An Introduction to Geology

CHAPTER

1

Pakistan's Charakusa Valley with the bold peaks of the Karakoram Range in the background. (Photo by Jimmie Chin/National Geographic/Getty)

The spectacular eruption of a volcano, the terror brought by an earthquake, the magnificent scenery of a mountain valley, and the destruction created by a landslide are all subjects for the geologist (Figure 1.1). The study of geology deals with many fascinating and practical questions about our physical environment. What forces produce mountains? Will there soon be another great earthquake in California? What was the Ice Age like? Will there be another? How were these ore deposits formed? Should we look for water here? Is strip mining practical in this area? Will oil be found if a well is drilled at that location?

The Science of Geology

The subject of this text is **geology,** from the Greek *geo,* "Earth" and *logos,* "discourse." It is the science that pursues an understanding of planet Earth. Geology is traditionally divided into two broad areas—physical and historical. **Physical geology,** which is the primary focus of this book, examines the materials composing Earth and seeks to understand the many processes that operate beneath and upon its surface. The aim of **historical geology,** on the other hand, is to understand the origin of Earth and its development through time. Thus, 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. It should also be pointed out that physical and historical geology are divided into many areas of specialization. Table 1.1 provides a partial list. Every chapter of this book represents one or more areas of specialization in geology.

To understand Earth is challenging because our planet is a dynamic body with many interacting parts and a complex

FIGURE 1.1 Reflection Lake in Washington's Mount Rainier National Park. Glaciers are still sculpting this large volcanic mountain. (Photo by Art Wolfe)

TABLE 1.1 Different Areas of Geologic Study*

Archaeological Geology
Biogeosciences
Engineering Geology
Geochemistry
Geomorphology
Geophysics
History of Geology
Hydrogeology
Mineralogy
Ocean Sciences
Paleoclimatology
Paleontology
Petrology
Planetary Geology
Sedimentary Geology
Seismology
Structural Geology
Tectonics
Volcanology

*This is a partial list of interest sections and specialties of associated societies affiliated with the Geological Society of America (www .geosociety.org) and the American Geophysical Union (www.agu.org), two professional societies to which many geologists belong.

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 landslides or volcanic eruptions occur. Just as often, change takes place so slowly that it goes unnoticed during a lifetime. Scales of size and space also vary greatly among the phenomena that geologists study. Sometimes they must focus on phenomena that are submicroscopic, and at other times they must deal with features that are continental or global in scale.

Geology is perceived as a science that is done in the out of doors, and rightly so. A great deal of geology is based on observations and experiments conducted in the field. But geology is also done in the laboratory where, for example, the study of various Earth materials provides insights into many basic processes. Frequently geology requires an understanding and application of knowledge and principles from physics, chemistry, and biology. Geology is a science that seeks to expand our knowledge of the natural world and our place in it.

Geology, People, and the Environment

The primary focus of this book is to develop an understanding of basic geological principles, but along the way, we will explore numerous important relationships between people and the natural environment. Many of the problems and issues addressed by geology are of practical value to people.

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 (Figure 1.2). Among the hazardous Earth processes studied by geologists are volcanoes, floods, tsunami, earthquakes, and landslides. Of course, geologic hazards are simply *natural* processes. They become hazards only when people try to live where these processes occur (Figure 1.3).

Resources represent another important focus of geology that is of great practical value to people. They include water and soil, a great variety of metallic and nonmetallic minerals, and energy. Together they form the very foundation of modern civilization. Geology deals not only with the formation and occurrence of these vital resources but also with maintaining supplies and with the environmental impact of their extraction and use.

Complicating all environmental issues is rapid world population growth and everyone's aspiration to a better standard of living. The population of our planet is about 6.5 billion people and is gaining about 100 million more people each year. This means a ballooning demand for resources and a growing pressure for people to dwell in environments having significant geologic hazards.

Not only do geologic processes have an impact on people but we humans can dramatically influence geologic processes

FIGURE 1.2 Natural hazards are part of living on Earth. Aerial view of earthquake destruction at Muzaffarabad, Pakistan, January 31, 2006. (Photo by Danny Kemp/AFP/Getty Images)

FIGURE 1.3 This is an image of Italy's Mt. Vesuvius in September 2000. This major volcano is surrounded by the city of Naples and the Bay of Naples. In 79 A.D. Vesuvius explosively erupted, burying the towns of Pompeii and Herculanaeum in volcanic ash. Will it happen again? Geologic hazards are *natural* processes. They only become hazards when people try to live where these processes occur. (Image courtesy of NASA)

as well. For example, 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 appropriate places throughout this book, you will have the opportunity to examine different aspects of our relationship with the physical environment. It will be rare to find a chapter that does not address some aspect of natural hazards, environmental issues, or resources. Significant parts of some chapters provide the basic geologic knowledge and principles needed to understand environmental problems. Moreover, a number of the book's special-interest boxes focus on geology, people, and the environment by providing case studies or highlighting a topical issue.

Some Historical Notes about Geology

The nature of our Earth—its materials and processes—has been a focus of study for centuries. Writings about such topics as fossils, gems, earthquakes, and volcanoes date back to the early Greeks, more than 2300 years ago.

Certainly the most influential Greek philosopher was Aristotle. Unfortunately, Aristotle's explanations about the natural world were not based on keen observations and experiments. Instead, they were arbitrary pronouncements. He believed that rocks were created under the "influence" of the stars and that earthquakes occurred when air crowded into the ground, was heated by central fires, and escaped explosively. When confronted with a fossil fish, he explained that "a great many fishes live in the earth motionless and are found when excavations are made."

Although Aristotle's explanations may have been adequate for his day, they unfortunately continued to be expounded for many centuries, thus thwarting the acceptance of more up-to-date accounts. Frank D. Adams states in *The Birth and Development of the Geological Sciences* (New York: Dover, 1938) that "throughout the Middle Ages Aristotle was regarded as the head and chief of all philosophers; one whose opinion on any subject was authoritative and final."

Catastrophism

In the mid-1600s, James Ussher, Anglican Archbishop of Armagh, Primate of all Ireland, published a major work that had immediate and profound influences. A respected scholar of the Bible, Ussher constructed a chronology of human and Earth history in which he determined that Earth was only a few thousand years old, having been created in 4004 B.C. Ussher's treatise earned widespread acceptance among Europe's scientific and religious leaders, and his chronology was soon printed in the margins of the Bible itself.

During the 17th and 18th centuries the doctrine of **catastrophism** strongly influenced people's thinking about Earth. Briefly stated, catastrophists believed that Earth's landscapes had been shaped primarily by great catastrophes. Features such as mountains and canyons, which today we know take great periods of time to form, were explained as having been produced by sudden and often worldwide disasters produced by unknowable causes that no longer operate. This philosophy was an attempt to fit the rates of Earth processes to the then-current ideas on the age of Earth.

The relationship between catastrophism and the age of Earth has been summarized as follows:

> That the earth had been through tremendous adventures and had seen mighty changes during its obscure past was plainly evident to every inquiring eye; but to concentrate these changes into a few brief millenniums required a tailor-made philosophy, a philosophy whose basis was sudden and violent change.*

The Birth of Modern Geology

Modern geology began in the late 1700s when James Hutton, a Scottish physician and gentleman farmer, published his *Theory of the Earth* (Figure 1.4). In this work, Hutton put forth a fundamental principle that is a pillar of geology today: **uniformitarianism.** It simply states that the *physical, chemical, and biological laws that operate today have also operated in the geologic past.* This means that the forces and processes that we observe presently shaping our planet have been at work for a very long time. Thus, to understand ancient rocks, we must first understand present-day processes and their results. This idea is commonly expressed by saying, "The present is the key to the past."

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*H. E. Brown, V. E. Monnett, and J. W. Stovall, *Introduction to Geology* (New York: Blaisdell, 1958).

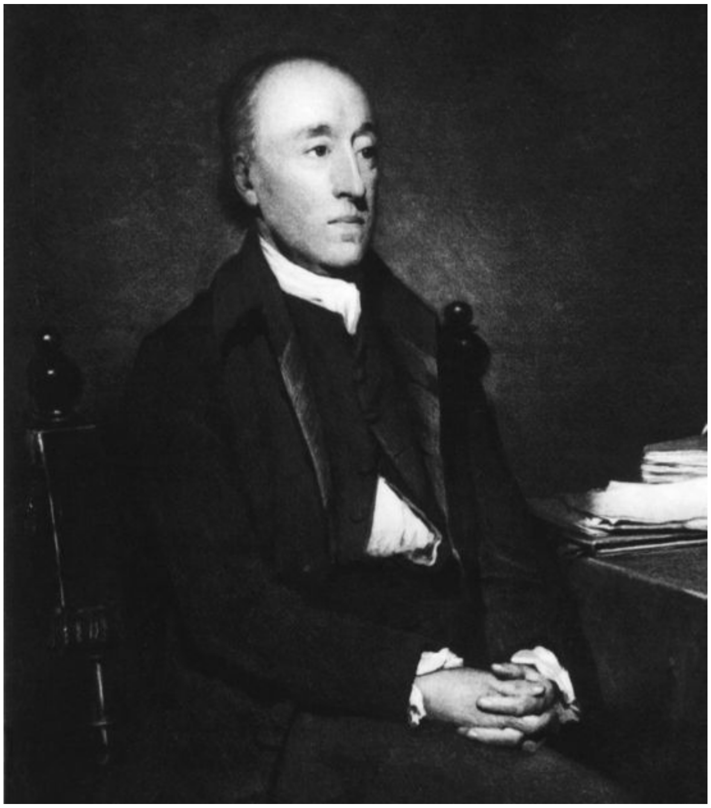

FIGURE 1.4 James Hutton (1726–1797), a founder of modern geology. (Photo courtesy of The Natural History Museum, London)

Prior to Hutton's *Theory of the Earth,* no one had effectively demonstrated that geological processes occur over extremely long periods of time. However, Hutton persuasively argued that forces that appear small could, over long spans of time, produce effects that were just as great as those resulting from sudden catastrophic events. Unlike his predecessors, Hutton carefully cited verifiable observations to support his ideas.

For example, when he argued that mountains are sculpted and ultimately destroyed by weathering and the work of running water, and that their wastes are carried to the oceans by processes that can be observed, Hutton said, "We have a chain of facts which clearly demonstrate . . . that the materials of the wasted mountains have traveled through the rivers"; and further, "There is not one step in all this progress . . . that is not to be actually perceived." He then went on to summarize this thought by asking a question and immediately providing the answer: "What more can we require? Nothing but time."

Today the basic tenets of uniformitarianism are just as viable as in Hutton's day. Indeed, we realize more strongly than ever that the present gives us insight into the past and that the physical, chemical, and biological laws that govern geological processes remain unchanging through time. However, we also understand that the doctrine should not be taken too literally. To say that geological processes in the past were the same as those occurring today is not to suggest that they always had the same relative importance or that they operated at precisely the same rate. Moreover, some important geologic processes are not currently observable, but evidence that they occur is well established. For example, we know that Earth has experienced impacts from large meteorites even though we have no human witnesses. Such events altered Earth's crust, modified its climate, and strongly influenced life on the planet.

The acceptance of uniformitarianism meant the acceptance of a very long history for Earth. Although Earth processes vary in intensity, they still take a very long time to create or destroy major landscape features (Figure 1.5).

For example, geologists have established that mountains once existed in portions of present-day Minnesota, Wisconsin, and Michigan. Today the region consists of low hills and plains. Erosion (processes that wear land away) gradually destroyed these peaks. Estimates indicate that the North American continent is being lowered at a rate of about 3 centimeters per 1000 years. At this rate it would take 100 million years for water, wind, and ice to lower mountains that were 3000 meters (10,000 feet) high.

But even this time span is relatively short on the time scale of Earth history, for the rock record contains evidence that shows Earth has experienced many cycles of mountain building and erosion. Concerning the ever-changing nature of

FIGURE 1.5 Weathering and erosion have gradually sculpted these striking rock formations in Arizona's Monument Valley. Geologic processes often act so slowly that changes may not be visible during an entire human lifetime. (Photo by David Muench Photography, Inc.)

Earth through great expanses of geologic time, Hutton made a statement that was to become his most famous. In concluding his classic 1788 paper published in the *Transactions of the Royal Society of Edinburgh,* he stated, "The results, therefore, of our present enquiry is, that we find no vestige of a beginning—no prospect of an end." A quote from William L. Stokes sums up the significance of Hutton's basic concept:

> In the sense that uniformitarianism implies the operation of timeless, changeless laws or principles, we can say that nothing in our incomplete but extensive knowledge disagrees with it.*

In the chapters that follow, we will be examining the materials that compose our planet and the processes that modify it. It is important to remember that, although many features of our physical landscape may seem to be unchanging over the decades we observe them, they are nevertheless changing, but on time scales of hundreds, thousands, or even many millions of years.

Geologic Time

Although Hutton and others recognized that geologic time is exceedingly long, they had no methods to accurately determine the age of Earth. However, in 1896 radioactivity was discovered. Using radioactivity for dating was first attempted in 1905 and has been refined ever since. Geologists are now able to assign fairly accurate dates to events in Earth history.† For example, we know the dinosaurs became extinct about 65 million years ago. Today the age of Earth is put at about 4.5 billion years.

Relative Dating and the Geologic Time Scale

During the 19th century, long before the advent of radiometric dating, a geologic time scale was developed using principles of relative dating. **Relative dating** means that events are placed in their proper sequence or order without knowing their age in years. This is done by applying principles such as the **law of superposition** (*super* = over, *positum* = to place), which states that in layers of sedimentary rocks or lava flows, the youngest layer is on top and the oldest is on the bottom (assuming that nothing has turned the layers upside down, which sometimes happens). Arizona's Grand Canyon provides a fine example in which the oldest rocks are located in the inner gorge and the youngest rocks are found on the rim (see Chapter 9 opening photo, p. 246, and Figure 15.2, p. 403). So the law of superposition establishes the *sequence* of rock layers—but not, of course, their numerical ages (Figure 1.6). Today such a proposal appears to be elementary, but 300 years ago it amounted to a major breakthrough in scientific reasoning by establishing a rational basis for relative time measurements.

