive ion is attracted to and surrounded on all sides by negative ions and vice versa. This arrangement maximizes the attraction between ions with opposite charges while minimizing the repulsion between ions with identical charges. Thus, ionic compounds consist of an orderly arrangement of oppositely charged ions assembled in a definite ratio that provides overall electrical neutrality.

The properties of a chemical compound are dramatically different from the properties of the various elements comprising it. For example, sodium is a soft silvery metal that is extremely reactive and poisonous. If you were to consume even a small amount of elemental sodium, you would need immediate medical attention. Chlorine, a green poisonous gas, is so toxic that it was used as a chemical weapon during World War I. Together, however, these elements produce sodium chloride, a harmless flavor enhancer that we call table salt. Thus, when elements combine to form compounds, their properties change significantly.

Covalent Bonds: Electron Sharing

Sometimes the forces that hold atoms together cannot be understood on the basis of the attraction of oppositely charged ions. One example is the hydrogen molecule (H_2), in which the two hydrogen atoms are held together tightly, and no ions are present. The strong attractive force that holds two hydrogen atoms together results from a **covalent bond**, *a chemical bond formed by the sharing of a pair of electrons between atoms.*

Imagine two hydrogen atoms (each with one proton and one electron) approaching one another as shown in **FIGURE 2.9**. Once they meet, the electron configuration will change so that



FIGU
of the
Sodiu

both electrons will primarily occupy the space between the atoms. In other words, the two electrons are shared by both hydrogen atoms and are attracted simultaneously by the positive charge of the proton in the nucleus of each atom. Although hydrogen atoms do not form ions, the force that holds these atoms together arises from the attraction of oppositely charged particles—positively charged protons in the nuclei and negatively charged electrons that surround these nuclei.

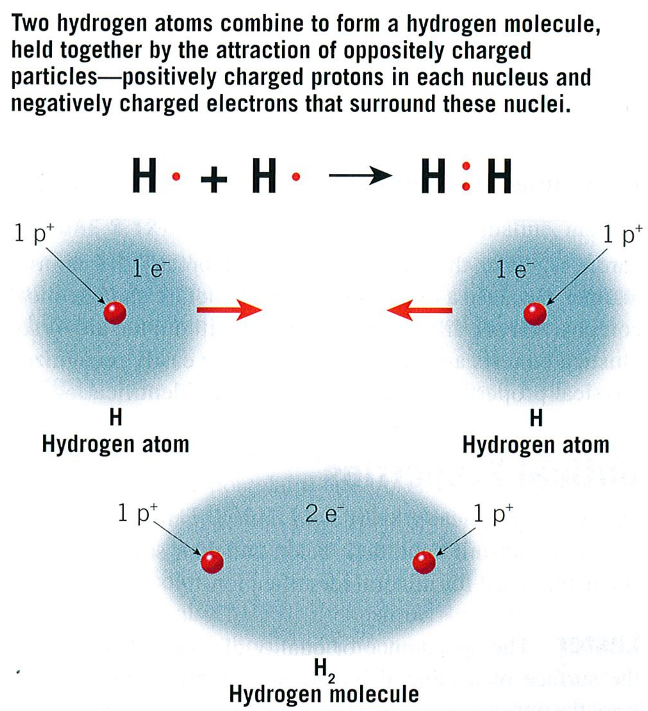
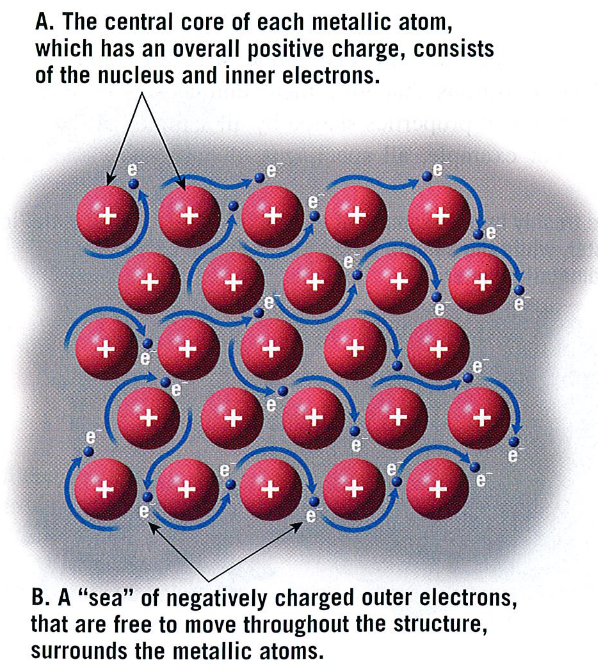


FIGURE 2.9 Covalent Bonding of Two Hydrogen Atoms (H) to Form a Hydrogen Molecule (H_2) When hydrogen atoms bond, the negatively charged electrons are shared by both hydrogen atoms and attracted simultaneously by the positive charge of the proton in the nucleus of each atom.

Metallic Bonds: Electrons Free to Move

A few minerals, such as native gold, silver, and copper, are made entirely of metal atoms that are packed tightly together in an orderly way. The bonding that holds these atoms together is the result of each atom contributing its valence electrons to a common pool of electrons that are free to move throughout the entire metallic structure. The contribution of one or more valence electrons leaves an array of positive ions immersed in a "sea" of valence electrons, as shown in **FIGURE 2.10**.

The attraction between the "sea" of negatively charged electrons and the positive ions produces the **metallic bonds** that give metals their unique properties. Metals are good conductors



FIGUR
Bonds
result
uting it
to a co
trons t
throug
structu
tween
charge
positiv
metalli
als the