CHAPTER 1

Introduction: How Do We Study Earth's Systems?

Chapter Themes

Why study the history of Earth?
How did the science of Earth systems arise?
What is a system and how does it work?
What are Earth's systems and what are their basic characteristics?
How do Earth's systems interact?
Why is geologic time important to understanding how Earth's systems interact?
How do different processes act on different durations of time?
How do we use the scientific method to study Earth's systems and the history of their interactions?

Chapter Outline

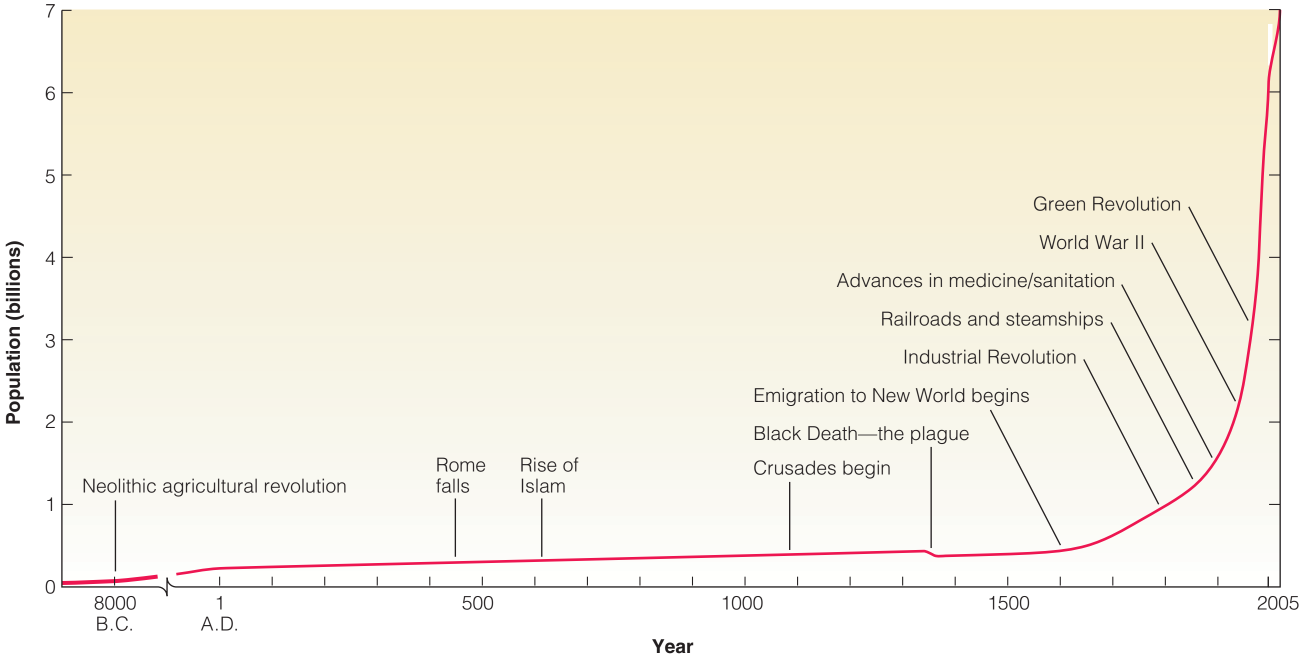


FIGURE 1.1 Human population growth. Global human population growth since 8000 B.C. [Data from: U.S. Census Bureau, International Programs Center, 2001.]

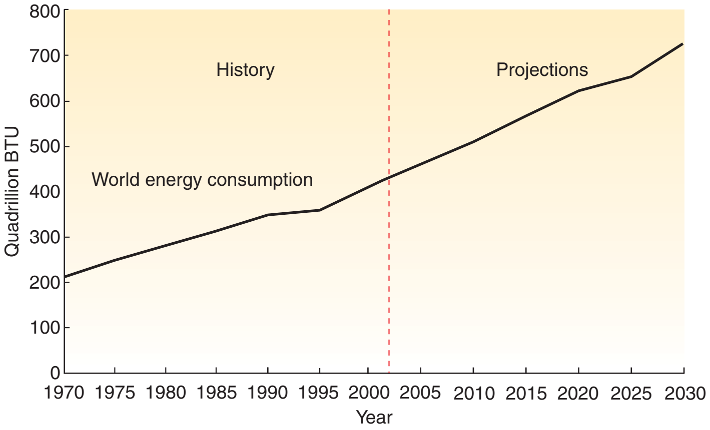
1.1 Why Study the History of Earth?

This book is about Earth, the natural processes that shape it, and the history of these processes and their interactions through vast intervals of time. ***Geology*** is the science that studies the history of the Earth and its life preserved as fossils.

Why should we be concerned about Earth's history? Because understanding how Earth changes tells us about how natural processes affect humans and how humans affect natural processes. Many natural processes act so slowly we would be unaware of them except for the geologic record of their activities preserved in the rocks. Most people are unaware that Earth's environments are constantly changing. We assume landscapes—mountains, valleys, rivers and streams, coasts, and oceans—do not change because the changes are typically so slow and subtle they take place over time spans equivalent to many, many human generations: from many millions of years down to millennia and centuries. Also, some processes are so infrequent or sudden we would not know they occur except, again, to look at the geologic record.

Scientists have only recently begun to appreciate just how strongly changes in Earth's environments have affected—and still affect—humankind, from our evolutionary beginnings through the origins of ancient settlements and civilizations, and perhaps their collapse, right up to the present (refer to this chapter's frontispiece). Humans have now begun to affect Earth's environments at rates much faster than the rates of natural processes. The rapid growth of human populations (**FIGURE 1.1**) has led to the spread of agriculture and deforestation, heavy industry and power plants fired by fossil fuels, and the dependence on petroleum (oil and gas) to power automobiles for transportation (**FIGURE 1.2**).

The burning of fossil fuels releases ***greenhouse gases***, especially carbon dioxide, into the atmosphere. Greenhouse gas traps solar radiation as heat in Earth's atmosphere, causing the atmosphere and Earth's surface to warm (**FIGURE 1.3**). Without carbon dioxide in the atmosphere, Earth's surface temperature would be about −18°C (Celsius), or about −0.5°F (Fahrenheit), instead of its current (and more comfortable!) temperature of +15°C (59°F). But humans have begun to burn fossil fuels at an unprecedented rate, and no one really knows what the outcome will be of the rapid accumulation of carbon dioxide in the atmosphere. In fact, carbon dioxide levels in the atmosphere have increased about 30% since the beginning of the Industrial Revolution (**FIGURE 1.4**). We know this based on carbon concentrations in gas bubbles found in cores taken through the glacial ice of Greenland and Antarctica because the bubbles record the composition of ancient atmospheres. As the use of fossil fuels has increased, so too has Earth's average surface temperature, so that the greenhouse effect is no longer considered by most scientists to be purely natural. As far as scientists can tell, the warming will continue through the



BTU = British thermal unit.

FIGURE 1.2 Historical and projected trends of world energy consumption. [Adapted from: the United States Department of Energy, Energy Information Administration, *International Energy Annual,* 2002, 2003 (May–July 2005), 2005 and *System for the Analysis of Global Energy Markets,* 2005 and 2006.]