Fossils, the remains or traces of prehistoric life, were also essential to the development of the geologic time scale (Figure 1.7). Fossils are the basis for the **principle of fossil succession,** which states that *fossil organisms succeed one another in a definite and determinable order, and therefore any time period can be recognized by its fossil content.* This principle was laboriously worked out over decades by collecting fossils from countless rock layers around the world. Once established, it allowed geologists to identify rocks of the same age in widely separated places and to build the geologic time scale shown in Figure 1.8.

Notice that units having the same designations do not necessarily extend for the same number of years. For example, the Cambrian period lasted about 50 million years, whereas the Silurian period spanned only about 26 million years. As we will emphasize again in Chapter 9, this situation exists because the basis for establishing the time scale was not the regular rhythm of a clock but the changing character of life forms through time. Specific dates were added long after the time scale was established. A glance at Figure 1.8 also reveals that the Phanerozoic eon is divided into many more units than earlier eons, even though it encompasses only about 12 percent of Earth history. The meager fossil record for these earlier eons is the primary reason for the lack of detail on this portion of the time scale. Without abundant fossils, geologists lose their primary tool for subdividing geologic time.

The Magnitude of Geologic Time

The concept of geologic time is new to many nongeologists. 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.*

By contrast, those who study geology must routinely deal with vast time periods—millions or billions (thousands of millions) of years. When viewed in the context of Earth's 4.5-billion-year history, a geologic 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 geology because many processes are so gradual that vast spans of time are needed before significant changes occur.

How long is 4.5 billion years? If you were to begin counting at the rate of one number per second and continued 24 hours a day, 7 days a week and never stopped, it would take about two lifetimes (150 years) to reach 4.5 billion! Another interesting basis for comparison is as follows:

> Compress, for example, the entire 4.5 billion years of geologic time into a single year. On that scale, the oldest rocks we know date from about mid-March. Living things first appeared in the sea in May. Land plants and animals emerged in late November and the widespread swamps that formed

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**Essentials of Earth History* (Englewood Cliffs, New Jersey: Prentice Hall, 1966), p. 34.

†Chapter 9 is devoted to a much more complete discussion of geologic time.

FIGURE 1.6 These rock layers are exposed in Minnewaska State Park, New York. Their relative ages can be determined by applying the law of superposition. The youngest rocks are on top, and the oldest are at the bottom. (Photo by Carr Clifton)

> the Pennsylvanian coal deposits flourished for about four days in early December. Dinosaurs became dominant in mid-December, but disappeared on the 26th, at about the time the Rocky Mountains were first uplifted. Manlike creatures appeared sometime during the evening of December 31st, and the most recent continental ice sheets began to recede from the Great Lakes area and from northern Europe about 1 minute and 15 seconds before midnight on the 31st. Rome ruled the Western world for 5 seconds from 11:59:45 to 11:59:50. Columbus discovered America 3 seconds before midnight, and the science of geology was born with the writings of James Hutton just slightly more than one second before the end of our eventful year of years.*

The foregoing is just one of many analogies 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.

The Nature of Scientific Inquiry

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 knowing how oil deposits form, geologists are able to predict the most favorable sites for exploration and, perhaps as important, how to avoid regions having little or no potential.

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. 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 theories (see Box 1.1).

Hypothesis

Once facts have been gathered and principles have been formulated to describe a natural phenomenon, investigators try to explain how or why things happen in the manner observed. They often do this by constructing a tentative (or

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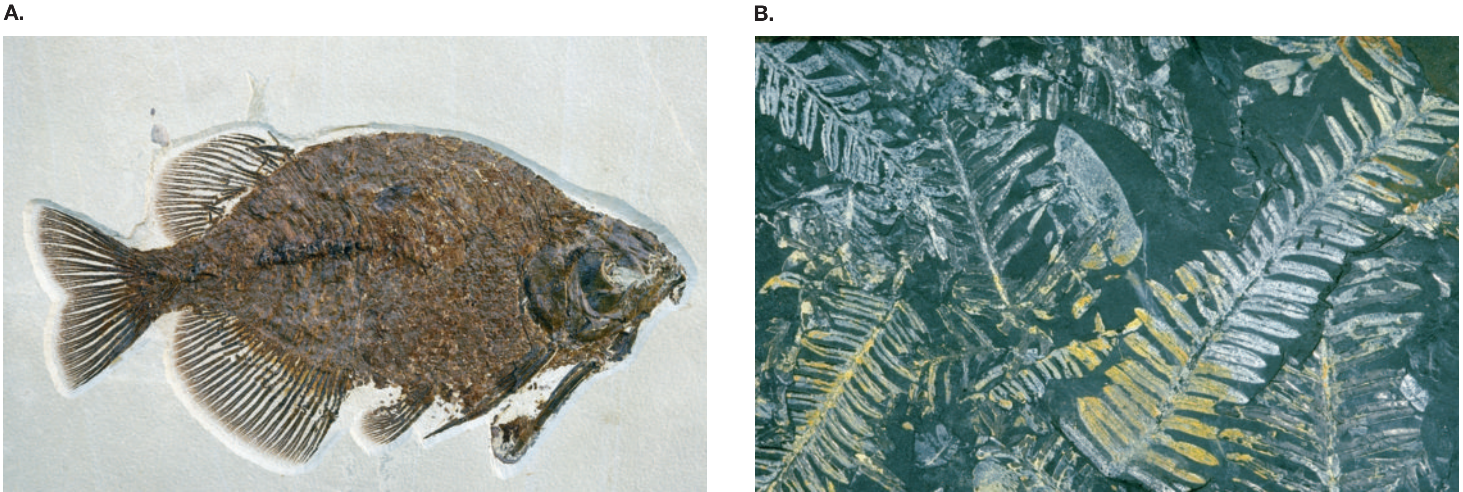
*Don L. Eicher, *Geologic Time,* 2nd ed. (Englewood Cliffs, New Jersey: Prentice Hall, 1978), pp. 18–19. Reprinted by permission.

FIGURE 1.7 Fossils are important tools for the geologist. In addition to being very important in relative dating, fossils can be useful environmental indicators. **A.** A fossil fish of Eocene age from the Green River Formation in Wyoming. (Photo by John Cancalosi/DRK Photo) **B.** Fossil ferns from the coal-forming Pennsylvanian Period, St. Clair, Pennsylvania. (Photo by Breck p. Kent)



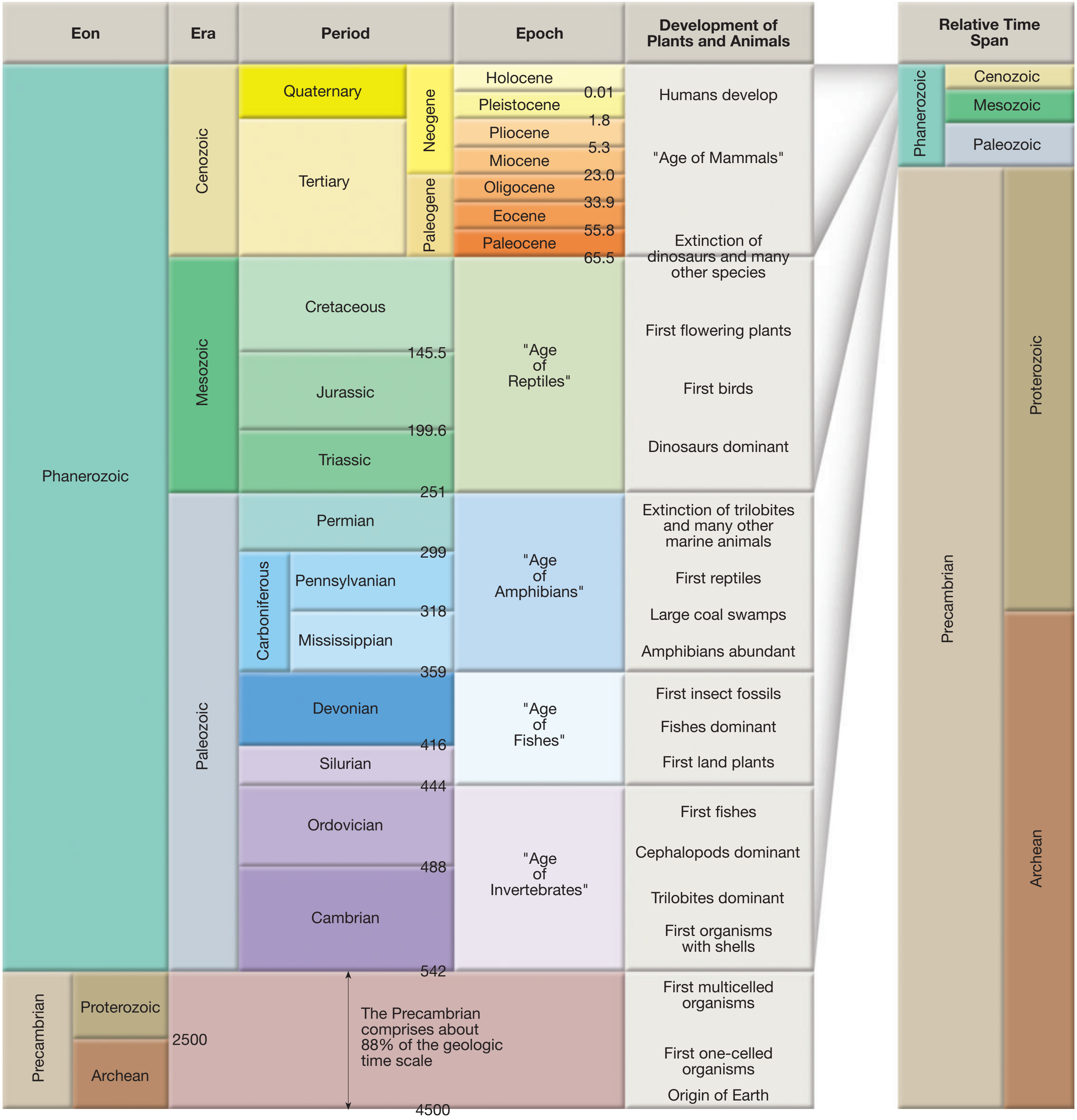


FIGURE 1.8 The geologic time scale. Numbers on the time scale represent time in millions of years before the present. These dates were added long after the time scale had been established using relative dating techniques. The Precambrian accounts for more than 88 percent of geologic time. (Data from Geological Society of America)

BOX 1.1 ▸ UNDERSTANDING EARTH

Studying Earth from Space

Scientific facts are gathered in many ways, including laboratory studies and field observations and measurements. Satellite images like the one in Figure 1.A are another useful source of data. Such images provide perspectives that are difficult to gain from more traditional sources. Moreover, the high-tech instruments aboard many satellites enable scientists to gather information from remote regions where data are otherwise scarce.

The image in Figure 1.A makes use of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). Because different materials reflect and emit energy in different ways, ASTER can provide detailed information about the composition of Earth's surface. Figure 1.A is a three-dimensional view looking north over Death Valley, California. The data have been computer enhanced to exaggerate the color variations that highlight differences in types of surface materials.

Salt deposits on the floor of Death Valley appear in shades of yellow, green, purple, and pink, indicating the presence of carbonate, sulfate, and chloride minerals. The Panamint Mountains to the west (left) and the Black Mountains to the east are made up of sedimentary limestones, sandstones, shales, and metamorphic rocks. The bright red areas are dominated by the mineral quartz, found in sandstone; green areas are limestone. In the lower center of the image is Badwater, the lowest point in North America.

The image in Figure 1.B is from NASA's *Tropical Rainfall Measuring Mission* (*TRMM*). Rainfall patterns over land have been studied for many years using ground-based radar and other instruments. Now the instruments aboard the *TRMM* satellite have greatly expanded our ability to collect precipitation data. In addition to data for land areas, this satellite provides extremely precise measurements of rainfall over the oceans where conventional land-based instruments cannot see. This is especially important because much of Earth's rain falls in ocean-covered tropical areas, and a great deal of the globe's weather-producing energy comes from heat exchanges involved in the rainfall process. Until the *TRMM*, information on the intensity and amount of rainfall over the tropics was scanty. Such data are crucial to understanding and predicting global climate change.