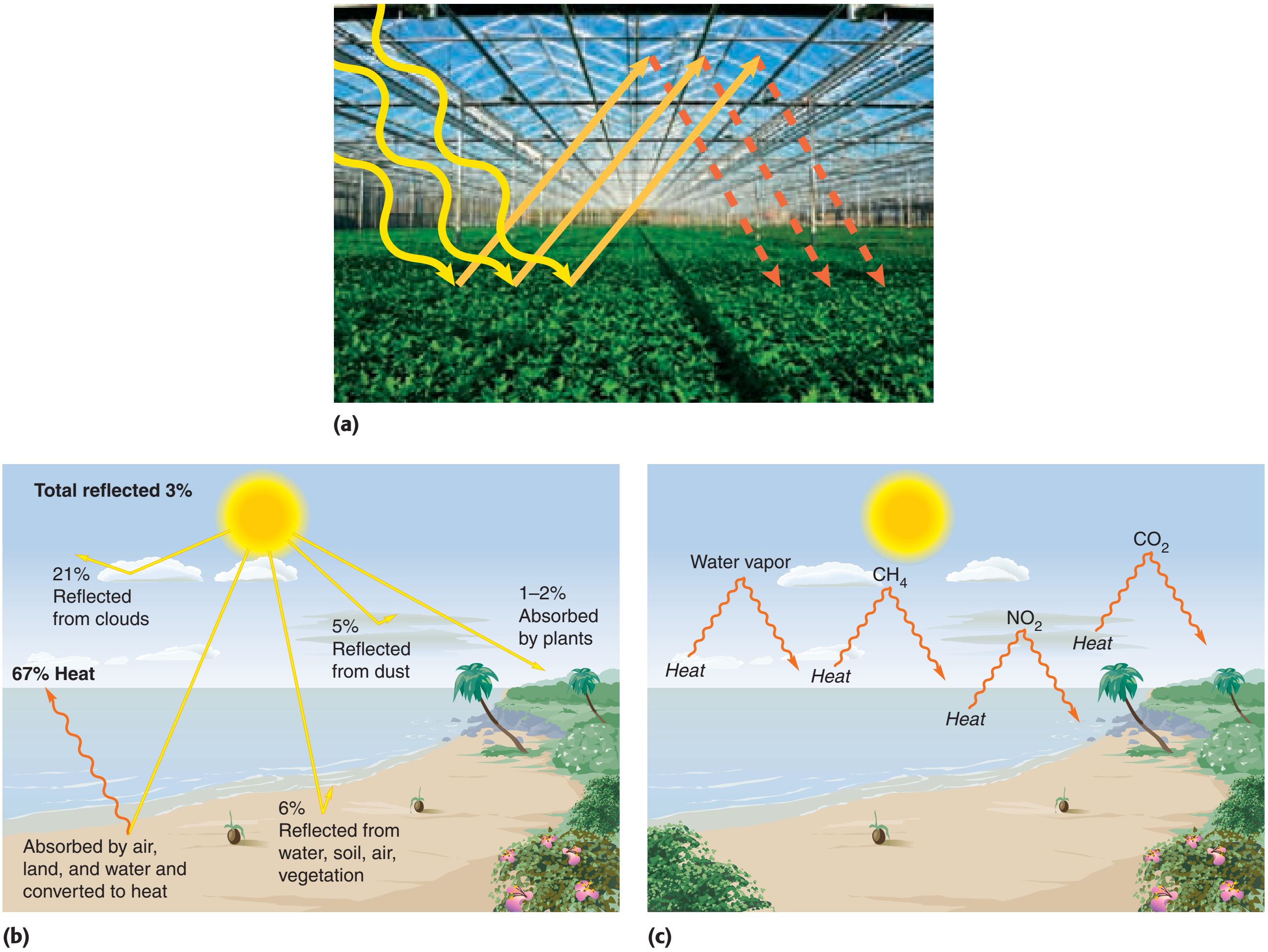
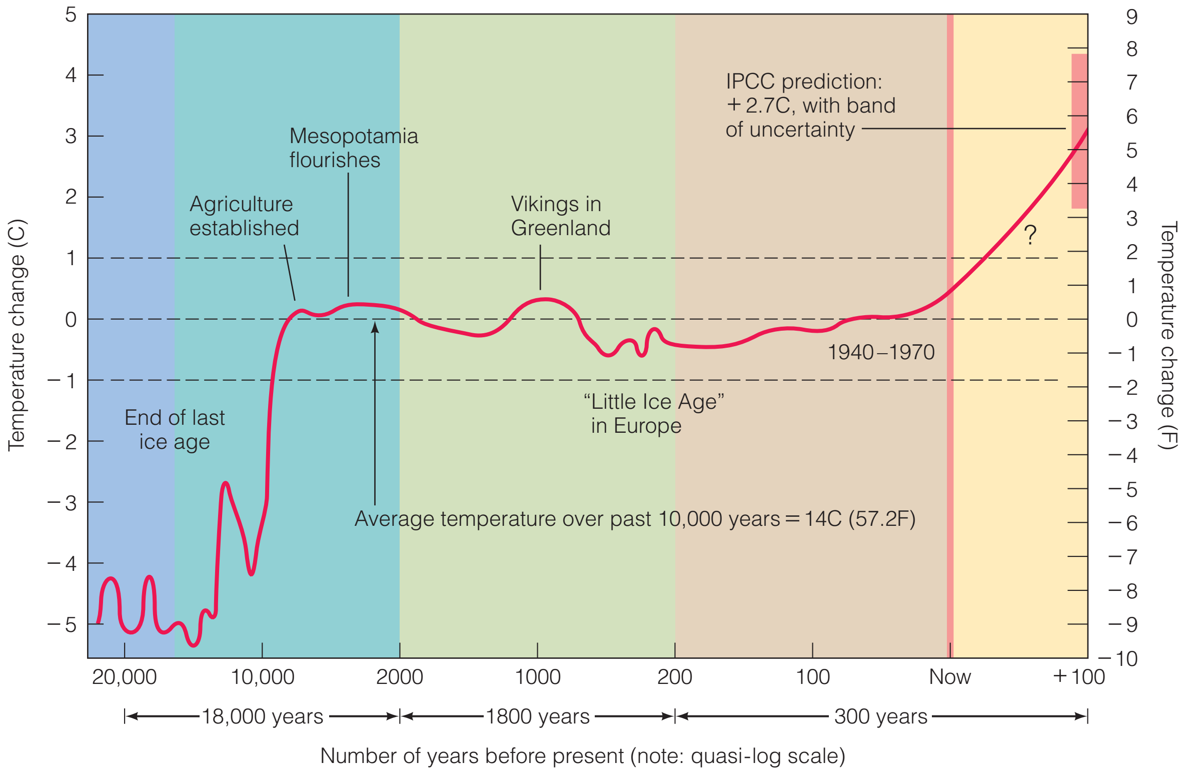
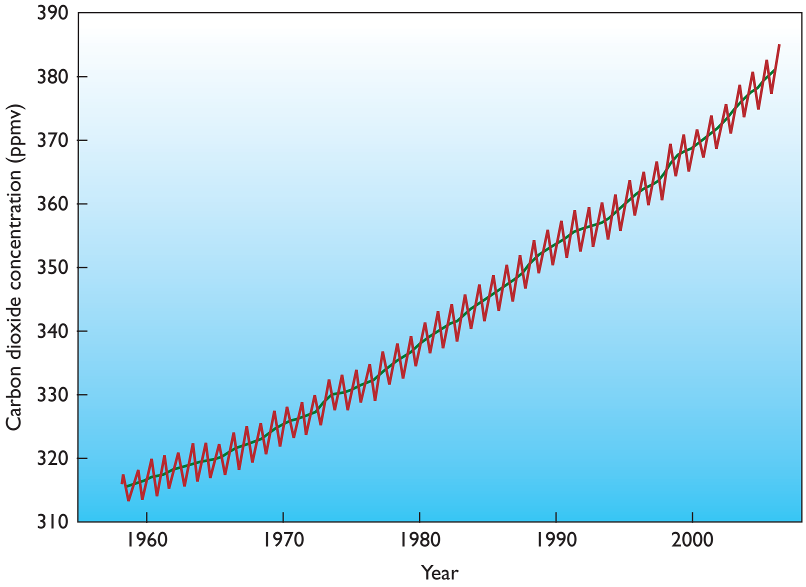


FIGURE 1.3 **(a)** How a greenhouse works. Solar energy penetrates through the glass and is reflected by the floor of the greenhouse as infrared radiation. The infrared radiation is trapped by the glass ceiling and warms the interior of the greenhouse. **(b)** The atmospheric greenhouse effect works in the same way. Atmospheric carbon dioxide acts like the glass ceiling of the greenhouse by trapping solar energy that has been reflected by **(c)** the Earth's surface as infrared radiation; this warms the atmosphere.



(a)



(b)

FIGURE 1.4 **(a)** Earth's average surface temperature increased during the last half century as compared to the previous 20,000 years. Note that some civilizations or settlements flourished during times of very mildly increased temperatures that were much lower than those of the past half century and projected into the future. There were also far smaller human populations during earlier times. (Compare Figure 1.1) [Adapted from: McMichael, A. J. 1993. *Planetary Overload.* Cambridge, UK: Cambridge University Press.] **(b)** Since carbon dioxide concentrations in the Earth's atmosphere began to be measured in 1958, atmospheric carbon dioxide has risen steadily. These measurements were taken at a station at Mauna Loa, Hawaii. Another station takes measurements in Antarctica. The oscillations reflect seasonal changes in photosynthesis. [Adapted from: Rhode, R. A. "Atmospheric Carbon Dioxide", Global Warming Art, October 1, 2008.]

21st century and beyond, potentially affecting future human generations, environments, and ecosystems.

The fact that Earth's environment has likely affected past civilizations and that ***anthropogenic***—or human-generated—activities such as fossil fuel combustion are now impacting Earth has led to the study of Earth as systems. A ***system*** can be viewed as a series of parts or components that interact together to produce a larger, more complex whole. Geology, then, is not just about describing and naming rocks and fossils. Geology is the science that examines the evolution of the natural processes on Earth, the evolution of life, and the evolution of these interactions and how they have caused Earth to evolve toward its present state. It is the geologic record of rocks and fossils that preserves the history of these interactions and which geology studies.

What are these systems and how do they interact? Over what scales of time do these systems and their processes interact? What methods do we use to study the history of these systems, and how do we determine the durations of time over which these systems interact? It is these questions to which we devote the rest of this chapter.

1.2 What Are the Major Earth Systems and What Are Their Characteristics?

Earth's surface environments are regulated by four major systems and their components (**FIGURE 1.5**). The ***solid Earth system*** consists of the nonliving, solid Earth, from its center to its surface, including the continents and the seafloor. The ***atmosphere*** comprises the gaseous envelope surrounding Earth, whereas the ***hydrosphere*** consists of the oceans, rivers and streams, lakes, and ice contained in mountain glaciers and polar ice caps. Glaciers and related environments are sometimes grouped into a separate system called the ***cryosphere***. Finally, the ***biosphere*** consists of all living organisms and their dead remains.

In this chapter we consider the traits systems share in common and postpone detailed discussion of Earth's individual systems to Chapter 2. First, each major Earth system consists of a series of parts or components that comprise a larger integrated and complex whole. Each of these components in turn consists of smaller parts with their own systems. Some compartments may serve as ***reservoirs***, in which certain types of matter (e.g., carbon from photosynthesis) may be stored

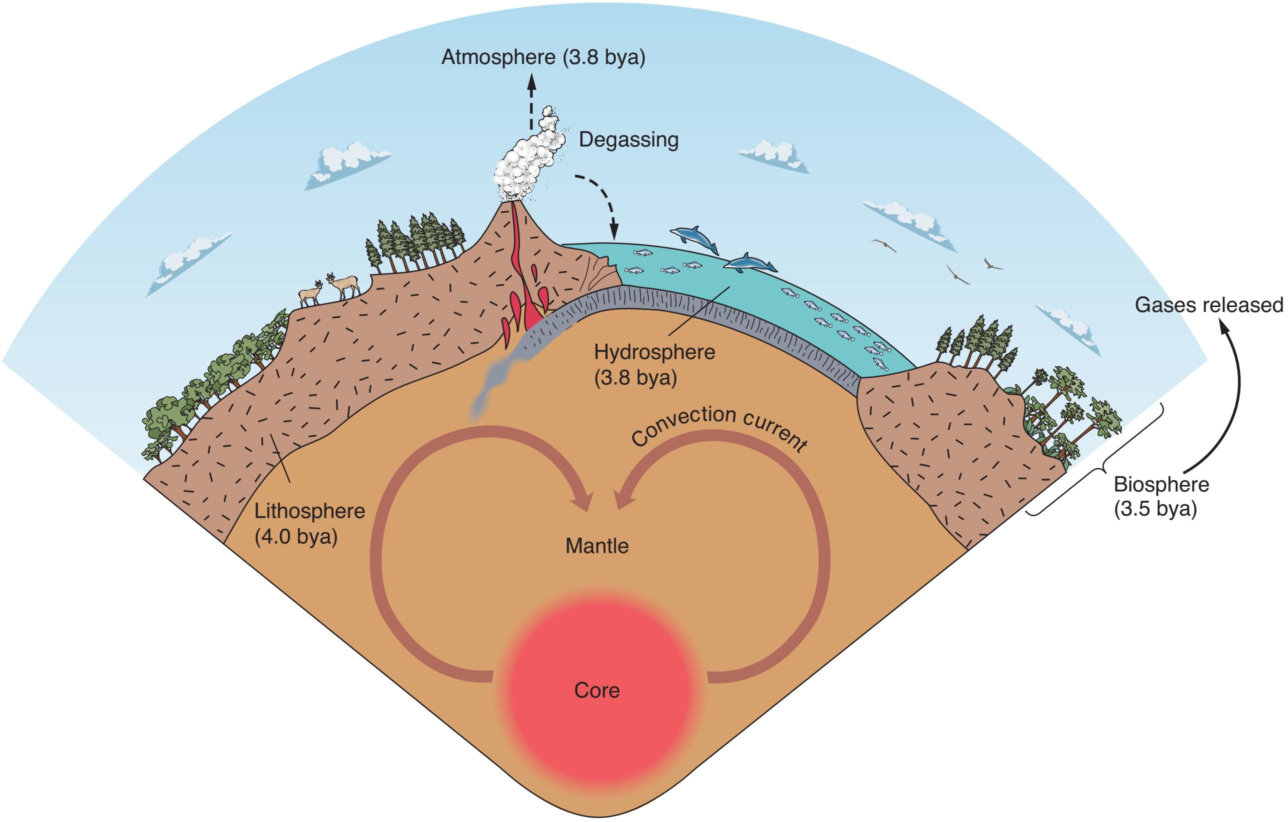


FIGURE 1.5 The four major systems of the Earth and the basic processes within each. Note that each system has its own components and that each system is cyclic. The approximate ages of the systems are shown as billions of years ago (bya).

or sequestered for some length of time ranging from perhaps days or weeks to tens of millions of years or more. Second, most natural systems, both living and nonliving, are ***open systems*** (**FIGURE 1.6**). This means the reservoirs of the systems exchange matter (chemical substances) and energy (like sunlight) with their surrounding environment. It is the flow of matter and energy through systems and their exchange of matter and energy with other systems and the surrounding environment—termed ***fluxes***—that keeps open systems functioning. For example, ***convection cells*** (like those found in a pot of boiling water) transfer heat and molten rock from deep within Earth toward its surface during the process of seafloor spreading. The heat is radiated from Earth's surface into the surrounding environment (space) as the molten material cools to form solid rock to produce the ocean floor and continents of Earth's outer shell, or ***crust***.