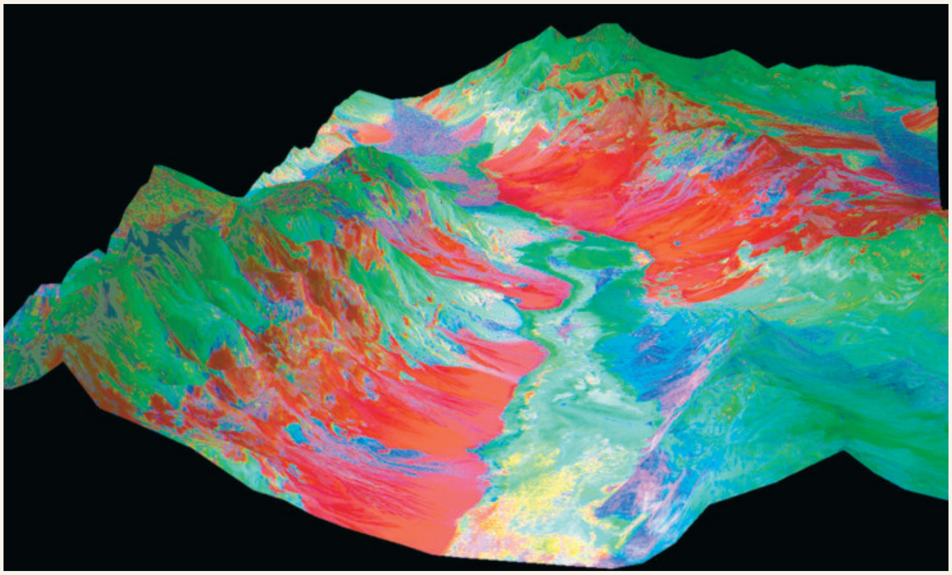
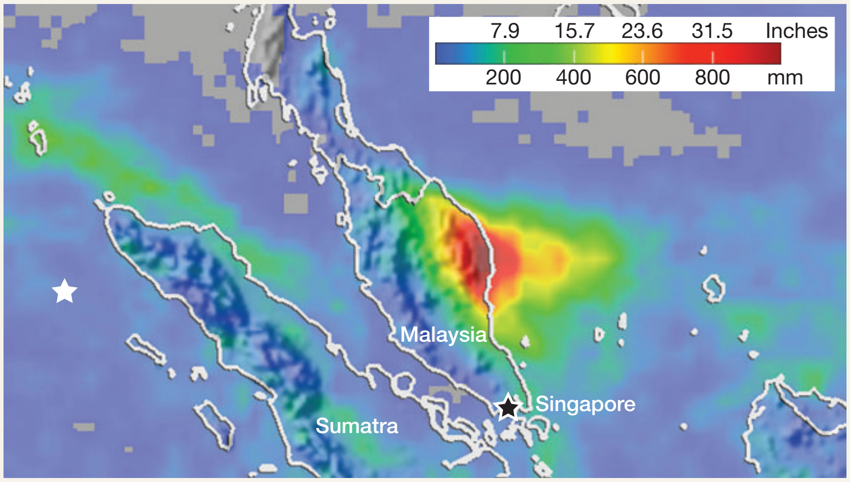


FIGURE 1.A This satellite image shows detailed information about the composition of surface materials in Death Valley, California. It was produced by superimposing nighttime thermal infrared data, acquired on April 7, 2000, over topographic data from the U.S. Geological Survey. (Image courtesy of NASA)

FIGURE 1.B This map of rainfall for December 7–13, 2004, in Malaysia was constructed using TRMM data. Over 800 millimeters (32 inches) of rain fell along the east coast of the peninsula (darkest red area). The extraordinary rains caused extensive flooding and triggered many mudflows. (NASA/TRMM image)



untested) explanation, which is called a scientific **hypothesis** or **model.** (The term *model,* although often used synonymously with hypothesis, is a less precise term because it is sometimes used to describe a scientific theory as well.) 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 models, 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 models, 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 model 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. Those 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.”

Theory

When a hypothesis has survived extensive scrutiny and when competing models have been eliminated, a hypothesis may be elevated to the status of a scientific **theory.** In everyday language we may 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.

Theories that are extensively documented are held with a very high degree of confidence. Theories of this stature that are comprehensive in scope have a special status. They are called **paradigms** because they explain a large number of interrelated aspects of the natural world. For example, the theory of plate tectonics is a paradigm of the geological sciences that 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—a topic we will consider later in this chapter.

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.”*

There is not a fixed path that scientists always follow that leads unerringly to scientific knowledge. Nevertheless, many scientific investigations involve the following steps: (1) the collection of scientific facts through observation and measurement (Figure 1.9); (2) the development of one or more working hypotheses or models to explain these facts; (3) development of observations and experiments to test the hypotheses; and (4) the acceptance, modification, or rejection of the model based on extensive testing (see Box 1.2).

Other scientific discoveries may result from purely theoretical ideas, which stand up to extensive examination. Some researchers use high-speed computers to simulate

FIGURE 1.9 This field geologist is checking a seismograph. (Photo by Andrew Rafkind/Getty Images Inc.—Stone Allstock)

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

BOX 1.2 ▸ UNDERSTANDING EARTH

Do Glaciers Move? An Application of the Scientific Method

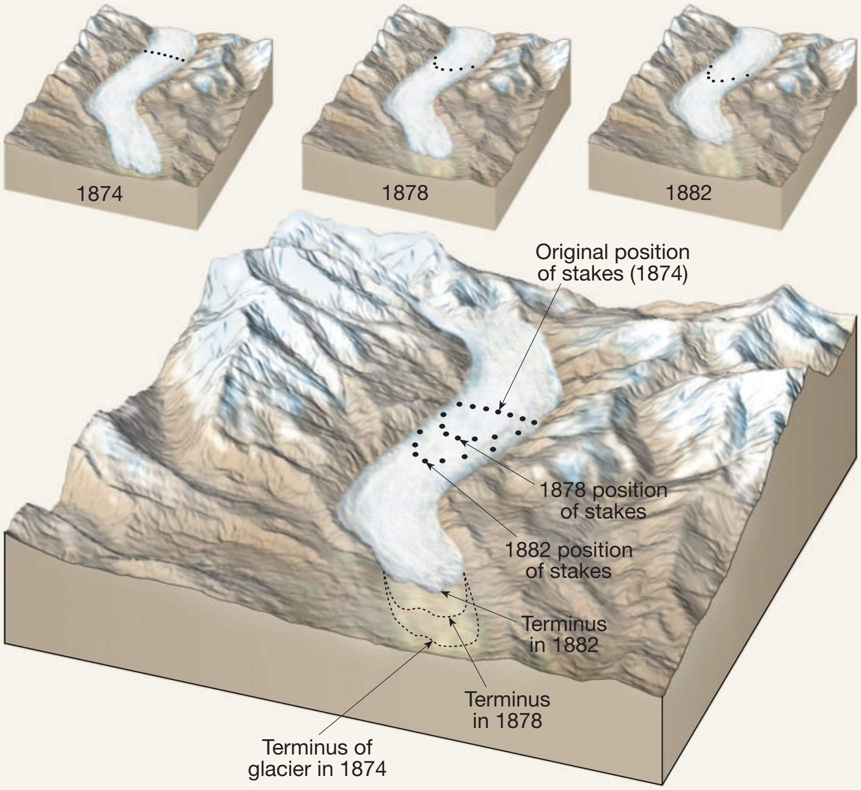
The study of glaciers provides an early application of the scientific method. High in the Alps of Switzerland and France, small glaciers exist in the upper portions of some valleys. In the late 18th and early 19th centuries, people who farmed and herded animals in these valleys suggested that glaciers in the upper reaches of the valleys had previously been much larger and had occupied downvalley areas. They based their explanation on the fact that the valley floors were littered with angular boulders and other rock debris that seemed identical to the materials that they could see in and near the glaciers at the heads of the valleys.

Although the explanation of these observations seemed logical, others did not accept the notion that masses of ice hundreds of meters thick were capable of movement. The disagreement was settled after a simple experiment was designed and carried out to test the hypothesis that glacial ice can move.

Markers were placed in a straight line completely across an alpine glacier. The position of the line was marked on the valley walls so that if the ice moved, the change in position could be detected. After a year or two the results were clear. The markers on the glacier had advanced down the valley, proving that glacial ice indeed moves. In addition, the experiment demonstrated that ice within a glacier does not move at a uniform rate, because the markers in the center advanced farther than did those along the margins. Although most glaciers move too slowly for direct visual detection, the experiment succeeded in demonstrating that movement nevertheless occurs. In the years that followed, this experiment was repeated many times with greater accuracy using more modern surveying techniques. Each time, the basic relationships established by earlier attempts were verified.

The experiment illustrated in Figure 1.C was carried out at Switzerland's Rhône Glacier later in the 19th century. It not only traced the movement of markers within the ice but also mapped the position of the glacier's terminus. Notice that even though the ice within the glacier was advancing, the ice front was retreating. As often occurs in science, experiments and observations designed to test one hypothesis yield new information that requires further analysis and explanation.

FIGURE 1.C Ice movement and changes in the terminus at Rhône Glacier, Switzerland. In this classic study of a valley glacier, the movement of stakes clearly show that glacial ice moves and that movement along the sides of the glacier is slower than movement in the center. Also notice that even though the ice front was retreating, the ice within the glacier was advancing.



what is happening in the "real" world. These models are useful when dealing with natural processes that occur on very long time scales or 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 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.

Plate Tectonics and Scientific Inquiry

There are many opportunities in the pages of this book to develop and reinforce your understanding of how science works and, in particular, how the science of geology works. You will learn about the methods involved in gathering data and develop a sense of the observational techniques and reasoning processes used by geologists. Chapter 2, "Plate Tectonics: A Scientific Revolution Unfolds," is an excellent example.

A. **B.**

FIGURE 1.10 **A.** View that greeted the *Apollo 8* astronauts as their spacecraft emerged from behind the Moon. (NASA Headquarters) **B.** Africa and Arabia are prominent in this image of Earth taken from *Apollo 17.* The tan cloud-free zones over the land coincide with major desert regions. The band of clouds across central Africa is associated with a much wetter climate that in places sustains tropical rain forests. The dark blue of the oceans and the swirling cloud patterns remind us of the importance of the oceans and the atmosphere. Antarctica, a continent covered by glacial ice, is visible at the South Pole. (NASA/Science Source/Photo Researchers, Inc.)

Students Sometimes Ask . . .

In class you compared a hypothesis to a theory. How is each one different from a scientific law?

A scientific *law* is a basic principle that describes a particular behavior of nature that is generally narrow in scope and can be stated briefly—often as a simple mathematical equation. Because scientific laws have been shown time and time again to be consistent with observations and measurements, they are rarely discarded. Laws may, however, require modifications to fit new findings. For example, Newton's laws of motion are still useful for everyday applications (NASA uses them to calculate satellite trajectories), but they do not work at velocities approaching the speed of light. For these circumstances, they have been supplanted by Einstein's theory of relativity.

Within 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. The revolution began in the early part of the 20th century with the radical proposal of *continental drift*—the idea that the continents moved about the face of the planet. This hypothesis 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 the *theory of plate tectonics,* provided geologists with the first comprehensive model of Earth's internal workings.

As you read Chapter 2, you will not only gain insights into the workings of our planet, you will also see an excellent example of the way geological "truths" are uncovered and reworked.

Earth's Spheres

An Introduction to Geology
▸ A View of Earth

The classic view of Earth, shown in Figure 1.10A, provided the *Apollo 8* astronauts and the rest of humanity with a unique perspective of our home. Seen from space, Earth is breathtaking in its beauty and startling in its solitude. Such an image reminds us that our home is, after all, a planet—small, self-contained, and in some ways even fragile.

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

The closer view of Earth from space, shown in Figure 1.10B, helps us appreciate why the physical environment is traditionally divided into three major parts: the water portion of our planet, the hydrosphere; Earth's gaseous envelope, the atmosphere; and, of course, the solid Earth, or geosphere. It needs to be emphasized that our environment is highly integrated and not dominated by rock, water, or air alone. Rather, it is characterized by continuous interactions as air comes in contact with rock, rock with water, and water with air. Moreover, the biosphere, which is the totality of all plant and animal life on our planet, interacts with 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 Earth's four spheres are incalculable. Figure 1.11 provides us with one 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.

FIGURE 1.11 The shoreline is one obvious meeting place for rock, water, and air. In this scene, ocean waves that were created by the force of moving air break against the rocky shore. The force of the water can be powerful, and the erosional work that is accomplished can be great. (Photo by Galen Rowell)

Hydrosphere

Earth is sometimes called the *blue* planet. 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. However, the hydrosphere also includes the fresh water 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 percentage indicates. In addition to providing the fresh water that is so vital to life on land, streams, glaciers, and groundwater are responsible for sculpting and creating many of our planet's varied landforms.

Atmosphere

Earth is surrounded by a life-giving gaseous envelope called the **atmosphere.** Compared with the solid Earth, the atmosphere is thin and tenuous. One half lies below an altitude of 5.6 kilometers (3.5 miles), and 90 percent occurs within just 16 kilometers (10 miles) of Earth's surface. By comparison, the radius of the solid Earth (distance from the surface to the center) is about 6400 kilometers (nearly 4000 miles)! Despite its modest dimensions, this thin blanket of air is an integral part of the planet. It not only provides the air that we breathe but also protects us from the Sun's intense heat and 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.

If, like the Moon, Earth had no atmosphere, our planet would not only be lifeless but 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. 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 into the atmosphere. 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, 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 not just respond to their physical environment. Indeed, the biosphere powerfully influences the other three spheres. Without life, the makeup and nature of the geosphere, hydrosphere, and atmosphere would be very different.

Geosphere

Lying beneath the atmosphere and the oceans is the solid Earth, or **geosphere.** The geosphere extends from the surface to the center of the planet, a depth of nearly 6400 kilometers, 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. A first look at the structure of Earth's interior and at the major surface features of the geosphere will come later in the chapter.

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.

Earth As 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 to 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 landslides. 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 (Figure 1.12).

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.* Using an interdisciplinary approach, those who practice Earth system science attempt to achieve the level of understanding necessary to comprehend and solve many of our global environmental problems.

FIGURE 1.12 This deadly landslide on Leyte Island in the Philippines occurred in February 2006, and was triggered by heavy rains that saturated materials on the mountainside. This is a simple example of interactions among different parts of the Earth system. (Photo by AP Photo/Wally Santana)

What Is a System? 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.

Loosely defined, a **system** can be any size group of interacting parts that form a complex whole. Most natural systems are driven by sources of energy that move matter and/or energy from one place to another. A simple analogy is a car's cooling system, which contains a liquid (usually water and antifreeze) that is driven from the engine to the radiator and back again. The role of this system is to transfer heat generated by combustion in the engine to the radiator, where moving air removes it from the system. Hence, the term cooling system.

Systems like a car's cooling system are self-contained with regard to matter and are called **closed systems.** Although energy moves freely in and out of a closed system, no matter (liquid in the case of our auto's cooling system) enters or leaves the system. (This assumes you don't get a leak in your radiator). By contrast, most natural systems are **open systems** and are far more complicated than the foregoing example. In an open system both energy and matter flow into and out of the system. In a weather system such as a hurricane, factors such as the quantity of water vapor available for cloud formation, the amount of heat released by condensing water vapor, and the flow of air into and out of the storm can fluctuate a great deal. At times the storm may strengthen; at other times it may remain stable or weaken.