Convection cells and seafloor spreading are also responsible for the movement of the continents and large pieces of the lithosphere (the crust and uppermost mantle) called plates by the processes of ***plate tectonics***. The outermost rigid portion of Earth is subdivided into a series of gigantic fragments called *plates; tectonics* (or tectonism) refers to the processes that cause the movement of these plates. These processes have produced mountain chains, ocean basins, and other features at Earth's surface while interacting with the other Earth systems to profoundly affect Earth's climate through geologic time.

Convection cells also occur within Earth's atmosphere. Atmospheric convection cells result from the differential heating of Earth's surface and distribute heat and moisture over Earth's surface, thereby affecting surface temperatures and the precipitation patterns of the hydrosphere. Water is critical to life as we know it on Earth; most organisms consist of over 60% water (and some over 90%). Water also provides habitats for organisms, such as oceans, lakes, and rivers. Like carbon dioxide, water vapor also acts as a greenhouse gas, affecting Earth's temperature and habitability.

The energy of sunlight is also used by plants during photosynthesis to produce simple sugars from carbon dioxide and water. These substances are then eaten by herbivores and broken down, releasing energy that may be used by, for example, prey to run from predators. The biosphere has had a profound impact on the evolution of the Earth. In fact, *life may be viewed as a geologic force*. Without the evolution of photosynthesis on Earth and the storage of carbon dioxide in plant matter, the carbon dioxide levels of Earth's atmosphere would more nearly resemble those of Mars or Venus and there would be little or no oxygen present for respiration (**FIGURE 1.7**). Plants also profoundly affect the physical and chemical breakdown—or ***weathering***—of the rocks of Earth's crust. Weathering processes are critical to the long-term, or *geologic*, cycle of carbon that occurs over tens of millions of years, as we will see shortly.

These examples illustrate another important point about Earth's systems, namely that they interact to regulate Earth's climate. These interactions occur through ***feedback***. Positive feedback promotes an effect, whereas negative feedback counters an effect. Most of us are all too familiar with one type of positive feedback: audio feedback. In a sound system the microphone converts sound (vibrations in the air) into electrical impulses that are sent to the amplifier, which enhances the signal and sends it to a speaker. The speaker then converts the amplified electrical signals back into vibrations (sound), which are picked up by the microphone and sent to the amplifier, producing an ear-piercing sound.

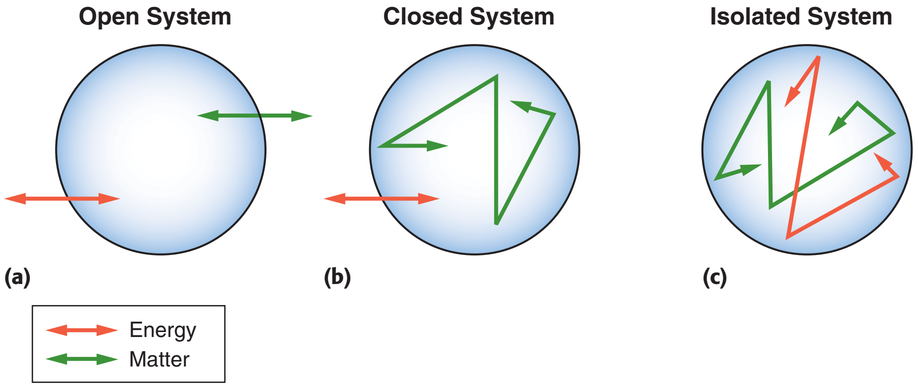


FIGURE 1.6 **(a)** An open system exchanges both matter and energy with its surroundings. **(b)** A closed system exchanges energy (by temperature changes) with its surroundings. **(c)** An isolated system does not exchange matter and energy with its surroundings.

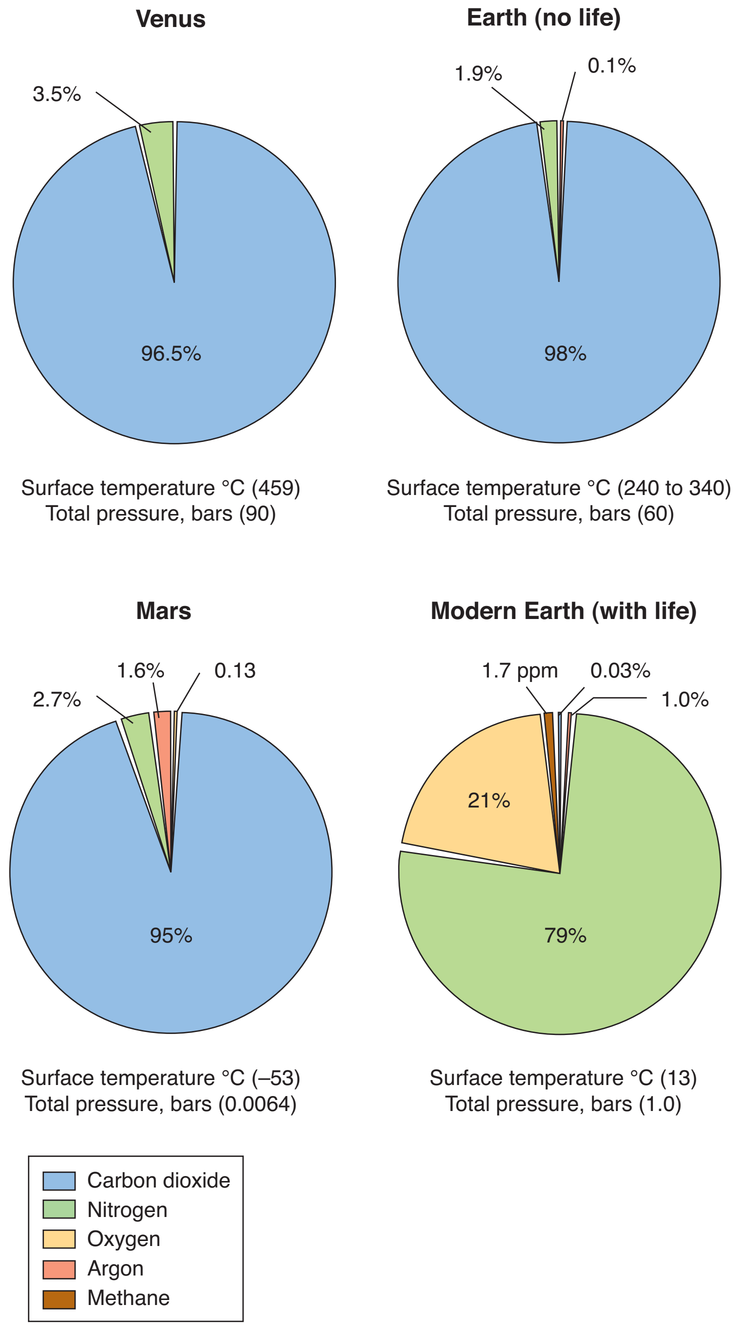


FIGURE 1.7 The carbon dioxide concentration of the Earth's atmosphere as compared to that of Mars and Venus if life had not evolved on Earth. [Data from: Lovelock, J. 1988. *The Ages of Gaia: A Biography of Our Living Earth.* New York: W. W. Norton.]

An example of negative feedback is the temperature control of a house (**FIGURE 1.8**). If the house becomes too cold (or too warm), a thermostat is triggered that turns on the furnace (or the air conditioner) to warm (or cool) the house to the desired level set on the thermostat. Both positive and negative feedback must act together to counterbalance one another; otherwise, a system would shift too far in one direction.

Now let's apply the concept of feedback to the regulation of Earth's systems. These feedbacks frequently involve the cycling and recycling of elements such as carbon and nutrients like phosphorus. These cycles are called ***biogeochemical cycles*** because they typically involve the cycling of these and other chemical elements between reservoirs located in the biosphere and geologic reservoirs such as rocks, sediments, and soils.

We focus on carbon dioxide because it is a greenhouse gas and affects Earth's surface temperature. Note in this example how the four major Earth systems interact with each other and how matter is transferred

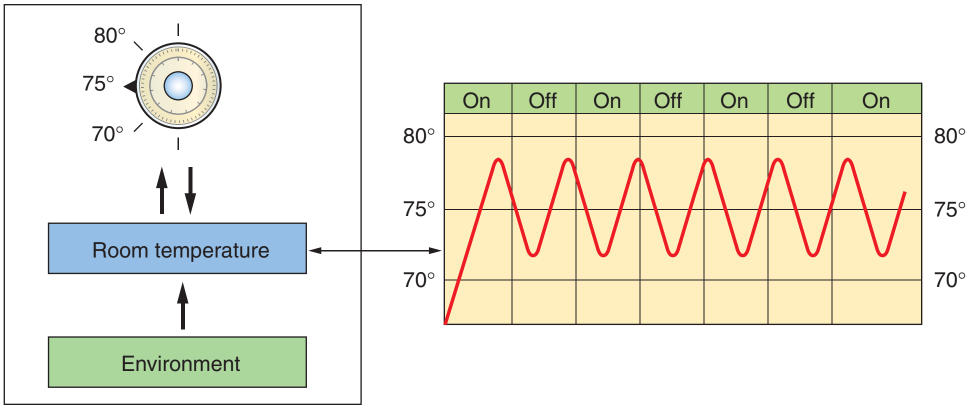


FIGURE 1.8 Positive and negative feedback are involved in temperature regulation by a thermostat. [Adapted from: Lovelock, J. 1991. *Healing Gaia: Practical Medicine for the Planet.* New York: Crown Publishers.]

from one kind of reservoir to another to regulate the level of atmospheric carbon dioxide and Earth's climate. Dramatic changes in the concentration of atmospheric carbon dioxide are inferred from Earth's geologic history. Enormous volumes of volcanic rock erupted onto Earth's surface at times in the ancient past because of the processes of plate tectonics. Because modern volcanoes pump carbon dioxide into the atmosphere, the ancient eruptions must have spewed enormous volumes of the same gas into the atmosphere. The carbon dioxide then remained in the atmosphere for long periods of time, spanning tens of millions of years. Based on the greenhouse effect, the carbon dioxide warmed the Earth, speeding up—through positive feedback—the chemical reactions involved in the weathering of rocks on land (**FIGURE 1.9**). As these reactions were speeded up, they in turn began to act as negative feedback: much of the carbon dioxide pumped into the atmosphere by volcanism was used up by weathering, eventually lowering atmospheric concentrations of carbon dioxide and lowering Earth's surface temperature. These weathering reactions produce a type of sedimentary rock called limestone. The carbon dioxide in the atmosphere is transferred to and sequestered (or stored) in limestone by unicellular photosynthetic plankton called coccolithophorids that secrete microscopic platelets of calcium carbonate ($CaCO_3$) to produce a form of limestone (**FIGURE 1.10**). In the geologic past these particular organisms produced vast amounts of limestone on the continents, but if the limestones are deposited in the deep sea, they may eventually be carried into deep-sea trenches (Figure 1.9A), where they are subducted and heated. The carbon dioxide stored in the limestone (as carbonate) is released and vented back to the atmosphere through volcanoes. These processes therefore act as positive feedback by increasing levels of carbon dioxide in the atmosphere (Figure 1.9A).

Why can't these weathering reactions decrease the carbon dioxide that has accumulated in the atmosphere from the combustion of fossil fuels and prevent global warming? Because these processes take millions to tens of millions of years to draw down the carbon dioxide. In fact, the weathering processes occur so slowly *they appear to be constant to us*. Even paint dries much, much faster than weathering occurs!

This example illustrates another important point about the study of Earth systems: *the importance of processes varies with the duration of time*. If we are looking for natural processes to draw down anthropogenic carbon dioxide, we must look for processes that act more quickly than rock weathering. Photosynthesis either on land or in the oceans acts much more rapidly than weathering and is one possible place where anthropogenic carbon dioxide could be stored (Figure 1.9B). However, one of the most fundamental questions of Earth systems science remains unanswered: how much anthropogenic carbon dioxide are forests, grasslands, and oceans capable of storing? Despite intensive research, estimates vary widely. Given that atmospheric carbon dioxide levels have continued to increase, it seems unlikely that these sites can store all the anthropogenic carbon dioxide fast enough to counteract fossil fuel combustion in the very near future.

Concept and Reasoning Checks

1. What are the characteristics of open systems?
2. Are natural systems open systems?
3. What are the basic components of each system described above?

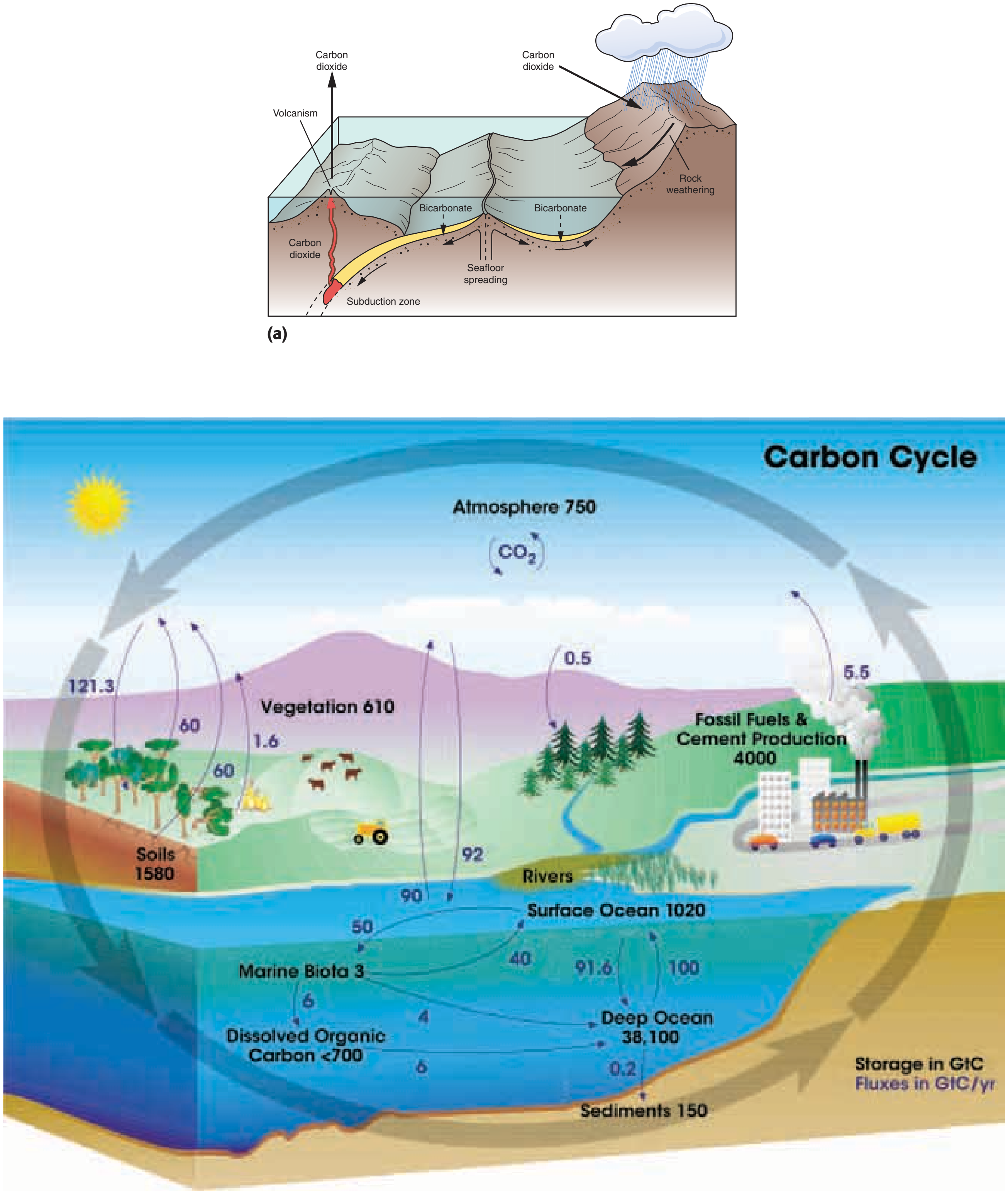


FIGURE 1.9 **(a)** The geologic cycle of carbon, in which the regulation of atmospheric carbon dioxide by positive and negative feedback occurs on long scales of geologic time and involves the sequestration of carbon in limestones by marine plankton. [Reproduced from: Ruddiman, W. F. and Kutzbach, J. E. 1991. Plateau uplift and climatic change. *Scientific American. 264*(3), 66–75.] **(b)** The carbon cycle on relatively short time scales of centuries to millennia involves land plants and marine plankton, which sequester carbon dioxide in living and dead organic matter. The amounts of carbon stored in each reservoir and the fluxes between reservoirs are shown in terms of 10^9 kilograms (or Gigatons, GtC), kilograms carbon. Arrows indicate the exchanges of carbon between reservoirs. Note that on relatively short time scales of centuries to millennia. the vast majority of carbon is stored in the deep ocean. [Courtesy of NASA Earth Science Enterprise.]

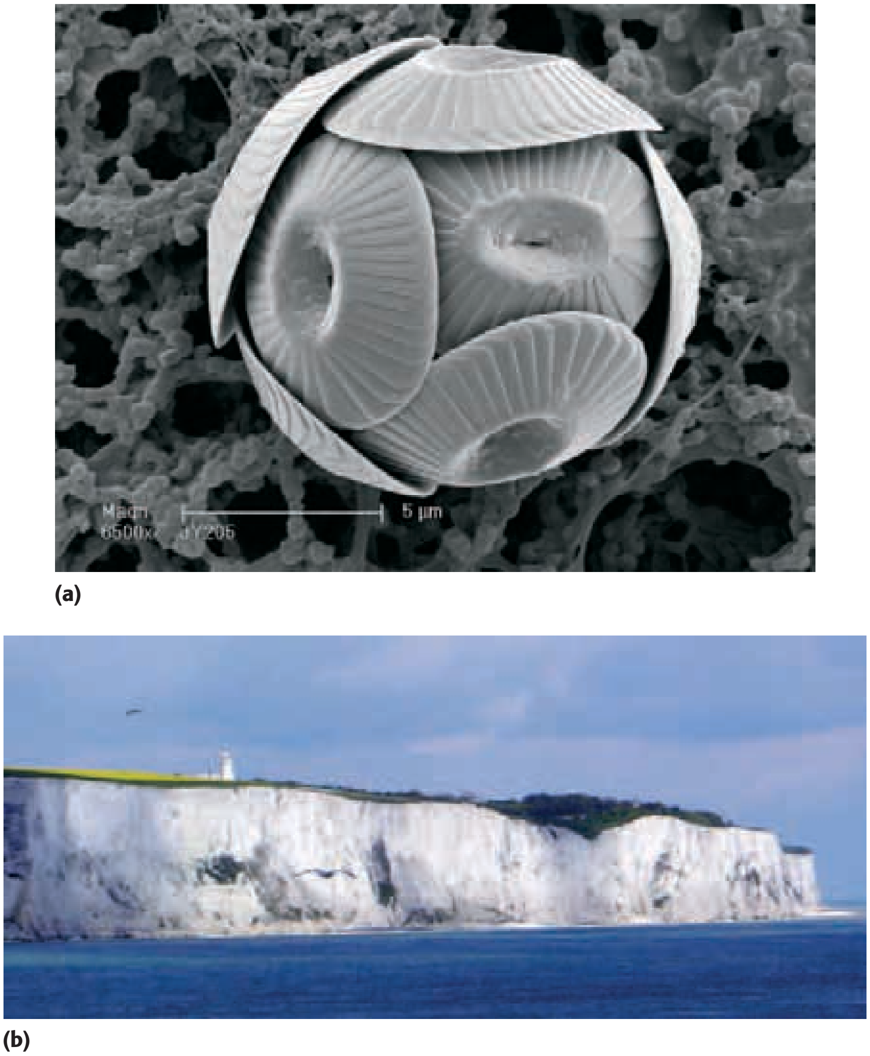


FIGURE 1.10 **(a)** A modern coccolithophorid. **(b)** The White Cliffs of Dover consist of chalk deposited during the Cretaceous Period when the seas flooded the continents.