Feedback Mechanisms Most natural systems have mechanisms that tend to enhance change, as well as other mechanisms that tend to resist change and thus stabilize the system. For example, when we get too hot, we perspire to cool down. This cooling phenomenon works to stabilize our body temperature and is referred to as a **negative feedback mechanism.** Negative feedback mechanisms work to maintain the system as it is or, in other words, to maintain the status quo. By contrast, mechanisms that enhance or drive change are called **positive feedback mechanisms.**

Most of Earth's systems, particularly the climate system, contain a wide variety of negative and positive feedback mechanisms. For example, substantial scientific evidence indicates that Earth has entered a period of global warming. One consequence of global warming is that some of the world's glaciers and ice caps have begun to melt. Highly reflective snow- and ice-covered surfaces are gradually being replaced by brown soils, green trees, or blue oceans, all of which are darker, so they absorb more sunlight. The result is a positive feedback that contributes to the warming.

On the other hand, an increase in global temperature also causes greater evaporation of water from Earth's land-sea surface. One result of having more water vapor in the air is an increase in cloud cover. Because cloud tops are white and highly reflective, more sunlight is reflected back to space, which diminishes the amount of sunshine reaching Earth's surface and thus reduces global temperatures. Further, warmer temperatures tend to promote the growth of vegetation. Plants in turn remove carbon dioxide (CO_2) from the air. Since carbon dioxide is one of the atmosphere's *greenhouse gases,* its removal has a negative impact on global warming.*

In addition to natural processes, we must also consider the human element. Extensive cutting and clearing of the tropical rain forests and the burning of fossil fuels (oil, natural gas, and coal) result in an increase in atmospheric CO_2. Such activity is contributing to the increase in global temperature that our planet is experiencing. One of the daunting tasks of Earth system scientists is to predict what the climate will be like in the future by taking into account many variables, including technological changes, population trends, and the overall impact of the numerous competing positive and negative feedback mechanisms. Chapter 21 on "Global Climate Change" explores this topic in some detail.

The Earth System

The Earth system has a nearly endless array of subsystems in which matter is recycled over and over again (Figure 1.13). One example that you will learn about in Chapter 7 traces the movements of carbon among Earth's four spheres. It shows us, for example, that the carbon dioxide in the air and the carbon in living things and in certain sedimentary rocks is all part of a subsystem described by the *carbon cycle.*

Cycles in the Earth System A more 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 by evaporation from Earth's surface and by 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 to be taken up by plants or become 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 reforming (Figure 1.13). The loop that involves the processes by which one rock changes to another is called the *rock cycle* and will be discussed at some length later in the chapter. The cycles of the Earth system, such as the hydrologic and rock cycles, are not independent of one another. To the contrary, there are many places where they interface. An **interface** is a common boundary where different parts of a system come in contact and interact. For example, in Figure 1.13, weathering at the surface gradually disintegrates and decomposes solid rock. The work of gravity and running water may eventually move this material to another place and deposit it. Later, groundwater percolating through the debris may leave behind mineral matter that cements the grains together into solid rock (a rock that is often very different from the rock we started with). This changing of one rock into another could not have occurred without the movement of water through the hydrologic cycle. There are many places where one cycle or loop in the Earth system interfaces with and is a basic part of another.

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 and hydrosphere and at Earth's surface. Weather and climate, ocean circulation,

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*Greenhouse gases absorb heat energy emitted by Earth and thus help keep the atmosphere warm.

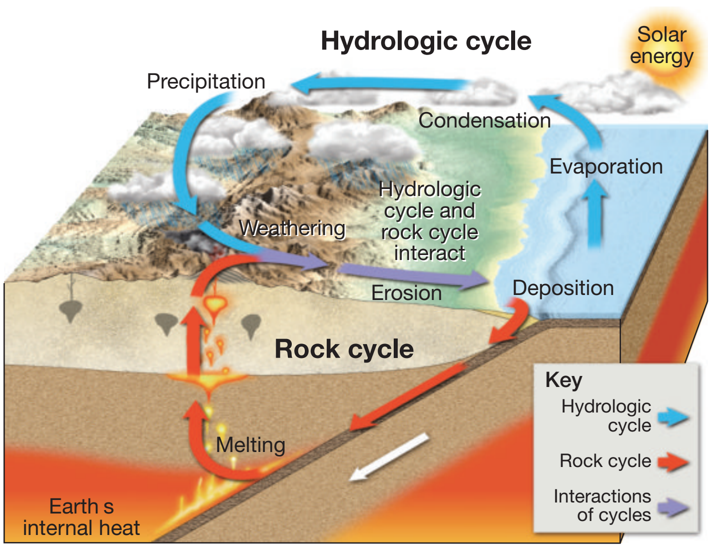

FIGURE 1.13 Each part of the Earth system is related to every other part to produce a complex interacting whole. The Earth system involves many cycles, including the hydrologic cycle and the rock cycle. Such cycles are not independent of each other. There are many places where they interface.

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 decay of radioactive elements powers the internal processes that produce volcanoes, earthquakes, and mountains.

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 1.14). 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, whereas new settings for life, such as the lake, would be created. The potential climate change could also impact sensitive life forms.

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.

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 of 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, and the rock cycle, to name a few. Remember that these components *and we humans* are all part of the complex interacting whole we call the Earth system.

FIGURE 1.14 When Mount St. Helens erupted in May 1980, the area shown here was buried by a volcanic mudflow. Now plants are reestablished and new soil is forming. (Jack W. Dykinga Associates)

Early Evolution of Earth

Recent earthquakes caused by displacements of Earth’s crust, along with lavas erupted from active volcanoes, represent only the latest in a long line of events by which our planet has attained its present form and structure. The geologic processes operating in Earth’s interior can be best understood when viewed in the context of much earlier events in Earth history.

Origin of Planet Earth

The following scenario describes the most widely accepted views of the origin of our solar system. Although this model is presented as fact, keep in mind that like all scientific hypotheses, this one is subject to revision and even outright rejection. Nevertheless, it remains the most consistent set of ideas to explain what we observe today.

Our scenario begins about 14 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 several dozen 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 hypothesis** proposes that the bodies of our solar system evolved from an enormous rotating cloud called the **solar nebula** (Figure 1.15). 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. 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 for the same reason 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 (Figure 1.15). 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 excited atomic particles. However, at distances beyond the orbit of Mars, the temperatures probably remained quite low. At −200°C, 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. The disk-shaped cloud also contained appreciable amounts of the lighter gases hydrogen and helium.

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 those substances with high melting points to condense into tiny particles that began to coalesce (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 (Figure 1.15). 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. Not all of these clumps of matter were incorporated into the protoplanets. Those rocky and metallic pieces that remained in orbit are called *meteorites* when they survive an impact with Earth.

As more and more material was swept up by the planets, the high-velocity impact of nebular debris caused the temperature of these bodies 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.

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.

Formation of Earth's Layered Structure

As material accumulated to form Earth (and for a short period afterward), the high-velocity impact of nebular debris and the decay of radioactive elements caused the temperature of our planet to steadily increase. During this time of intense heating, Earth became hot enough that iron and nickel began to melt. Melting produced liquid blobs of heavy metal that sank toward the center of the planet. This process occurred rapidly on the scale of geologic time and produced Earth's dense iron-rich core.

The early period of heating resulted in another process of chemical differentiation, whereby melting formed buoyant masses of molten rock that rose toward the surface, where they solidified to produce a primitive crust. These rocky materials were enriched in oxygen and "oxygen-seeking" elements, particularly silicon and aluminum, along with lesser amounts of calcium, sodium, potassium, iron, and magnesium. In addition, some heavy metals such as gold, lead, and uranium, which have low melting points or were highly soluble in the ascending molten masses, were scavenged from Earth's interior and concentrated in the developing crust. This early period of chemical segregation established the three basic divisions of Earth's interior—the iron-rich *core;* the thin *primitive crust;* and Earth's largest layer, called the *mantle,* which is located between the core and crust.

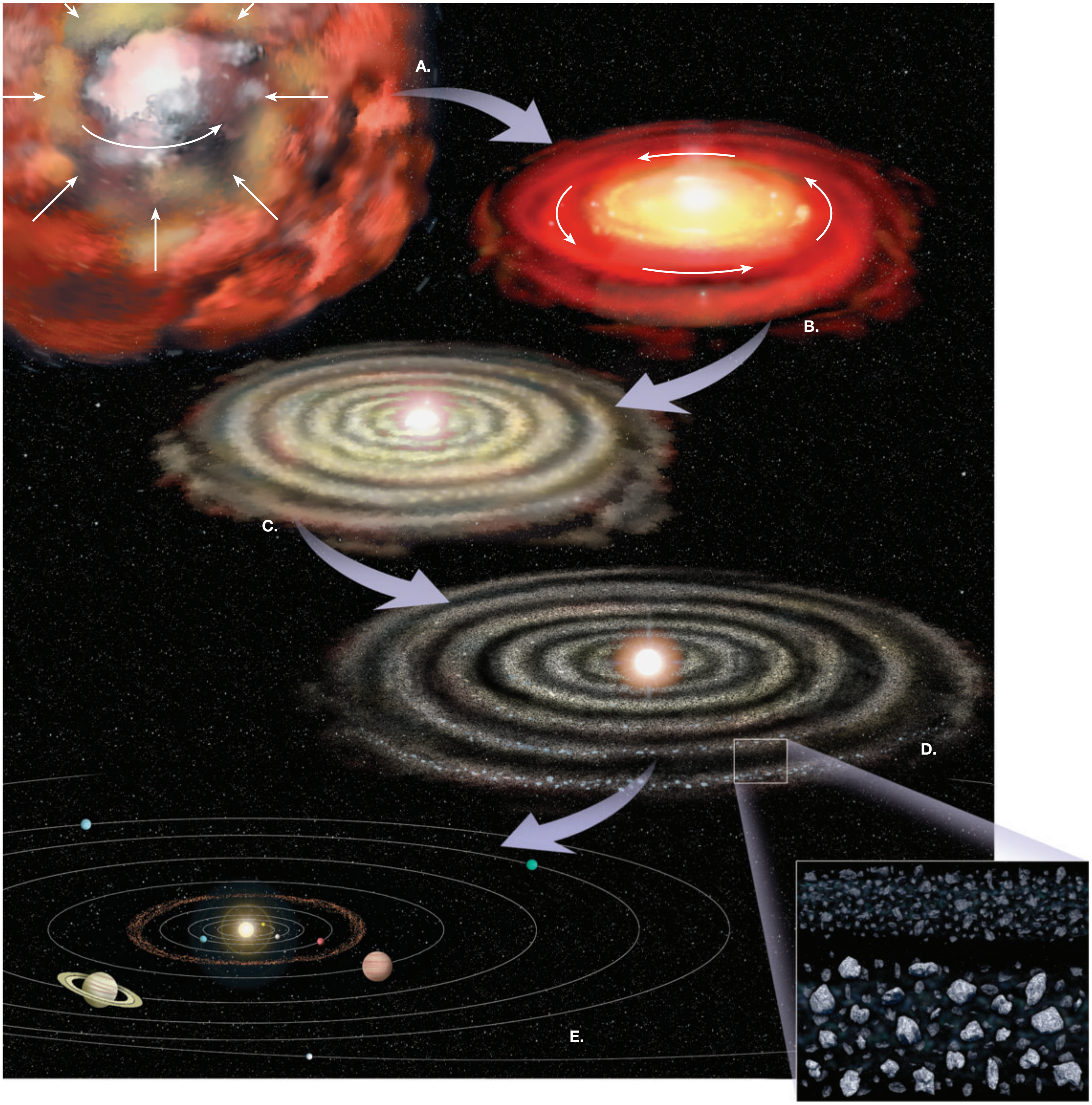

FIGURE 1.15 Formation of the solar system according to the nebular hypothesis. **A.** The birth of our solar system began as dust and gases (nebula) started to gravitationally collapse. **B.** The nebula contracted into a rotating disk that was heated by the conversion of gravitational energy into thermal energy. **C.** Cooling of the nebular cloud caused rocky and metallic material to condense into tiny solid particles. **D.** Repeated collisions caused the dust-size particles to gradually coalesce into asteroid-size bodies. **E.** Within a few million years these bodies accreted into the planets.

An important consequence of this early period of chemical differentiation is that large quantities of gaseous materials were allowed to escape from Earth's interior, as happens today during volcanic eruptions. By this process a primitive atmosphere gradually evolved. It is on this planet, with this atmosphere, that life as we know it came into existence.

Following the events that established Earth's basic structure, the primitive crust was lost to erosion and other geologic processes, so we have no direct record of its makeup. When and exactly how the continental crust—and thus Earth's first landmasses—came into existence is a matter of ongoing research. Nevertheless, there is general agreement that the continental crust formed gradually over the last 4 billion years. (The oldest rocks yet discovered are isolated fragments found in the Northwest Territories of Canada that have radiometric dates of about 4 billion years.) In addition, as you will see in Chapter 2, Earth is an evolving planet whose continents (and ocean basins) have continually changed shape and even location during much of this period.

Earth's Internal Structure

An Introduction to Geology
▸ Earth's Layered Structure

In the preceding section, you learned that the segregation of material that began early in Earth's history resulted in the formation of three major layers defined by their chemical composition—the crust, mantle, and core. In addition to these compositionally distinct layers, Earth can be divided into layers based on physical properties. The physical properties used to define such 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 our understanding of basic geologic processes, such as volcanism, earthquakes, and mountain building (Figure 1.16).

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 35 to 40 kilometers (25 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 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.*

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 about 2900 kilometers (1800 miles). The boundary between the crust and mantle represents a marked change in chemical composition. The dominant rock 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 The upper mantle extends from the crust–mantle boundary down to a depth of about 660 kilometers (410 miles). The upper mantle can be divided into three different parts. The top portion of the upper mantle is part of the stiff *lithosphere,* and beneath that is the weaker **asthenosphere.** The bottom part of the upper mantle is called the *transition zone.*

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 in thickness, the lithosphere is more than 250 kilometers thick below the oldest portions of the continents (Figure 1.16). Beneath this stiff layer to a depth of about 350 kilometers 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 will consider in the next chapter.