1.3 Geologic Time and Process

Our discussion of feedback has raised the related issues of time and process. The processes relevant to the study of Earth's systems vary according to the duration of time involved. *Many processes occur so slowly they are imperceptible to us on human time scales*, like those involved in rock weathering and the geologic cycle of carbon discussed above. Nevertheless, these processes have a profound impact on Earth's environments over long spans of many millions of years. On the other hand, some processes are so rare we would not know they occur except, again, to look at the geologic record of rocks and fossils. In either case, though, *the only way to detect the existence of these processes, their potential impact on humanity, and humanity's potential impact on them is to examine the geologic record of these changes as they are preserved by the rocks and fossils.*

To come to grips with this important realization, one must wrestle with the enormity of ***geologic time***. As the first Earth scientists began to study the planet's history in earnest, they quickly recognized that rocks occur in layers that lay on top of one another. In the 1600s this basic observation led to the ***Principle of Superposition***, which states that in a sequence of rocks, younger rocks lie on top of older rocks (**FIGURE 1.11**). Thus, the sequence of rocks provides what are called ***relative ages***, meaning that something is older or younger than something else. Still, most scientists refrained from speculating on how old the rocks were and generally assumed the Earth was only a few thousand years old based on biblical interpretation. During the 18th and early 19th centuries, however, scientists began to realize that Earth was far older than previously imagined. One of the primary pieces of evidence for this conclusion was the relationship of

FIGURE 1.11 The Principle of Superposition states that younger rocks are laid down on top of older rocks. Thus, the oldest rocks occur at the bottom of the section and the youngest at the top.

stratified rocks at Siccar Point, along the northeast coast of England. Here, horizontally layered (or ***stratified***) rocks (from "stratum" for layer) had originally been laid down and then tilted and eroded, after which more stratified rocks were deposited on top (**FIGURE 1.12**). Because processes that could produce such phenomena are not observed, the implication was that the processes must occur very slowly as compared with human time scales. The recognition of the enormity of time is generally attributed to the so-called father of geology, James Hutton (1726–1797), a Scottish farmer who was a member of a small circle of Enlightenment naturalists and scientists of the 1700s and who periodically met in the pubs of Edinburgh, Scotland to discuss natural history and science (or "natural philosophy", as it was called in those days).

About this time fossils were also coming to be accepted as evidence for prehistoric life. The presence of fossils as evidence of ancient life eventually led to the recognition in 1815 of the ***Principle of Faunal Succession***, which states that different groups of fossils follow each other in a characteristic upward sequence, that is, through time. Faunal succession was originally established in England, but with its recognition scientists began to look more closely at the occurrence of fossil assemblages elsewhere. This led to the development of the geologic time scale, the subdivisions of which are largely based on the occurrence of distinctive fossil assemblages through time (**FIGURE 1.13**). For example, the Cretaceous Period, when Earth was quite warm and the seas quite high, is named for the widespread chalks ("creta") that consist of the microscopic remains of ancient plankton (such as coccolithophorids) that floated in the seas during this period (Figure 1.10B).

Much later, during the 20th century, ***absolute ages*** (dates in years) began to be determined from the rates of ***radioactive decay*** of certain minerals. Because radioactive elements decay at known rates, they can be used to calculate the ages of the rocks in which they occur. The modern time scale, which incorporates both changes in fossil assemblages through time and absolute ages, is routinely used in studies of Earth systems, and we will refer to it frequently throughout this book.

The initial recognition that Earth was quite old raised several profound scientific and philosophical questions: Are the processes that we observe and measure today on human time scales necessarily representative of the geologic past? In other words, does

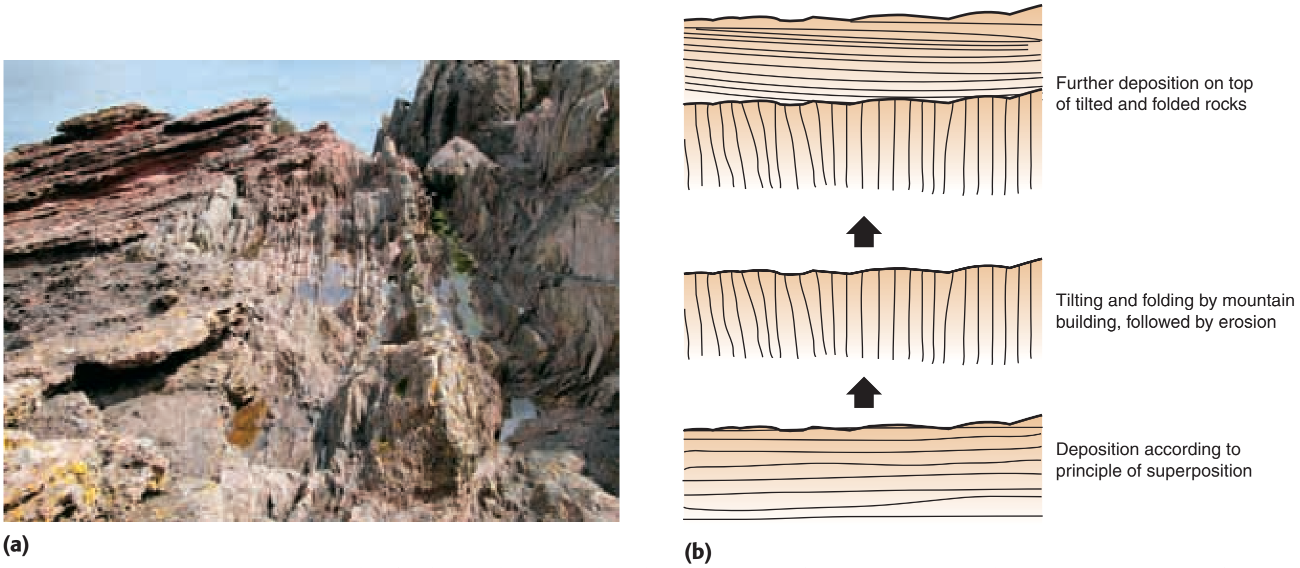


FIGURE 1.12 **(a)** Siccar Point, Scotland, where, along with his observations on the formation of soils, James Hutton is said to have recognized the enormity of the Earth's age. **(b)** Interpretation of the events affecting the relations of the strata.

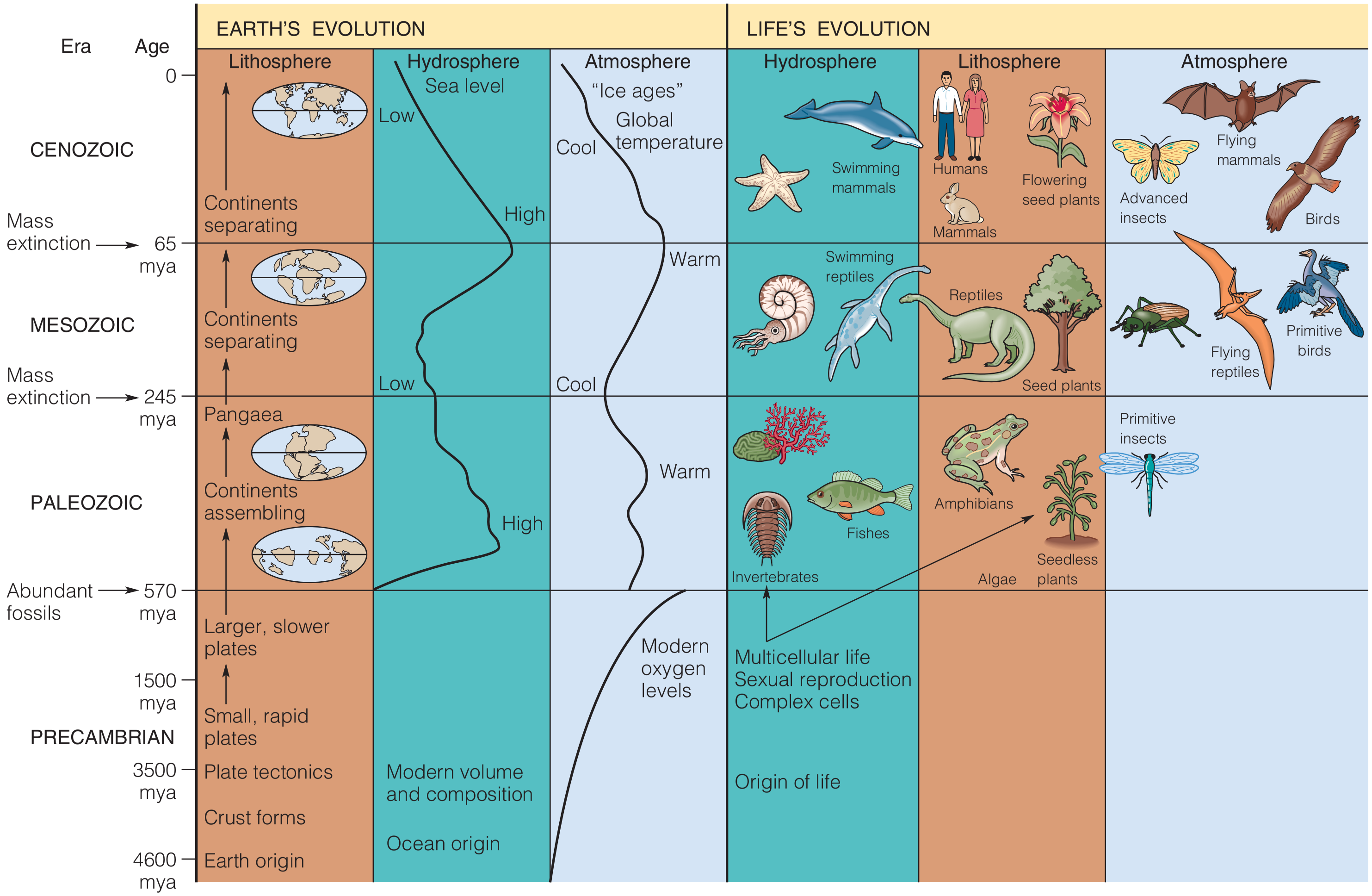


FIGURE 1.13 The simplified geologic time scale and its basic subdivisions. Many of the subdivisions are based on the Principle of Faunal Succession, which recognizes that the Earth's biota has changed through time. Some of the major changes in the biotas are shown. The absolute ages come from radioactive elements that decay at known rates.

nature act in a uniform manner? If so, then it must take a long time for many geologic processes to have an effect. Or can the *rates* of the processes vary, and can the *processes* themselves vary through time?

The guiding principle that leads Earth scientists through the maze of Earth processes and systems is the ***Principle of Uniformitarianism***. This principle is frequently stated as "the present is the key to the past." In other words the processes we observe today are the same as those that have always operated. The origins of uniformitarianism are typically traced to James Hutton's *Theory of the Earth, with Proofs and Illustrations* (1795), which discussed his observations and those of others (**FIGURE 1.14**). Some earlier scientists had begun to think along similar lines, even going so far as to believe Earth was quite old, but Hutton was the first to have synthesized his ideas into a theory based on observation. Hutton had been trained as a physician and, as a student, had defended a thesis on the circulation of human blood. Hutton's studies in medicine undoubtedly influenced his view of Earth's processes. After he inherited a small farm, Hutton became interested in how soils form and are replenished. Among his conclusions was that natural processes are self-renewing, or cyclic, like the circulation of the blood (and the processes of Earth's systems introduced above). He also became interested in how rocks form. Hutton was well aware of the power of heat because of other studies of how to make steam engines more efficient for the ongoing Industrial Revolution. He ultimately concluded that mountain building results from the activity of heat and that Earth therefore had to have an internal source of heat. In Hutton's theory volcanoes acted as valves to release the heat and pressure generated within the Earth (we now know, that the source of Earth's internal heat is radioactive decay, which drives the processes of plate tectonics).

Hutton's work laid the foundation for more serious geologic inquiry in the 19th and 20th centuries. Among these works, those of Sir Charles Lyell (1797–1875) have perhaps had the greatest influence on geology (Figure 1.14). Hutton was not a particularly good writer, but Lyell was much better and developed Hutton's views further by gathering enormous amounts of evidence from his travels in Europe. Lyell's synthesis of his observations and conclusions resulted in the publication of his three-volume treatise, entitled *Principles of Geology*, in England in 1830; 11 more editions of the *Principles* followed into the 1870s.

Lyell is usually credited with developing the Principle of Uniformitarianism, which he used to counter the rival doctrine of what he derisively called


(a)

(b)

FIGURE 1.14 Two founders of geology. **(a)** James Hutton (1726–1797). **(b)** Sir Charles Lyell (1797–1875), who is credited with the formulating the Principle of Uniformitarianism.

catastrophism. According to Lyell, catastrophism viewed the Earth's geologic record as having resulted from a series of sudden global catastrophes. Lyell also argued that catastrophism was an attempt to make Earth's age fit with a chronology (time scale) derived from the Bible. This portrayal of catastrophism by Lyell was grossly inaccurate, but Lyell was a lawyer, and he used his skills at argumentation and rhetoric to build a convincing argument for his own case.

According to Lyell, the Principle of Uniformitarianism meant that the natural processes of today have *always remained the same*. Indeed, given that Earth is now known to be approximately 4.5 to 5 billion years old (based on absolute ages), there has been plenty of time for very slow processes to produce major changes on Earth, just as Lyell (and Hutton) said. Lyell also concluded, however, that not only are the rates of geologic processes typically slow and gradual, but *modern processes are exactly the same as those that have acted in the past*. Lyell did not deny that catastrophic changes such as earthquakes or volcanic eruptions occurred on a *local basis*, but he condemned the concept of *global* catastrophes that he attributed to the so-called catastrophists. Lyell's concept of slow, gradual change dominated geologic thought until well into the 20th century, and his influence on the Earth sciences up to the present cannot be overestimated.

The uniformitarian approach is sometimes referred to as ***actualism***. According to actualism, processes observed in modern environments, using modern ***analogs*** or examples, can be extrapolated to the interpretation of ancient environments. Thus, if a past phenomenon can be explained as a result of processes *actually* observed today, then we need not invent or search for other processes to explain the phenomenon. In this view the Principle of Uniformitarianism is the broader assumption that the behavior of nature has been uniform through time. Geologists are especially proud to claim the Principle of Uniformitarianism as their own because of its implications for Earth history. Nonetheless, *the Principle of Uniformitarianism underlies all scientific inquiry*. No form of scientific research could be conducted if nature did not behave—and if we did not *assume* that nature did not behave—in a relatively uniform manner. For example, chemical elements and the compounds they form must have always behaved the same way chemically; otherwise, a chemist could not conduct meaningful research, even under the controlled conditions of a laboratory experiment. Normally, actualism and the Principle of Uniformitarianism seem to work quite well, as attested to by, say, obtaining similar results in laboratory experiments.

What is typically left unsaid about uniformitarianism and actualism is that the past is more often than not the key to the present. As we will see time and again throughout this book, the geologic record demonstrates that there are processes acting on Earth that either act so slowly or so infrequently as to be imperceptible on human time scales. Moreover, scientific reasoning from rocks and fossils often indicates that given enough time, unusual processes or events not observed today have also occurred. In fact, we now know that present-day conditions were often not representative of the past and that a number of unusual, or even catastrophic, changes on Earth have occurred. For example, we now know from the geologic record that movement of the continents on geologic scales of time has interacted with the other Earth systems to drastically alter climate and produce ***mass extinctions***, during which large portions of the biosphere have been decimated. The geologic record also tells us that at times meteors have collided with Earth to produce certain mass extinctions (**FIGURE 1.15**). Thus, Earth scientists have broadened their view of the Principle of Uniformitarianism to mean that (1) processes have largely remained the same but the *rates* of the processes can vary, (2) processes vary according to the duration of time (as we saw with sea level and the carbon cycle above), and (3) sometimes highly unusual conditions and phenomena occur, including catastrophic ones like meteor impacts and mass extinctions.

FIGURE 1.15 The geologic record of a mass extinction. The hammer spans a dark layer enriched in the chemical element iridium preserved in sedimentary rocks in Colorado. The iridium layer formed about 65 million years ago at the end of the Cretaceous Period as a result of the collision of the Earth with an extraterrestrial body. This particular extinction is thought to have resulted in the extinction of the dinosaurs.

1.4 Directionality and the Evolution of Earth Systems

Another important aspect of Lyell's *Principles of Geology* was that he did not discuss what he called Earth's "cosmogony," or origins; to do so, according to Lyell, exceeded the bounds of uniformitarianism. This is because Lyell envisioned Earth as being in ***equilibrium***, meaning that a system exhibits no *net* change. Thus, according to Lyell, Earth had undergone no net change through time. To be sure, Lyell envisioned Earth as changing, but he envisioned no overall, or net, change to Earth. In Lyell's view, for example, mountains forming in one place were counterbalanced by erosion somewhere else. We have already seen an example of such cyclic behavior of Earth's systems in which components of the system counterbalance one another through positive and negative feedback: the geologic cycle of carbon.

Although Earth's systems do behave in a cyclic manner, as Lyell envisioned, there is substantial evidence that Earth has also evolved, that is, that the seemingly equilibrium states of Earth (no net change) have actually shifted through time in particular directions. Indeed, as indicated by the title of this book, *Earth's systems have evolved and continue to evolve*. The word ***evolution*** means to develop or unfold. In the case of Earth as a whole, with all its interacting systems, the evolution of Earth has resulted in ***directionality***—or ***secular change***—through time. Thus, even though Earth's systems act in a cyclic manner, they are also tending to change, inexorably, in certain directions through geologic time. *This secular change in Earth's systems is another fundamental reason for studying Earth's history.* Slow, directional change means that a system may appear to exhibit no net change, like the environments we observe on human time scales, when in fact environments may be changing in a directional manner on geologic scales of time. Furthermore, what we observe or measure today is by no means always representative of Earth's distant past because conditions on Earth have changed. Therefore, we cannot fully understand Earth's systems simply by looking at how they behave at present because Earth's systems have evolved. Indeed, Earth's history has really consisted of a succession of vastly different worlds leading up to ours.

Directional changes in Earth's systems have resulted from the flow of matter and energy between Earth's systems through geologic time (discussed in subsequent chapters). Among the numerous examples of directionality in the history of Earth's systems that we consider are (1) the formation of the solid Earth by cooling from a molten ball as the solar system formed, (2) the formation and evolution of the continents by the continued transfer of molten material and heat from within Earth's interior to the lithosphere, (3) the early evolution of the atmosphere during the degassing of the primitive Earth by volcanoes, and (4) the origin and evolution of life, which led first to photosynthesis and the oxygenation of the atmosphere and ultimately to the origin of more complex organisms. The biosphere eventually began to be integrated with the other Earth's systems and acted as a geologic force to produce new cycles, such as the geologic cycle of carbon described above.

Concept and Reasoning Checks

1. What distinguishes the Principle of Uniformitarianism as Lyell recognized it from the Principle of Uniformitarianism as it is now recognized?
2. What sorts of evidence indicates directionality in Earth's history?
3. What has caused directional change in Earth's history?

1.5 Geology as an Historical Science

Geology and the other Earth sciences are often termed ***historical sciences***. What is meant by the term "historical science"? So far in this chapter we have dealt with Earth systems as if they are components of a larger entity resembling a machine. The idea that nature and its components can be treated as machines is not new. It dates at least to the time of René Descartes (1596–1650), a French mathematician and philosopher for whom the Cartesian coordinate system of geometry is named.

With the doctrine that nature is a machine came another view: that nature can be understood by taking it apart, like a machine, into smaller parts that are more easily analyzed. This view has had a tremendous impact on scientific thinking and is referred to as ***reductionism***. For example, we broke the larger whole Earth system into four basic component systems: atmosphere, biosphere, hydrosphere, and solid Earth. Admittedly, these are very large parts, each of which is itself a system! But, by breaking a system (in this case, the whole Earth) down into smaller components, we can presumably examine the structure and behavior of the smaller components and identify particular cause and effect relationships. Each component may in turn consist of smaller compartments with their own systems and fluxes. However, as we have already seen, Earth's systems are not isolated but open to each other, and we cannot fully understand them without understanding their interactions.

Much of science is also based on the assumption that each effect (observation, outcome) has a *particular* cause and that we can predict an effect given a particular cause; this view of science is called ***determinism***. Many of the phenomena and processes studied by scientists, including those who study Earth systems, occur on sufficiently short time scales that the processes and their effects can be observed or measured. Determinism is associated with the simplest notion of cause and effect, namely that an effect has a single cause, like that observed in a laboratory setting, where all factors thought to affect the laboratory system are held constant and the factor of interest is allowed to vary. The notion that the simplest explanation of a phenomenon is the one that is most likely to be correct is called ***Ockham's Razor***, or the ***Principle of Parsimony***, after William of Ockham (ca. 1295–1350). This principle has become an integral part of the scientific method because it emphasizes that one should seek simplicity in scientific explanation.

Nevertheless, Earth's phenomena—its processes and their outcomes—are not strictly deterministic because in natural settings the same effect may have multiple or overlapping causes. On seasonal time scales, for example, atmospheric carbon dioxide is regulated by seasonal changes in sunlight and photosynthesis (Figure 1.4B), but on scales of many millions of years, continental weathering also affects atmospheric carbon dioxide. Another prime example of the notion of ***multiple causation***, which we examine in later chapters, is the mass extinction of Earth's biota. Mass extinctions occurred a number of times during Earth's history, but the exact cause of each episode has varied, and in some cases there may have been more than one cause that overlapped in time.

The processes that occurred during the ancient past have also undoubtedly varied with historical circumstances, or contingency. ***Contingency*** means that historical circumstances influence the outcome of one or more processes or events. In other words, processes and events in Earth's history are conditional—or contingent—on what happened before. For example, although the chemical reactions themselves involved in weathering have remained the same (based on the Principle of Uniformitarianism), their rates have been affected by the kinds of rocks exposed at Earth's surface (which in turn depends on processes like plate tectonics and mountain building), the presence or absence of land plants (the roots of which accelerate weathering), and the concentration of atmospheric carbon dioxide, which, as we saw above, also affects rates of weathering.