It is important to emphasize that the strength of various Earth materials is a function of both their composition and of 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 about 410 kilometers to about 660 kilometers in depth is the part of the upper mantle called the **transition zone.** The top of the transition zone is identified by a sudden increase in density from about 3.5 to 3.7 gm/cm^3. This change occurs because minerals in the rock peridotite respond to the

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

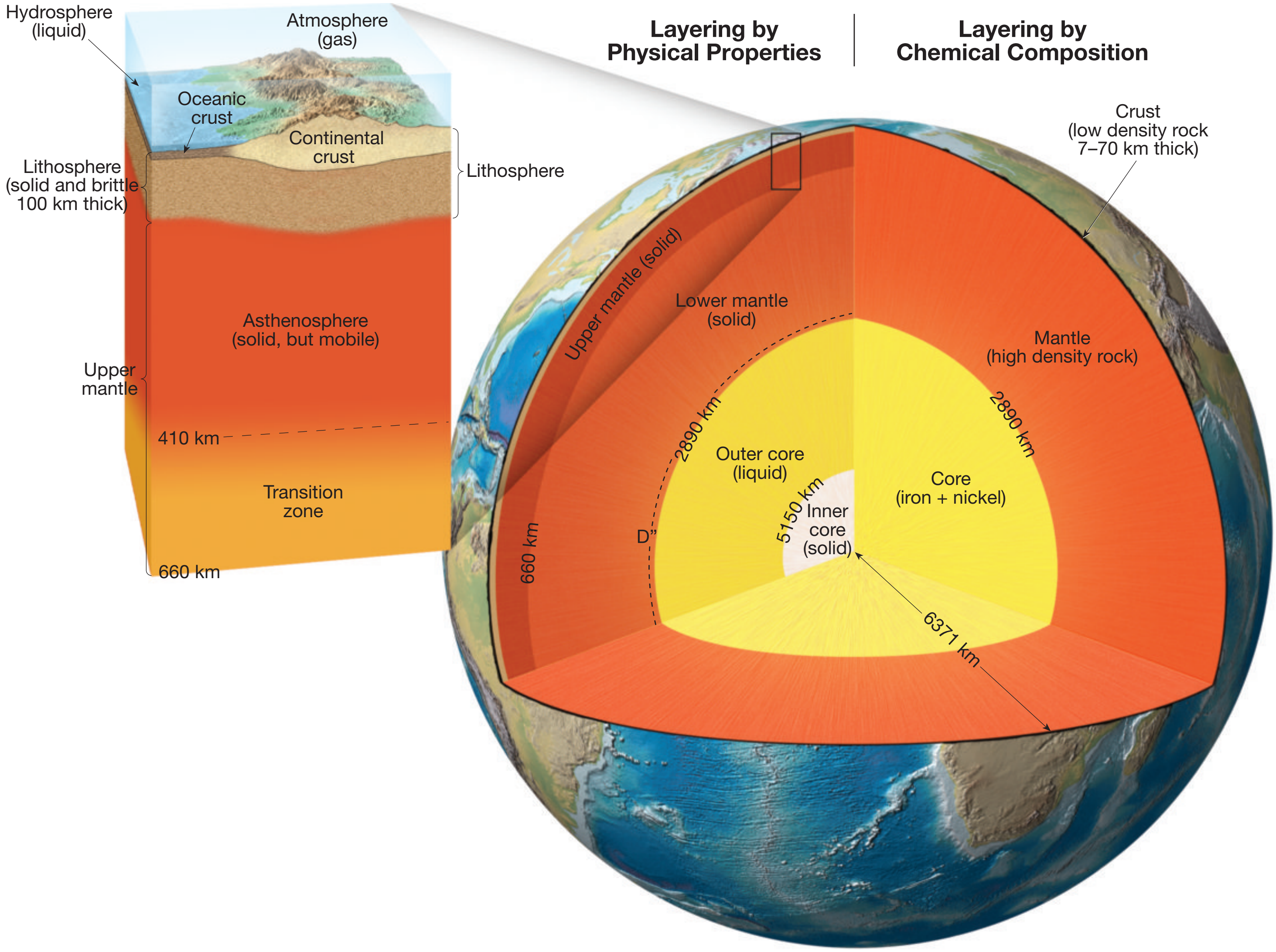


FIGURE 1.16 Views of Earth's layered structure. The right side of the large cross section shows that Earth's interior is divided into three different layers based on compositional differences—the crust, mantle, and core. The left side of the large cross section depicts layers of Earth's interior based on physical properties—the lithospere, asthenosphere, transition zone, D″ layer, outer core, and inner core. The block diagram to the left of the large cross section shows an enlarged view of the upper portion of Earth's interior.

increase in pressure by forming new minerals with closely packed atomic structures.

The Lower Mantle From a depth of 660 kilometers 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.

In the bottom few hundred kilometers of the mantle is a highly variable and unusual layer called the **D″ layer** (pronounced "dee double-prime"). The nature of this boundary layer between the rocky mantle and the hot liquid iron outer core will be examined in Chapter 12.

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* 2270 kilometers (1410 miles) thick. It is the movement of metallic iron within this zone that generates Earth's magnetic field. The **inner core** is a sphere having 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.

How Do We Know What We Know?

At this point you may be asking yourself, "How did we learn about the composition and structure of Earth's interior?" You might suspect that the internal structure of Earth has been sampled directly. However, the deepest mine in the world (the Western Deep Levels mine in South Africa) is only about 4 kilometers (2.5 miles) deep, and the deepest drilled hole in the world (completed in the Kola Peninsula of Russia in 1992) goes down only about 12 kilometers (7.5 miles). In essence, humans have never drilled a hole into the mantle (and will never drill into the core) in order to directly sample these materials.

Despite these limitations, theories that describe the nature of Earth's interior have been developed that closely fit most observational data. Thus, our model of Earth's interior represents the best inferences we can make based on the available data. For example, the layered structure of Earth has been established using indirect observations. Every time there is an earthquake, waves of energy (called *seismic waves*) penetrate Earth's interior, much like X rays penetrate the human body. Seismic waves change their speed and are bent and reflected as they move through zones having different properties. An extensive series of monitoring stations around the world detect and record this energy. With the aid of computers, these data are analyzed and used to determine the structure of Earth's interior. For more about how this is done, see Chapter 12, "Earth's Interior."

What evidence do we have to support the alleged composition of our planet's interior? It may surprise you to learn that rocks that originated in the mantle have been collected at Earth's surface. These include diamond-bearing samples, which laboratory studies indicate can form only in very high-pressure environments. Since these rocks must have crystallized at depths exceeding 200 kilometers (120 miles), they are inferred to be samples of the mantle that underwent very little alteration during their ascent to the surface. In addition, we have been able to examine slivers of the uppermost mantle and overlying oceanic crust that have been thrust high above sea level in locations such as Cyprus, Newfoundland, and Oman.

Establishing the composition of the core is another matter altogether. Because of its great depth and high density, not a single sample of the core has reached the surface. Nevertheless, we have significant evidence to suggest that this layer consists primarily of iron.

Surprisingly, meteorites provide important clues to the composition of the core and mantle. (Meteorites are solid, extraterrestrial objects that strike Earth's surface.) Most meteorites are fragments derived from the collisions of larger bodies, principally from the asteroid belt between the orbits of Mars and Jupiter. They are important because they represent samples of the material (*planetesimals*) from which the inner planets, including Earth, formed. Meteorites are composed mainly of an iron-nickel alloy (*irons*), silicate minerals (*stones*), or a combination of both (*stony-irons*) of these materials. The stones have an average composition that is close to that calculated for the mantle. Irons, on the other hand, contain a much higher percentage of this metallic material than is presently found in either Earth's crust or mantle. If Earth did indeed form from the same material in the solar nebula that generated the meteorites and the other terrestrial planets, it must contain a much higher percentage of iron than is found in crustal rock. Consequently, we can conclude that the core is greatly enriched in this heavy metal.

This view is also supported by studies of the Sun's composition, which indicate that iron is the most abundant substance found in the solar system that possesses the density that has been calculated for the core. Furthermore, Earth's magnetic field requires that the core be made of a material that conducts electricity, such as iron. Because all of the available evidence points to the core as being composed largely of iron, we take this to be a fact, at least until new evidence tells us differently.

The Face of Earth

An Introduction to Geology
▸ Features of the Continents and Floor of the Ocean

The two principal divisions of Earth's surface are the continents and the ocean basins (Figure 1.17). A significant difference between these two areas is their relative levels. 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), continental blocks lie close to sea level, except for limited areas of mountainous terrain. By contrast, the average depth of the ocean floor 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 elevation difference between the continents and ocean basins is primarily the result of differences in their respective densities and thicknesses. Recall that the continents average 35–40 kilometers in thickness and are composed of granitic rocks having a density of about 2.7 g/cm^3. The basaltic rocks that comprise the oceanic crust average only 7 kilometers 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 1.18 that the young mountain belts tend to be long, narrow topographic features at the margins of continents, and the flat, stable areas are typically located in the interior of the continents.

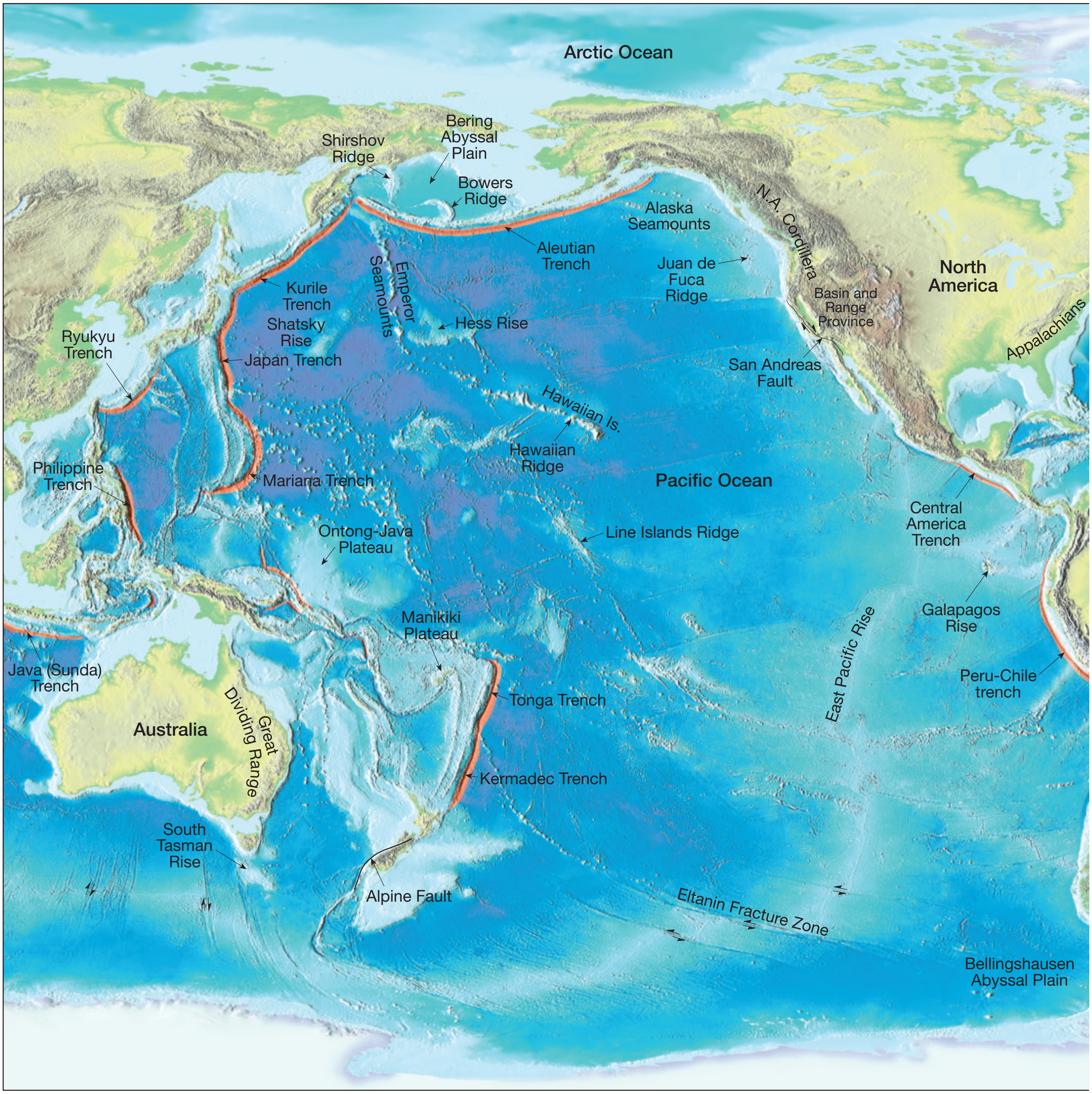


FIGURE 1.17 The topography of Earth's solid surface is shown on these two pages.

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 island arcs (Figure 1.17). Island arcs are active mountainous regions composed largely of volcanic rocks and deformed sedimentary rocks. Examples include the Aleutian Islands, Japan, the Philippines, and New Guinea.