1.6 The Scientific Method and the Study of Earth's Evolving Systems

Many students have been introduced to "the" scientific method, but the scientific method in Earth sciences differs somewhat from that which is normally taught in the classroom. The scientific method as it is used in historical sciences like geology is a recurring theme throughout this book. We first examine the "standard" scientific method and then examine how science is conducted in Earth sciences like geology.

According to the method accepted by most scientists, "proof" in science is based on formulating ideas or explanations called ***hypotheses*** (singular, ***hypothesis***) of how nature works and then *testing* the hypotheses. Formulating hypotheses can result from leaps of imagination (sometimes called the "Eureka!" moment), through intuition, after reading a series of scientific articles, or after long hours of observation and measurement. Once a hypothesis has been formulated, it must be tested. Quite often, testing hypotheses involves monotonous, repetitive measurement and hard work that proceeds slowly and laboriously. The point of formulating and testing a hypothesis is to predict what will happen, based on the hypothesis, and then see if the prediction holds or not. *Prediction is widely viewed as the hallmark of science because if we can predict a particular outcome of a test, then we are satisfied that we understand the processes of cause and effect sufficiently to make the prediction in the first place.* Not surprisingly, then, untestable hypotheses are viewed very skeptically by scientists. If a hypothesis is tested and corroborated, it gains stature as an acceptable explanation of the phenomenon in question. If the predictions are not corroborated, we go back to the drawing board. Perhaps the hypothesis needs to be modified because some of the observations or measurements upon which it is based are incorrect, or perhaps the hypothesis was not tested properly.

Whatever the case, the scientific method is *iterative,* meaning it may have to be repeated. This also means the method is *self-correcting*. In other words, the scientific method feeds back on itself in a kind of feedback loop that is supposed to keep the thinking reasonable and on the right track (**FIGURE 1.16**). Through this process of finding out what *doesn't* work, we presumably come to a better understanding of what *does* work. In other words, scientists attempt to *falsify*

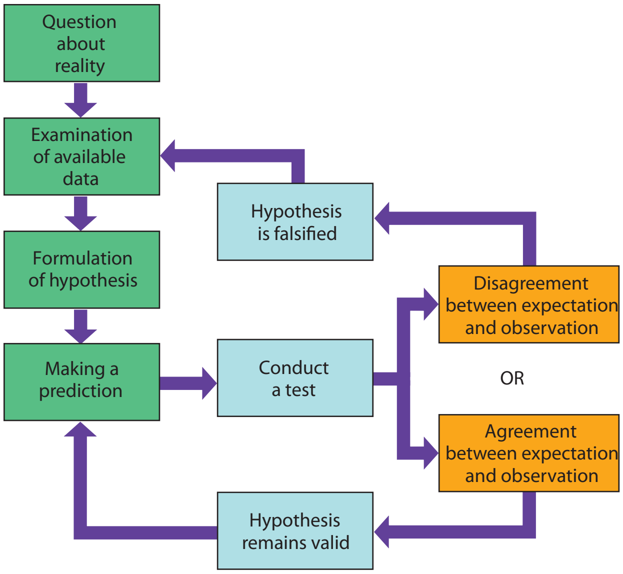


FIGURE 1.16 The iterative process of the scientific method.

everything they can, and whatever is left presumably explains the phenomenon of interest, *at least for the time being*. The development of the modern scientific method as outlined so far is attributed to the 20th century philosopher, Karl Popper. Popper first published his highly influential *The Logic of Scientific Discovery* in 1934. Although philosophers (and some scientists) argue about Popper's approach, it is widely used by scientists. Popper stated that *the best hypotheses are the ones that can be easily falsified* because then one knows for sure that the hypothesis is false and can move on to other hypotheses. However, although the hypotheses that are not falsified gain support, they too may someday be falsified as new data appear or new tests developed, for example by new technologies.

Scientists use the procedures of reasoning called induction and deduction to formulate and test hypotheses. In both procedures scientists essentially construct an argument (or hypothesis) based on *premises*, which may be statements, observations, or measurements, and then draw a *conclusion* from the premises. In ***induction***, the conclusion, although supported by the premises, does not necessarily follow from them. The conclusion of an inductive argument is normally a generalization based on the premises. This is typical of induction: the conclusion contains more information than the premises of the argument. Take the following example:

> Premise: Carbon dioxide is a greenhouse gas (see Figure 1.3).
> Premise: Carbon dioxide is produced by the burning of fossil fuels (see Figure 1.4).
> Premise: The amount of carbon dioxide in the atmosphere is increasing (see Figure 1.4).
> Premise: Earth is warming based on temperature measurements (Figure 1.4).
> Conclusion: Earth is warming because of the burning of fossil fuels.

Most hypotheses are tentative conclusions generated using induction. Once a hypothesis has been generated, it is used to make predictions; this process is called ***deduction***. In deduction the conclusion follows necessarily from the premises. The predictions derived by deduction are usually pretty straightforward, so that we can be sure of what it is that's being tested, how to test it, and get a clear outcome. If the predictions or the tests or both are too complicated, then we cannot be sure about the results when we test a prediction. Take the following example:

> Premise: The swans seen to date are white.
> Premise: The future resembles the past (Principle of Uniformitarianism, which is assumed).
> Conclusion: The next swan I observe will be white.

This *particular* approach to science is best exemplified by experimental sciences such as physics and chemistry. Experiments usually involve a laboratory system (or a field setting) in which all conditions are held constant except one to determine the role of that particular condition, known as a variable, in the system; this makes prediction much easier. Each experiment must be accompanied by what is called a ***control***, which is identical to the other experimental setups, except that none of the conditions is varied. The control allows one to distinguish any other potential change that may have occurred while a particular variable was being manipulated during the experiment. Earth scientists may also use experiments to formulate and test hypotheses about what happens in nature. These experiments may be done in the laboratory (for example, on the melting and crystallization of rocks) or in the field (such as experiments on rates of weathering under different conditions). The results are then applied to understanding the Earth under more complex conditions. So far, this is the scientific method into which students have been indoctrinated.

More often than not, however, geologists use data that already exist in nature and that are the end products of natural processes. Geologists typically test hypotheses by first looking for rocks, sediments, or fossils of the appropriate age—on land, in cores taken in the oceans, or both—and make observations or measurements on the variables of interest. Then, geologists use what some have termed *postdiction* (to distinguish it from *pre*diction), meaning *geologists must frequently reason backward from geologic data such as rocks and fossils to infer the processes that produced what is being observed or measured.* This is why the Principle of Uniformitarianism is so important, because without it we would not be able to justify such a procedure. In fact, if it were not for the assumption of uniformitarianism we could not have made the arguments above about the whiteness of swans or warming by fossil fuel combustion.

Geologists interested in, say, changes in ocean circulation through time might examine deep-sea cores at selected sites where deep currents were hypothesized to change and measure variables—such as changes in the sediment or fossils—that might indicate changes in sediment deposition and erosion, photosynthesis, or water temperature. For example, basic observations (which serve as premises) of modern environments might suggest the following argument:

> Observation: Carbon-rich muds are black in color.
>
> Observation: Carbon-rich muds form under low-oxygen conditions.
>
> Conclusion: Ancient black mud indicates low oxygen conditions.

On the other hand, *it is not uncommon for the geologic record to indicate unusual, perhaps even unique, conditions not observed by humans.* In other words, nature has not always behaved "uniformly" in the sense we normally think of on human time scales; there is ample evidence for highly unusual and perhaps even unique conditions or events that have occurred during Earth's history. This is like observing a black swan when all other swans previously observed were white. Take the following example (refer to Figure 1.15):

> Observation: High concentrations of the element iridium are found in rocks at the end of the Cretaceous Period.
>
> Observation: Iridium is not normally found at Earth's surface but is found in meteorites.
>
> Conclusion: There was an impact at the end of the Cretaceous Period.

When was the last time you observed a meteor impact?

Obviously, there is a greater amount of uncertainty involved in testing most hypotheses in Earth sciences because Earth scientists are less assured of the constancy of conditions in the natural environment through time than in a laboratory. In fact, contrary to popular opinion, science and scientific conclusions are not necessarily black and white, and there is typically a great deal of gray area in which opinions overlap or strong disagreements occur, *based on the same evidence.* Moreover, answers to questions may come in the form of yet deeper questions, even in experimental sciences like physics and chemistry. Thus, more than one explanation may exist for a particular phenomenon or process. Students and nonscientists often find the multiplicity of answers to a single question infuriating and confusing, but this is not unhealthy because it stimulates further research. Remember that scientists attempt to falsify as many explanations as possible, and what is left is the best explanation. If new data or new interpretations of the data come to light, then we may have to question the old "truths" and leave the door open to improved and more complete understanding.

Ideally, scientists are supposed to formulate multiple hypotheses to explain natural phenomena. If scientists favor a "pet" hypothesis over another, they are, according to conventional wisdom, more likely to overlook important phenomena or data bearing on the question of interest. This ***method of multiple working hypotheses*** was proposed in 1897 by the American geologist T. C. Chamberlin. The method of multiple working hypotheses is especially apropos to Earth sciences, in which multiple factors acting on different scales of time may interact to produce a final effect (see discussion of multiple causation above).

However, rather than each scientist formulating multiple hypotheses, what typically happens is that scientists working on a particular research problem tend to form "social" groups that favor a particular hypothesis. Although this is perhaps undesirable and may seem odd, it is understandably human. Each scientist has had different training and different experiences than others, so it is not surprising if each one brings different viewpoints to a problem and different ways of thinking about it and attempting to solve it. Those with similar viewpoints on a particular question tend to proceed by *consensus,* more or less mutual agreement. Very importantly, however, different parties or individuals may strongly disagree with the consensus on a particular question; "group think" may therefore stifle independent thought and scientific research. In fact we are far from knowing everything there is to know about Earth and its history. If this were true, we would not have the multiplicity of hypotheses about certain events and processes on Earth!

As we will also see, the "experts" have frequently been wrong. In future chapters, for example, we examine how the hypothesis of "continental drift" was formulated about 1915. This hypothesis was constructed using an inductive argument, the premises of which were the "jigsaw" fit of the continents and matching rocks and fossils on continents now located on opposite sides of the Atlantic Ocean. From these premises it was concluded by Alfred Wegener that the continents must have originally been joined together into a larger supercontinent named Pangea ("all land"; **FIGURE 1.17**).

It was this hypothesis that would ultimately lead to the theory of plate tectonics. Wegener's observations (premises) were as follows:

> Observation: Freshwater reptiles belonging to the same groups are found as fossils in Africa and South America.
>
> Observation: These reptiles could not have swum across the Atlantic Ocean.
>
> Observation: Similar sequences of rocks are found on either side of the Atlantic Ocean.
>
> Observation: Similar structural features (or deformations) in Earth's crust are seen on either side of the Atlantic.
>
> Observation: These features match when the continents are moved together.
>
> Conclusion: The continents were once united into a larger supercontinent.