The other major mountainous 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,

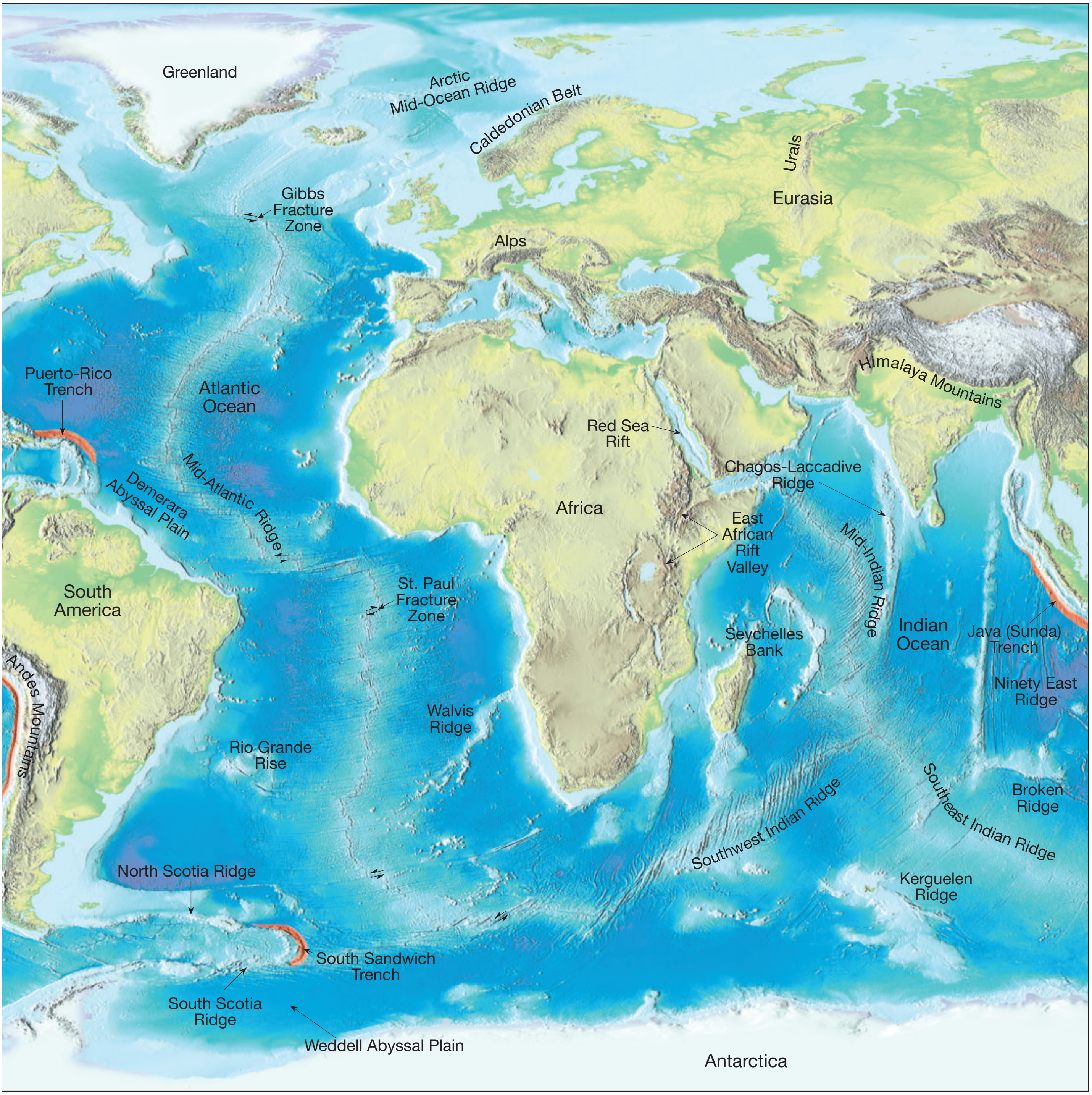


FIGURE 1.17 (continued)

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, the result of millions of years of erosion.

The Stable Interior Unlike the young mountain belts, which have formed within the last 100 million years, the interiors of the continents, called **cratons,** have been relatively stable (undisturbed) for the last 600 million years, or even longer. Typically these crustal blocks were involved in a mountain-building episode 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 1.18 that the Canadian Shield is exposed in much of the northeastern part of North America. Radiometric dating of various shields has revealed that they are truly ancient regions. All contain Precambrian-age rocks

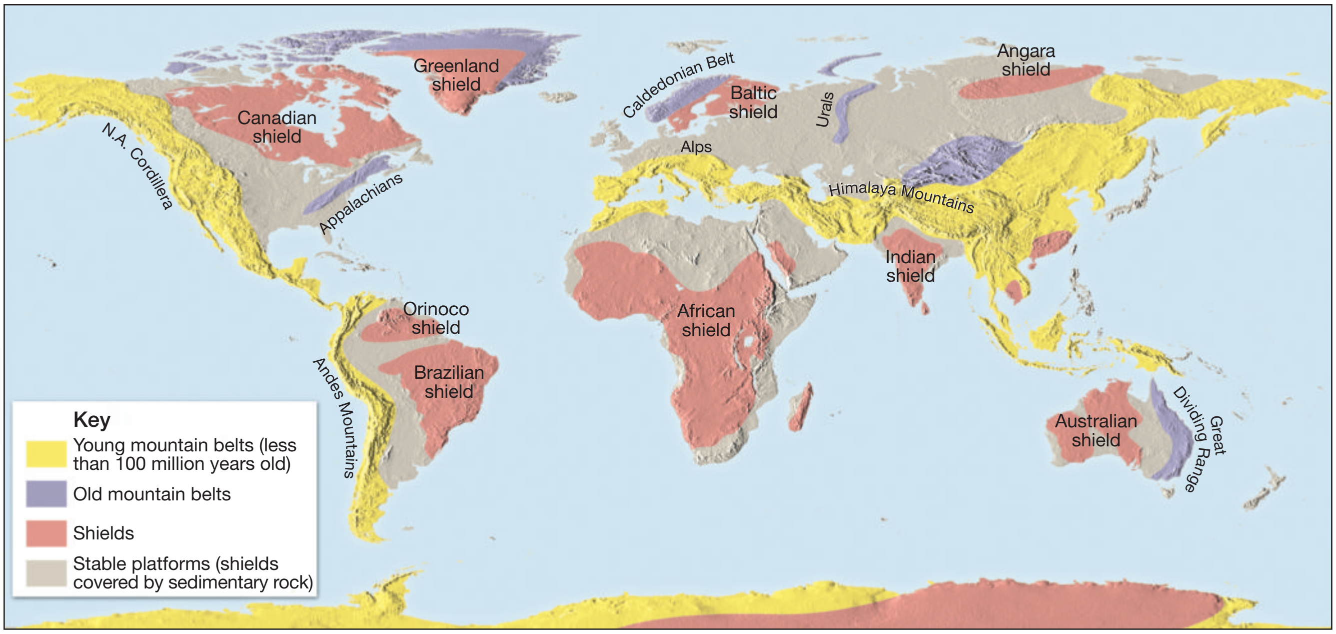


FIGURE 1.18 This map shows the general distribution of Earth's mountain belts, stable platforms, and shields.

that are more than 1 billion years old, with some samples approaching 4 billion years in age. Even these oldest-known rocks exhibit evidence of enormous forces that have folded, faulted, and metamorphosed them. 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 craton 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.

Major Features of the Ocean Floor

If all water were drained from the ocean basins, a great variety of features would be seen, including linear chains of volcanoes, deep canyons, plateaus, and large expanses of monotonously flat plains. In fact, the scenery would be nearly as diverse as that on the continents (see Figure 1.17).

During the past 50 years, oceanographers using modern depth-sounding equipment have slowly mapped significant portions of the ocean floor. From these studies they have delineated three major topographically distinct units: *continental margins, deep-ocean basins,* and *oceanic (mid-ocean) ridges.*

Continental Margins The **continental margin** is that 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 clearly a flooded extension of the continents. A glance at Figure 1.17 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 (Figure 1.17). 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 1.17 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 plateau northeast of Madagascar.

Oceanic Ridges The most prominent feature on the ocean floor is the **oceanic** or **mid-ocean ridge.** As shown in Figure 1.17, 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 oceanic trenches? What forces crumple rocks to produce majestic mountain ranges? These are questions that will be addressed in the next chapter as we begin to investigate the dynamic processes that shaped our planet in the geologic past and will continue to shape it in the future.

Rocks and the Rock Cycle

An Introduction to Geology
▸ Rock Cycle

Rock is the most common and abundant material on Earth. To a curious traveler, the variety seems nearly endless. When a rock is examined closely, we find that it consists of smaller crystals or grains called minerals. *Minerals* are chemical compounds (or sometimes single elements), each with its own composition and physical properties. The grains or crystals may be microscopically small or easily seen with the unaided eye.

The nature and appearance of a rock is strongly influenced by the minerals that compose it. In addition, a rock's *texture*—the size, shape, and/or arrangement of its constituent minerals—also has a significant effect on its appearance. A rock's mineral composition and texture, in turn, are a reflection of the geologic processes that created it.

The characteristics of the rocks in Figure 1.19 provided geologists with the clues they needed to determine the processes that formed them. This is true of all rocks. Such analyses are critical to an understanding of our planet. This understanding has many practical applications, as in the search for basic mineral and energy resources and the solution of environmental problems.

Basic Rock Types

Geologists divide rocks into three major groups: igneous, sedimentary, and metamorphic. In Figure 1.19, the lava flow in northern Arizona is classified as igneous, the sandstone in Utah's Zion National Park is sedimentary, and the schist exposed at the bottom of the Grand Canyon is metamorphic. What follows is a brief look at these three basic rock groups. As you will learn, each group is linked to the others by the processes that act upon and within the planet.

Igneous Rocks **Igneous rocks** (ignis = fire) form when molten rock, called *magma,* cools and solidifies. Magma is melted rock that can form at various levels deep within Earth's crust and upper mantle. As magma cools, crystals of various minerals form and grow. When magma remains deep within the crust, it cools slowly over thousands of years. This gradual loss of heat allows relatively large crystals to develop before the entire mass is completely solidified. Coarse-grained igneous rocks that form far below the surface are called *intrusive.* The cores of many mountains consist of igneous rock that formed in this way. Only subsequent uplift and erosion expose this rock at the surface. A common and important example is *granite* (Figure 1.20). This coarse-grained intrusive rock is rich in the light-colored silicate minerals quartz and feldspar. Granite and related rocks are major constituents of the continental crust.

Sometimes magma breaks through at Earth's surface, as during a volcanic eruption. Because it cools quickly in a surface environment, the molten rock solidifies rapidly, and there is not sufficient time for large crystals to grow. Rather, there is the simultaneous formation of many tiny crystals. Igneous rocks that form at Earth's surface are described as *extrusive* and are usually fine-grained. An abundant and important example is *basalt* (Figure 1.19A). This black to dark-green rock is rich in silicate minerals that contain significant iron and magnesium. Because of its higher iron content, basalt is denser than granite. Basalt and related rocks make up the oceanic crust as well as many volcanoes both in the ocean and on the continents.

Sedimentary Rocks *Sediments,* the raw materials for **sedimentary rocks,** accumulate in layers at Earth's surface. They are materials derived from preexisting rocks by the processes of *weathering.* Some of these processes physically break rock into smaller pieces with no change in composition. Other weathering processes decompose rock—that is, chemically change minerals into new minerals and into substances that readily dissolve in water.

The products of weathering are usually transported by water, wind, or glacial ice to sites of deposition where they form relatively flat layers called *beds.* Sediments are commonly turned into rock or *lithified* by one of two processes. *Compaction* takes place as the weight of overlying materials

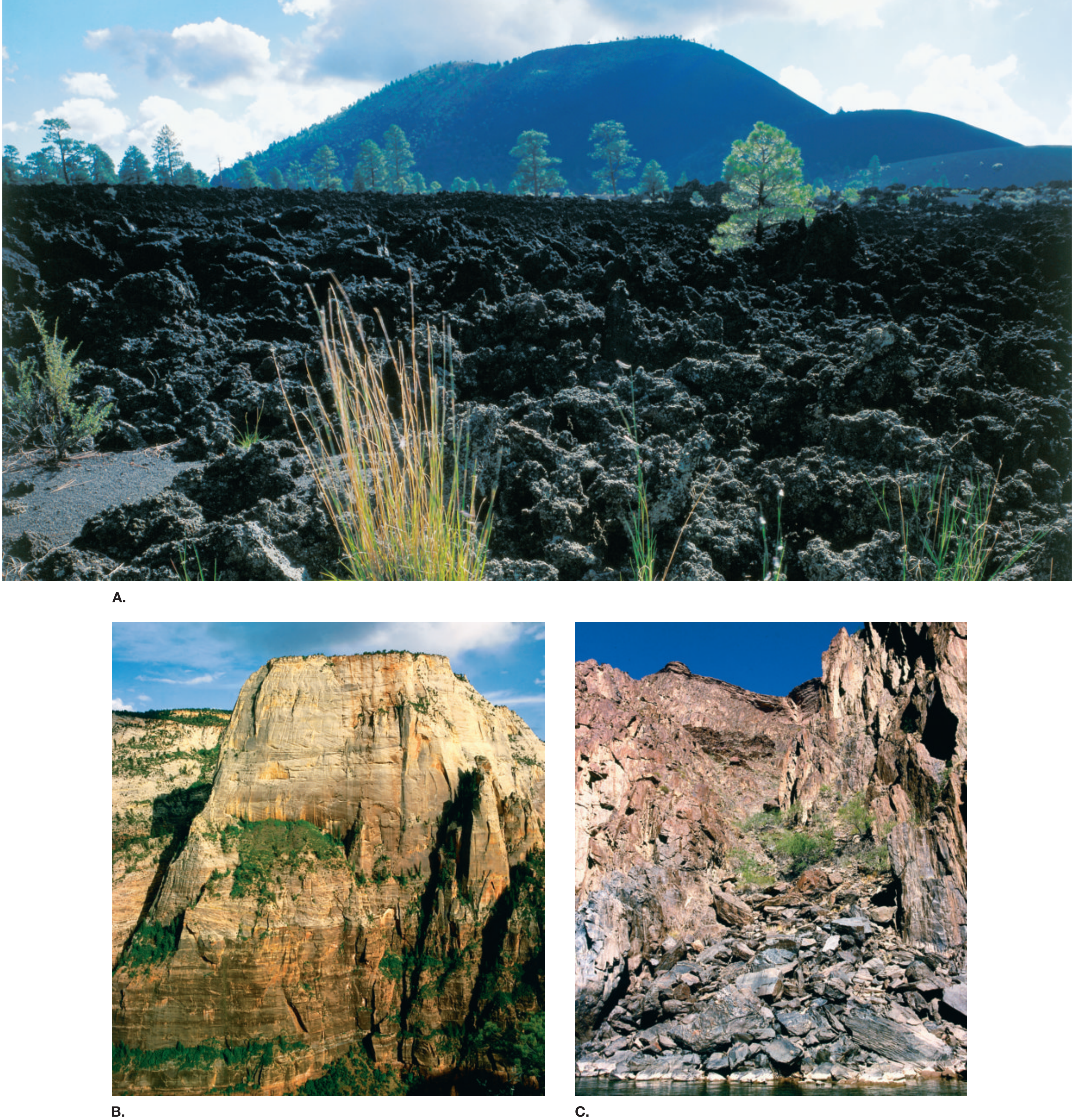


FIGURE 1.19 **A.** This fine-grained black rock, called *basalt,* is part of a lava flow from Sunset Crater in northern Arizona. It formed when molten rock erupted from the volcano hundreds of years ago and solidified. (Photo by David Muench) **B.** This rock is exposed in the walls of southern Utah's Zion National Park. This layer, known as the Navajo Sandstone, consists of durable grains of the glassy mineral quartz that once covered this region with mile after mile of drifting sand dunes. (Photo by Tom Bean/DRK Photo) **C.** This rock unit, known as the Vishnu Schist, is exposed in the inner gorge of the Grand Canyon. Its formation is associated with environments far below Earth's surface where temperatures and pressures are high and with ancient mountain-building processes that occurred in Precambrian time. (Photo by Tom Bean/DRK Photo)

squeezes sediments into denser masses. *Cementation* occurs as water containing dissolved substances percolates through the open spaces between sediment grains. Over time the material dissolved in water is chemically precipitated onto the grains and cements them into a solid mass.

Sediments that originate and are transported as solid particles are called *detrital sediments,* and the rocks they form are called *detrital sedimentary rocks.* Particle size is the primary basis for naming the members in this category. Two common examples are *shale* and *sandstone.* Shale is a fine-grained rock consisting of clay-size (less than 1/256 mm) and silt-size (1/256 to 1/16 mm) particles. The deposition of these tiny grains is associated with "quiet" environments such as swamps, river floodplains, and portions of deep-ocean basins. *Sandstone* is the name given sedimentary rocks in which sand-size (1/16 to 2 mm) grains predominate. Sandstones are associated with a variety of environments, including beaches and dunes (Figure 1.19B).

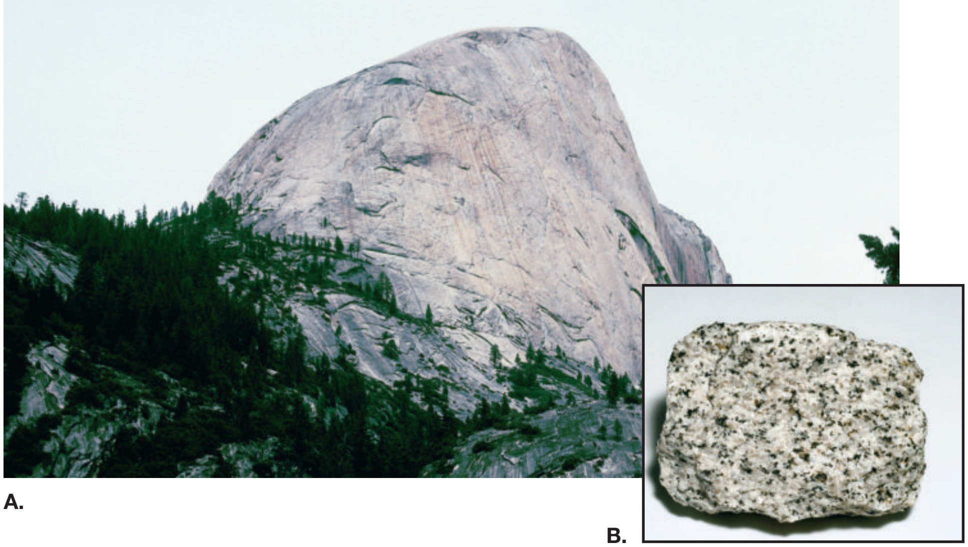


FIGURE 1.20 Granite is an intrusive igneous rock that is especially abundant in Earth's continental crust. **A.** Erosion has uncovered this mass of granite in California's Yosemite National Park. **B.** This sample of granite shows its coarse-grained texture. (Photo by E. J. Tarbuck)

Chemical sedimentary rocks form when material dissolved in water precipitates. Unlike detrital sedimentary rocks that are subdivided on the basis of particle size, the primary basis for distinguishing among chemical sedimentary rocks is their mineral composition. Limestone, the most common chemical sedimentary rock, is composed chiefly of the mineral calcite (calcium carbonate, $CaCO_3$). There are many varieties of limestone (Figure 1.21). The most abundant types have a biochemical origin, meaning that water-dwelling organisms extract dissolved mineral matter and create hard parts such as shells. Later these hard parts accumulate as sediment.

Geologists estimate that sedimentary rocks account for only about 5 percent (by volume) of Earth's outer 16 kilometers (10 miles). However, the importance of this group of rocks is far greater than this percentage implies. If you sampled the rocks exposed at Earth's surface, you would find that the great majority are sedimentary. In fact, about 75 percent of all rock outcrops on the continents are sedimentary. Therefore, we can think of sedimentary rocks as comprising a relatively thin and somewhat discontinuous layer in the uppermost portion of the crust. This makes sense because sediment accumulates at the surface.

It is from sedimentary rocks that geologists reconstruct many details of Earth's history. Because sediments are deposited in a variety of different settings at the surface, the rock layers that they eventually form hold many clues to past surface environments. They may also exhibit characteristics that allow geologists to decipher information about the method and distance of sediment transport. Furthermore, it is sedimentary rocks that contain fossils, which are vital sources of data in the study of the geologic past.

Metamorphic Rocks **Metamorphic rocks** are produced from preexisting igneous, sedimentary, or even other metamorphic rocks. Thus, every metamorphic rock has a parent rock—the rock from which it formed. *Metamorphic* is an appropriate name because it literally means to "change form." Most changes occur at the elevated temperatures and pressures that exist deep in Earth's crust and upper mantle.

The processes that create metamorphic rocks often progress incrementally, from slight changes (low-grade metamorphism) to substantial changes (high-grade metamorphism). For example, during low-grade metamorphism, the common sedimentary rock shale becomes the more compact metamorphic rock *slate.* By contrast, high-grade metamorphism causes a transformation that is so complete that the identity of the parent rock cannot be determined. Furthermore, when rocks at depth (where temperatures are high)

FIGURE 1.21 Limestone is a chemical sedimentary rock in which the mineral calcite predominates. There are many varieties. The topmost layer in Arizona's Grand Canyon, known as the Kaibab Formation, is limestone of Permian age that had a marine origin. (Photo by E. J. Tarbuck)

are subjected to directed pressure, they gradually deform to generate intricate folds. In the most extreme metamorphic environments, the temperatures approach those at which rocks melt. However, *during metamorphism the rock must remain essentially solid,* for if complete melting occurs, we have entered the realm of igneous activity.

Most metamorphism occurs in one of three settings:

1. When rock is intruded by a magma body, *contact* or *thermal metamorphism* may take place. Here, change is driven by a rise in temperature within the host rock surrounding an igneous intrusion.
2. *Hydrothermal metamorphism* involves chemical alterations that occur as hot, ion-rich water circulates through fractures in rock. This type of metamorphism is usually associated with igneous activity that provides the heat required to drive chemical reactions and circulate these fluids through rock.
3. During mountain building, great quantities of deeply buried rock are subjected to the directed pressures and high temperatures associated with large-scale deformation called *regional metamorphism.*

The degree of metamorphism is reflected in the rock's texture and mineral makeup. During regional metamorphism the crystals of some minerals will recrystallize with an orientation that is perpendicular to the direction of the compressional force. The resulting mineral alignment often gives the rock a layered or banded appearance termed a *foliated texture. Schist* and *gneiss* are two examples (Figure 1.22A).

Not all metamorphic rocks have a foliated texture. Such rocks are said to exhibit a *nonfoliated texture.* Metamorphic rocks composed of only one mineral that forms equidimensional crystals are, as a rule, not visibly foliated. For example, limestone, if pure, is composed of only a single mineral, calcite. When a fine-grained limestone is metamorphosed, the small calcite crystals combine to form larger, interlocking crystals. The resulting rock resembles a coarse-grained igneous rock. This nonfoliated metamorphic equivalent of limestone is called *marble* (Figure 1.22B).

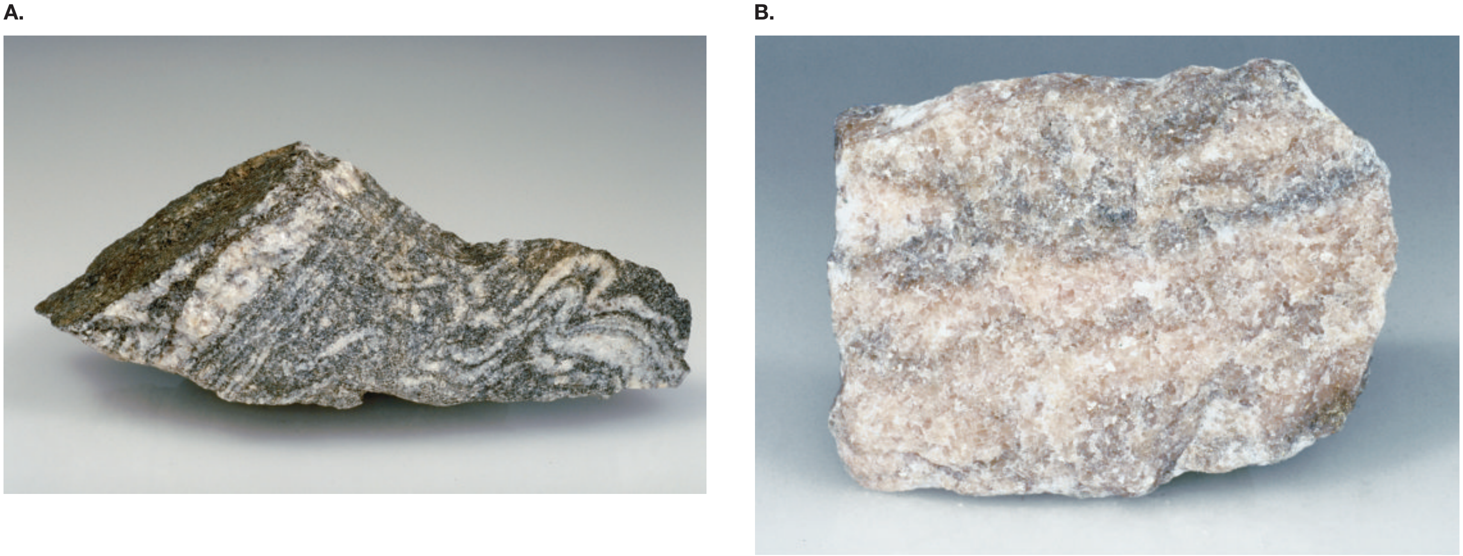
Extensive areas of metamorphic rocks are exposed on every continent. Metamorphic rocks are an important component of many mountain belts, where they make up a large portion of a mountain's crystalline core. Even the stable continental interiors, which are generally covered by sedimentary rocks, are underlain by metamorphic basement rocks. In all of these settings, the metamorphic rocks are usually highly deformed and intruded by igneous masses. Indeed, significant parts of Earth's continental crust are composed of metamorphic and associated igneous rocks.

The Rock Cycle: One of Earth's Subsystems

Earth is a system. This means that our planet consists of many interacting parts that form a complex whole. Nowhere is this idea better illustrated than when we examine the rock cycle (Figure 1.23). The **rock cycle** allows us to view many of the interrelationships among different parts of the Earth system. It helps us understand the origin of igneous, sedimentary, and metamorphic rocks and to see that each type is linked to the others by processes that act upon and within the planet. Learn the rock cycle well; you will be examining its interrelationships in greater detail throughout this book.

The Basic Cycle We begin at the bottom of Figure 1.23 with magma, molten rock that forms deep beneath Earth's surface. Over time, magma cools and solidifies. This process,

FIGURE 1.22 Common metamorphic rocks. **A.** The foliated rock gneiss often has a banded appearance and frequently has a mineral composition similar to the igneous rock granite. **B.** Marble is a coarse, crystalline, nonfoliated rock whose parent rock is limestone. (Photos by E. J. Tarbuck)