However, in 1915 there was no known force (which we now know to be related to convection cells and seafloor spreading) that moved the continents. As a result, almost all other scientists rejected the hypothesis. Not until the second half of the 20th century did scientists begin to obtain data that indicated the existence of convection cells deep within the Earth and their role in driving plate tectonics and the movement of the continents.

Thus, if a particular hypothesis survives repeated testing, several things may happen. First, as the hypothesis is tested and confirmed over time it may come to be elevated to the status of a ***theory***. As noted above, the hypothesis of continental drift was only corroborated many years after its formulation by other observations. Then, the hypothesis began to be regarded as part of a larger theory now called plate tectonics. The value of a theory, like the theory of plate tectonics, is that it takes observations and data and synthesizes them into a more coherent, explanatory picture. Hutton's *Theory of the Earth* and Lyell's *Principles of Geology* are examples of geologic theory. The prime value of a theory is that it suggests further hypotheses and tests to substantiate or refute the theory; thus, a theory may be modified, as was Lyell's original view of uniformitarianism, or even overturned. Another way in which theory develops is when scientists formulate conceptual frameworks that produce hypotheses that can be tested. This kind of theory may originate as "thought experiments" in a scientist's mind when they imagine "What if. . . . ?".

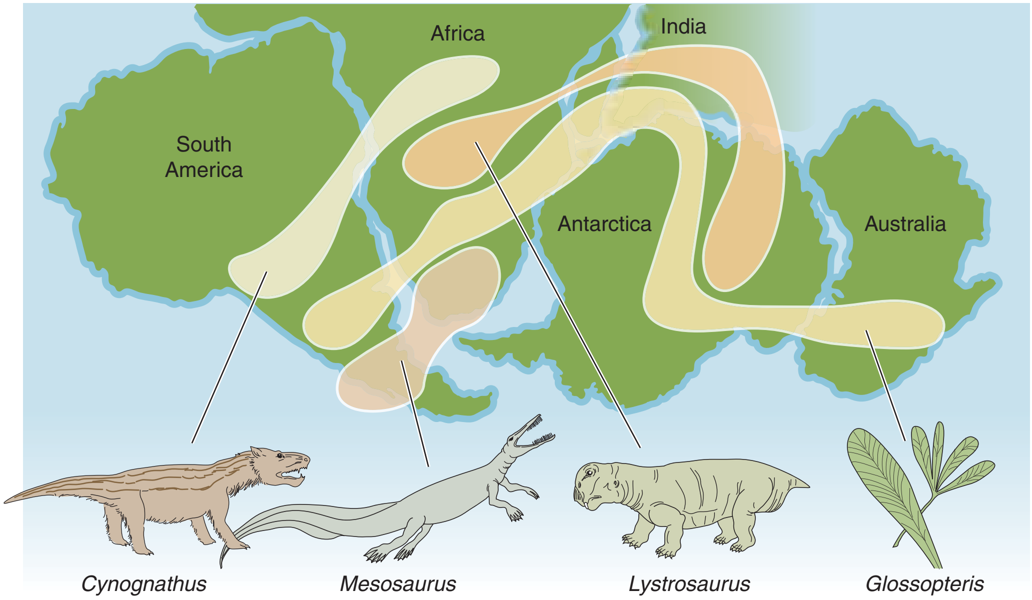


FIGURE 1.17 The hypothesis of continental drift was based on the "jigsaw" fit of the continents and matching rocks and fossils on continents now located on opposite sides of the Atlantic Ocean. [Adapted from: Colbert, C. H. 1973. *Wandering Lands and Animals.* London: Hutchinson & Company.]

In either case the formulation of a theory represents a scientifically valid approach. If a scientific relationship is called a theory, there must be a reason. Thus, one must be wary when they hear phrases like "it's only a theory" or "it's just theoretical." What are the data for the theory? Have hypotheses stemming from the theory been tested and corroborated?

More much certain relationships between phenomena, which are considered fundamental truths, are called ***laws***. Laws are frequently descriptive. Sir Isaac Newton's laws of motion, which can be used to predict eclipses and planetary movements both in the future and the past, are examples of laws. Partly because of the power of these laws, Newton is often considered the quintessential scientist of all time. For a relationship to be a law, it must be repeatable and hold under a variety of conditions. Newton's laws of motion hold, for example, in other solar systems; otherwise, they would not be laws. Thus, laws are *abstractions*. They tell us what is supposed to happen, irrespective of other factors such as contingency or historical circumstances.

By contrast, Earth scientists deal with history, which is about changing conditions through time. Even if history does seem to repeat itself, the conditions are never *exactly* the same because of contingency. So, instead of laws Earth scientists tend to rely on theory, usually backed up by observation and measurement, and, to a lesser extent, experiment. Instead of laws, general truths in geology are usually referred to as ***principles***. A principle is like a good "rule of thumb" because it may have some exceptions, whereas laws are supposed to be invariable. The Principles of Superposition and Uniformitarianism are examples. Superposition typically holds unless, for example, rocks have been overturned by mountain building and their order from top to bottom is reversed.

Despite this outline of basic method, most scientists don't go around thinking continuously about using the scientific method; their thinking is typically much, much looser than that. Instead, scientists tend to look primarily for two things: (1) phenomena that require explanation (i.e., a "good" research question or problem) and (2) ways to test hypotheses or explain phenomena. As you proceed through the text, you should be aware of how hypotheses or theories have been arrived at and tested in Earth sciences. Scientific "reasoning" is a bit like a road map. The scientists get in the car and go. The road serves as the "method" or, perhaps more accurately, the "technique" the scientist uses to make measurements and observations, with the scientist following it to wherever it leads. Curiosity (and typically the availability of research funding) fuels the drive. Sometimes the scientist has an idea (prediction) of where he or she should wind up (village, town, city, etc.). Other times, scientists may take on a "road trip" (kind of like John Steinbeck's *Travels with Charley*), not knowing where they will wind up and what they will find (although this seems less common today because of the emphasis on the funding for particular projects). If a prediction (town, city, etc.) has multiple routes converging on it, different scientists following different roads (techniques) may converge on the same prediction (town, city) or they may not (perhaps they made a wrong turn somewhere that leads to the wrong place or a dead end). In the latter case, the scientists may pull over to the side of the road and reexamine the map or (like some people) they may keep driving, insisting they are really on the right road and if they just keep going, they will eventually get to wherever it is they want to go.

Concept and Reasoning Check

1. How does the science of geology resemble or differ from other sciences with regard to processes and their rates, experimental versus natural conditions, causation, contingency, and laws?

1.7 Summary

- Earth's climate has influenced human civilization for thousands of years and will continue to do so in the future. During the 20th century the expanding human population, agriculture, and industrialization all began to significantly affect Earth's environments. The view among scientists that human activities are dramatically impacting Earth's climate and biota led to the science of Earth systems.
- A system is a series of parts or compartments that comprise a larger integrated whole. The major Earth systems are the solid Earth, atmosphere, hydrosphere, and biosphere. Each system is an open system characterized by the cyclic flow of matter and energy.
- Earth's systems interact with one another through positive and negative feedback to maintain a relatively constant environment. Positive feedback promotes an effect, whereas negative feedback counters an effect.

- Earth scientists use the same basic approach as other scientists in seeking cause and effect relationships: the Principle of Uniformitarianism.
- Many Earth processes have largely remained the same through time, acting imperceptibly, whereas other processes have acted suddenly and catastrophically, such as extraterrestrial impacts. In fact, there has been plenty of time for both slow processes and unusual ones to have caused enormous change on Earth.
- Earth has not existed strictly in an equilibrium state of no net change through time. Earth has evolved, and its history exhibits secular change, or directionality.
- Given the variety of processes that occur over long spans of time, geologists and other Earth scientists typically cannot reduce the scientific study of Earth's systems to simple cause and effect relationships like those observed in controlled laboratory settings.
- We really cannot understand all processes of Earth or humankind's rapid impact on Earth's environments without understanding Earth's geologic record and processes that occur on different scales of time.

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Key Terms

absolute age
actualism
analog
anthropogenic
atmosphere
biogeochemical cycle
biosphere
catastrophism
contingency
control
convection cells
crust
cryosphere
deduction
determinism
directionality (secular change)
equilibrium
evolution
Faunal Succession, Principle of
feedback
flux
geologic time
geology
greenhouse gas
historical science
hydrosphere
hypothesis
induction
law
mass extinctions
method of multiple working hypotheses
multiple causation
Ockham's Razor (Principle of Parsimony)
open system
plate tectonics
principle
radioactive decay
reductionism
relative age
reservoir
solid Earth system
stratified
Superposition, Principle of
system
theory
Uniformitarianism, Principle of
weathering

Review Questions

1. What are the four basic Earth systems?
2. What are the basic characteristics of a natural system?
3. Diagram the flow of matter and energy that occurs in the atmosphere, lithosphere, biosphere, and hydrosphere.
4. How do each of Earth's systems interact to control atmospheric carbon dioxide on geologic scales of time?
5. How does the biosphere regulate atmospheric carbon dioxide on different scales of time?
6. Describe positive and negative feedback. Give examples using Earth's systems.
7. Give examples of how life has acted as a geologic force.
8. What is meant by the term "geologic time"?
9. Why is the Principle of Uniformitarianism important to the study of Earth's systems?
10. How does the modern view of uniformitarianism differ from that of Lyell's?
11. What is the importance of the following to the history of Earth's systems: (a) contingency and (b) directionality.
12. What are some key reasons for studying the history of Earth?

Food for Thought

1. Do you believe the Earth is in equilibrium? Why or why not?
2. Why do you suppose the measurements of Figure 1.4B were taken in Hawaii?
3. As described in the text, the impact of anthropogenic activities on Earth greatly accelerated during the 20th century. Based on absolute ages, Earth is about 5 billion years old. To get some idea of how fast anthropogenic impacts have occurred, calculate the percentage of Earth's existence represented by the 20th century.
4. Assume that anthropogenic carbon dioxide emissions actually cause global warming. Are there any plausible negative feedback mechanisms that would decrease atmospheric carbon dioxide in coming decades that would keep atmospheric carbon dioxide at relatively constant levels?
5. Distinguish between the different meanings that have been given to the term "uniformitarianism."
6. Are microscopic organisms necessarily insignificant in the regulation of Earth's systems? Give an example.
7. What is a control and why is it important to a laboratory experiment? How can "natural" conditions recorded in rocks and sediments serve as controls?
8. James Hutton likened the Earth to a machine, whereas some later workers have likened it to a giant organism. Is one of these descriptions better than the other? Why?
9. Distinguish between laws as they are used in experimental sciences and the use of principles like those used in geology.

Yellowstone Gorge, Yellowstone National Park, Wyoming. The bright colors of the rocks result from lava flows and ash falls.