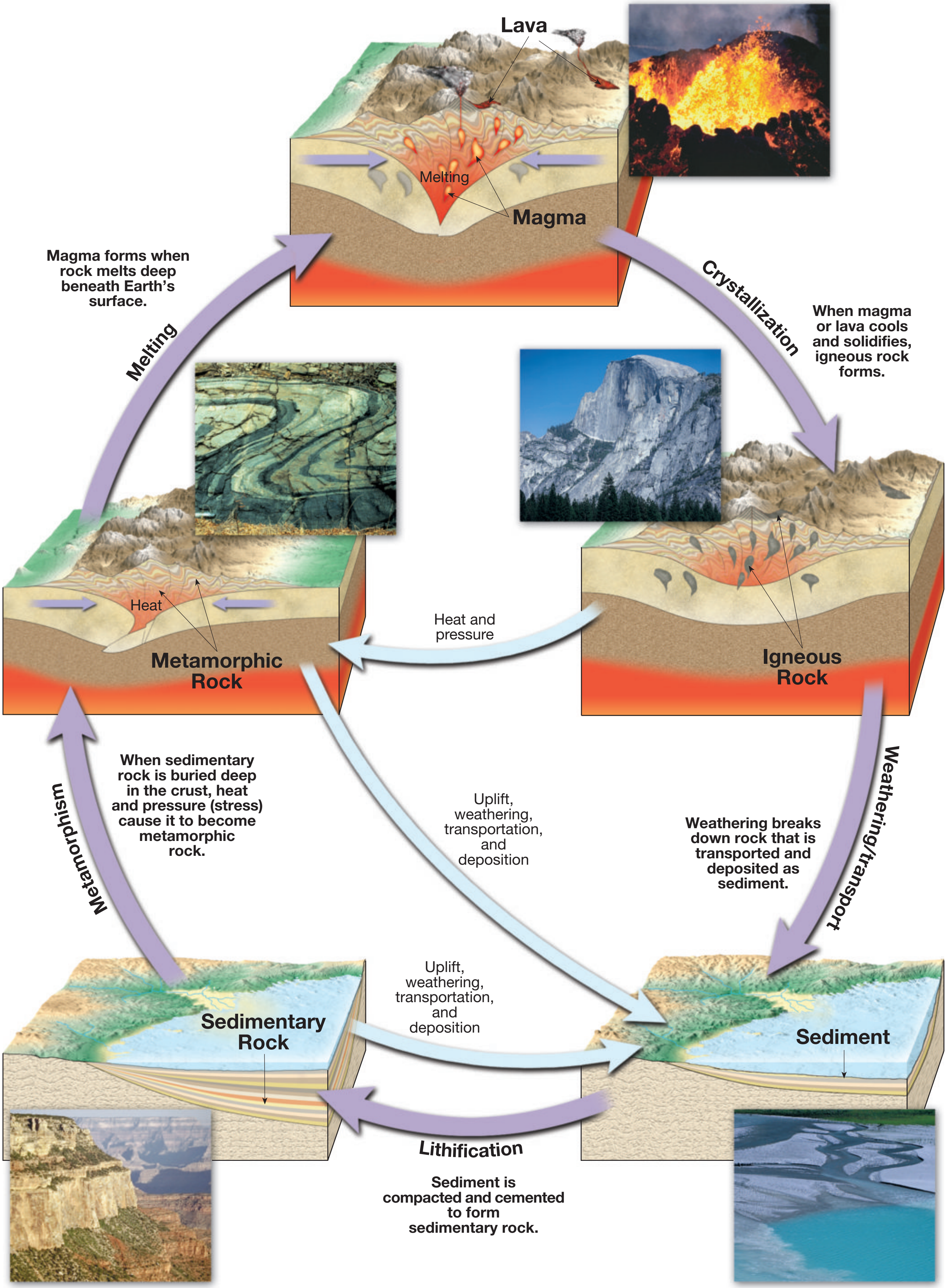


FIGURE 1.23 Viewed over long spans, rocks are constantly forming, changing, and reforming. The rock cycle helps us understand the origin of the three basic rock groups. Arrows represent processes that link each group to the others.

called *crystallization,* may occur either beneath the surface or, following a volcanic eruption, at the surface. In either situation, the resulting rocks are called *igneous rocks.*

If igneous rocks are exposed at the surface, they will undergo *weathering,* in which the day-in and day-out influences of the atmosphere slowly disintegrate and decompose rocks. The materials that result are often moved downslope by gravity before being picked up and transported by any of a number of erosional agents, such as running water, glaciers, wind, or waves. Eventually these particles and dissolved substances, called *sediment,* are deposited. Although most sediment ultimately comes to rest in the ocean, other sites of deposition include river floodplains, desert basins, swamps, and dunes.

Next the sediments undergo *lithification,* a term meaning "conversion into rock." Sediment is usually lithified into *sedimentary rock* when compacted by the weight of overlying layers or when cemented as percolating groundwater fills the pores with mineral matter.

If the resulting sedimentary rock is buried deep within Earth and involved in the dynamics of mountain building or intruded by a mass of magma, it will be subjected to great pressures and/or intense heat. The sedimentary rock will react to the changing environment and turn into the third rock type, *metamorphic rock.* When metamorphic rock is subjected to additional pressure changes or to still higher temperatures, it will melt, creating magma, which will eventually crystallize into igneous rock.

Processes driven by heat from Earth's interior are responsible for creating igneous and metamorphic rocks. Weathering and erosion, external processes powered by energy from the Sun, produce the sediment from which sedimentary rocks form.

Alternative Paths The paths shown in the basic cycle are not the only ones that are possible. To the contrary, other paths are just as likely to be followed as those described in the preceding section. These alternatives are indicated by the blue arrows in Figure 1.23.

Igneous rocks, rather than being exposed to weathering and erosion at Earth's surface, may remain deeply buried. Eventually these masses may be subjected to the strong compressional forces and high temperatures associated with mountain building. When this occurs, they are transformed directly into metamorphic rocks.

Metamorphic and sedimentary rocks, as well as sediment, do not always remain buried. Rather, overlying layers may be stripped away, exposing the once buried rock. When this happens, the material is attacked by weathering processes and turned into new raw materials for sedimentary rocks.

Although rocks may seem to be unchanging masses, the rock cycle shows that they are not. The changes, however, take time—great amounts of time.

Summary

- *Geology* means "the study of Earth." The two broad areas of the science of geology are (1) *physical geology,* which examines the materials composing Earth and the processes that operate beneath and upon its surface; and (2) *historical geology,* which seeks to understand the origin of Earth and its development through time.
- The relationship between people and the natural environment is an important focus of geology. This includes natural hazards, resources, and human influences on geologic processes.
- During the 17th and 18th centuries, *catastrophism* influenced the formulation of explanations about Earth. Catastrophism states that Earth's landscapes have been developed primarily by great catastrophes. By contrast, *uniformitarianism,* one of the fundamental principles of modern geology advanced by *James Hutton* in the late 1700s, states that the physical, chemical, and biological laws that operate today have also operated in the geologic past. The idea is often summarized as "The present is the key to the past." Hutton argued that processes that appear to be slow-acting could, over long spans of time, produce effects that were just as great as those resulting from sudden catastrophic events.
- Using the principles of *relative dating,* the placing of events in their proper sequence or order without knowing their age in years, scientists developed a geologic time scale during the 19th century. Relative dates can be established by applying such principles as the *law of superposition* and the *principle of fossil succession.*
- All science is based on the assumption that the natural world behaves in a consistent and predictable manner. The process by which scientists gather facts and formulate scientific *hypotheses* and *theories* is called the *scientific method.* To determine what is occurring in the natural world, scientists often (1) collect facts, (2) develop a scientific hypothesis, (3) construct experiments to test the hypothesis, and (4) accept, modify, or reject the hypothesis on the basis of extensive testing. Other discoveries represent purely theoretical ideas that have stood up to extensive examination. Still other scientific advancements have been made when a totally unexpected happening occurred during an experiment.
- Earth's physical environment is traditionally divided into three major parts: the solid Earth or *geosphere;* the water portion of our planet, the *hydrosphere;* and Earth's gaseous envelope, the *atmosphere.* In addition, the

biosphere, the totality of life on Earth, interacts with each of the three physical realms and is an equally integral part of Earth.

- Although each of Earth's four spheres can be studied separately, they are all related in a complex and continuously interacting whole that we call the *Earth system. Earth system science* uses an interdisciplinary approach to integrate the knowledge of several academic fields in the study of our planet and its global environmental problems.
- A *system* is a group of interacting parts that form a complex whole. *Closed systems* are those in which energy moves freely in and out, but matter does not enter or leave the system. In an open system, both energy and matter flow into and out of the system.
- Most natural systems have mechanisms that tend to enhance change, called *positive feedback mechanisms,* and other mechanisms, called *negative feedback mechanisms,* that tend to resist change and thus stabilize the system.
- The two sources of energy that power the Earth system are (1) the Sun, which drives the external processes that occur in the atmosphere, hydrosphere, and at Earth's surface; and (2) heat from Earth's interior, which powers the internal processes that produce volcanoes, earthquakes, and mountains.
- The *nebular hypothesis* describes the formation of the solar system. The planets and Sun began forming about 5 billion years ago from a large cloud of dust and gases. As the cloud contracted, it began to rotate and assume a disk shape. Material that was gravitationally pulled toward the center became the *protosun.* Within the rotating disk, small centers, called *protoplanets,* swept up more and more of the cloud's debris. Because of the high temperatures near the Sun, the inner planets were unable to accumulate many of the elements that vaporize at low temperatures. Because of the very cold temperatures existing far from the Sun, the large outer planets consist of huge amounts of ices and lighter materials. These substances account for the comparatively large sizes and low densities of the outer planets.
- Earth's internal structure is divided into layers based on differences in chemical composition and on the basis of changes in physical properties. Compositionally, Earth is divided into a thin outer *crust,* a solid rocky *mantle,* and a dense *core.* Other layers, based on physical properties, include the *lithosphere, asthenosphere, transition zone, lower mantle, D″ layer, outer core,* and *inner core.*
- Two principal divisions of Earth's surface are the *continents* and *ocean basins.* A significant difference is their relative levels. The elevation differences between continents and ocean basins is primarily the result of differences in their respective densities and thicknesses.
- The largest features of the continents can be divided into two categories: *mountain belts* and the *stable interior.* The ocean floor is divided into three major topographic units: *continental margins, deep-ocean basins,* and *oceanic ridges.*
- The *rock cycle* is one of the many cycles or loops of the Earth system in which matter is recycled. The rock cycle is a means of viewing many of the interrelationships of geology. It illustrates the origin of the three basic rock types and the role of various geologic processes in transforming one rock type into another.

Review Questions

1. Geology is traditionally divided into two broad areas. Name and describe these two subdivisions.
2. Briefly describe Aristotle's influence on the science of geology.
3. How did the proponents of catastrophism perceive the age of Earth?
4. Describe the doctrine of uniformitarianism. How did the advocates of this idea view the age of Earth?
5. About how old is Earth?
6. The geologic time scale was established without the aid of radiometric dating. What principles were used to develop the time scale?
7. How is a scientific hypothesis different from a scientific theory?
8. List and briefly describe the four "spheres" that constitute our environment.
9. How is an open system different from a closed system?
10. Contrast positive feedback mechanisms and negative feedback mechanisms.
11. What are the two sources of energy for the Earth system?
12. Briefly describe the events that led to the formation of the solar system.
13. List and briefly describe Earth's compositional divisions.
14. Contrast the asthenosphere and the lithosphere.
15. Describe the general distribution of Earth's youngest mountains.
16. Distinguish between shields and stable platforms.
17. List the three major topographic units of the ocean floor.

18. Name each of the rocks described below:

- light-colored, coarse-grained intrusive rock
- detrital rock rich in clay-size particles
- a fine-grained black rock that makes up the oceanic crust
- nonfoliated rock, for which limestone is its parent rock

19. For each characteristic below, indicate whether it is associated with igneous, sedimentary, or metamorphic rocks:

- may be intrusive or extrusive
- lithified by compaction and cementation
- sandstone is an example
- some members of this group are foliated
- this group is divided into detrital and chemical categories
- gneiss is a member of this group

20. Using the rock cycle, explain the statement “One rock is the raw material for another.”

Key Terms

abyssal plain (p. 24)
asthenosphere (p. 19)
atmosphere (p. 13)
biosphere (p. 13)
catastrophism (p. 4)
closed system (p. 15)
continental margin (p. 24)
continental rise (p. 24)
continental shelf (p. 24)
continental slope (p. 24)
core (p. 20)
craton (p. 23)
crust (p. 19)
D″ layer (p. 20)
deep-ocean basin (p. 24)
deep-ocean trench (p. 24)
Earth system science (p. 14)
fossil succession, principle of (p. 6)
geology (p. 2)
geosphere (p. 14)
historical geology (p. 2)
hydrosphere (p. 13)
hypothesis (p. 10)
igneous rock (p. 25)
inner core (p. 20)
interface (p. 15)
lithosphere (p. 19)
lower mantle (p. 20)
mantle (p. 19)
metamorphic rock (p. 27)
model (p. 10)
nebular hypothesis (p. 17)
negative feedback mechanism (p. 15)
oceanic (mid-ocean) ridge (p. 25)
open system (p. 15)
outer core (p. 20)
paradigm (p. 10)
physical geology (p. 2)
positive feedback mechanism (p. 15)
relative dating (p. 6)
rock cycle (p. 28)
seamount (p. 25)
sedimentary rock (p. 25)
shield (p. 23)
solar nebula (p. 17)
stable platform (p. 24)
superposition, law of (p. 6)
system (p. 14)
theory (p. 10)
transition zone (p. 19)
uniformitarianism (p. 4)

Web Resources

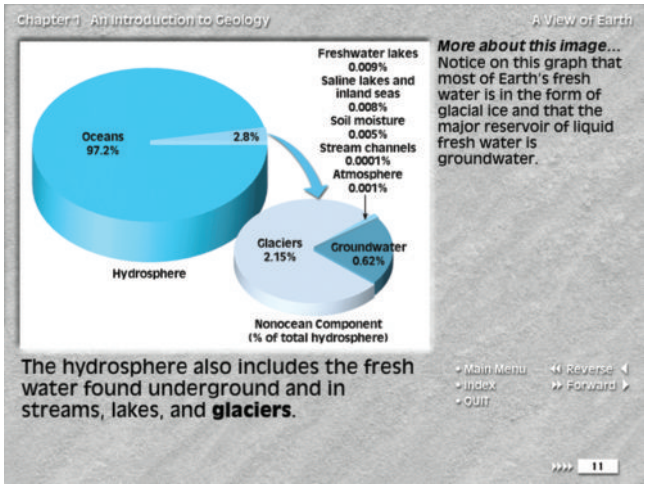
The *Earth* Website uses the resources and flexibility of the Internet to aid in your study of the topics in this chapter. Written and developed by geology instructors, this site will help improve your understanding of geology. Visit **http://www.prenhall.com/tarbuck** and click on the cover of *Earth 9e* to find:

- Online review quizzes.
- Critical thinking exercises.
- Links to chapter-specific Web resources.
- Internet-wide key-term searches.

http://www.prenhall.com/tarbuck

GEODe: Earth

GEODe: Earth makes studying faster and more effective by reinforcing key concepts using animation, video, narration, interactive exercises and practice quizzes. A copy is included with every copy of *Earth*.



More about this image...
Notice on this graph that most of Earth's fresh water is in the form of glacial ice and that the major reservoir of liquid fresh water is groundwater.

The hydrosphere also includes the fresh water found underground and in streams, lakes, and **glaciers**.

The rocks comprising mountains provide striking visual evidence of enormous compressional forces that have deformed large sections of the crust.