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The strata exposed in Arizona’s Grand Canyon contain clues to hundreds of millions of years of Earth history. (Photo © by Carr Clifton)
In the eighteenth century, James Hutton recognized the immensity of Earth history and the importance of time as a component in all geological processes. In the nineteenth century, others effectively demonstrated that Earth had experienced many episodes of mountain building and erosion, which must have required great spans of geologic time. Although these pioneering scientists understood that Earth was very old, they had no way of knowing its true age. Was it tens of millions, hundreds of millions, or even billions of years old? Rather, a geologic time scale was developed that showed the sequence of events based on relative dating principles. What are these principles? What part do fossils play? With the discovery of radioactivity and the development of radiometric dating techniques, geologists now can assign fairly accurate dates to many of the events in Earth history. What is radioactivity? Why is it a good “clock” for dating the geologic past? In this chapter we shall answer these questions.

Geology Needs a Time Scale

In 1869 John Wesley Powell, who was later to head the U.S. Geological Survey, led a pioneering expedition down the Colorado River and through the Grand Canyon (Figure 10.1). Writing about the rock layers that were exposed by the downcutting of the river, Powell said that “the canyons of this region would be a Book of Revelations in the rock-leaved Bible of geology.” He was undoubtedly impressed with the millions of years of Earth history exposed along the walls of the Grand Canyon (see chapter-opening photo).

Powell realized that the evidence for an ancient Earth is concealed in its rocks. Like the pages in a long and complicated history book, rocks record the geological events and changing life forms of the past. The book, however, is not complete. Many pages, especially in the early chapters, are missing. Others are tattered, torn, or smudged. Yet enough of the book remains to allow much of the story to be deciphered.

Interpreting Earth history is a prime goal of the science of geology. Like a modern-day sleuth, the geologist must interpret clues found preserved in the rocks. By studying rocks, especially sedimentary rocks, and the features they contain, geologists can unravel the complexities of the past.

Geological events by themselves, however, have little meaning until they are put into a time perspective. Studying history, whether it be the Civil War or the Age of Dinosaurs, requires a calendar. Among geology’s major contributions to human knowledge is the geologic time scale and the discovery that Earth history is exceedingly long.

The geologists who developed the geologic time scale revolutionized the way people think about time and how they perceive our planet. They learned that Earth is much older than anyone had previously imagined and that its surface and interior have been changed.

Figure 10.1  A. Start of the expedition from Green River station. A drawing from Powell’s 1875 book. B. Major John Wesley Powell, pioneering geologist and the second director of the U.S. Geological Survey. (Courtesy of the U.S. Geological Survey, Denver)
over and over again by the same geological processes that operate today.

A Brief History of Geology

In the mid-1600s, James Ussher, Anglican Archbishop of Armagh, Primate of all Ireland, published a work that had immediate and profound influence on people’s view of Earth’s age. 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 seventeenth and eighteenth centuries the doctrine of catastrophism strongly influenced people’s thinking about Earth. Briefly stated, catastrophists believed that Earth’s landscapes had been developed 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 triggered by unknowable causes that no longer operate. This philosophy was an attempt to fit the rate of Earth processes to the prevailing ideas on the age of Earth.

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. 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” (see Box 10.1).

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 weak, slow-acting processes could, over long spans of time, produce effects just as great as those resulting from sudden catastrophic events. Unlike his predecessors, Hutton carefully cited verifiable observations to support his ideas.

UNDERSTANDING EARTH: Deciphering the Past by Understanding the Present

Louis Agassiz, a Swiss scientist born in 1807, was instrumental in formulating modern ideas about the Ice Age (Figure 10.A). The development of this knowledge provides an excellent example of the application of the principle of uniformitarianism.

In 1821 Agassiz heard another scientist present a paper in which he indicated that glacial features occurred in places that were a significant distance from existing glaciers in the Alps. This, of course, implied that the glaciers had once occupied areas considerably beyond their present limits. Agassiz was skeptical about this hypothesis and set out to invalidate it. Ironically, his fieldwork in the Alps convinced him of the merits of his colleague’s hypothesis. Agassiz found the same unique deposits and features that can be seen forming in association with active glaciers in places far beyond the limits of the ice. Subsequent work led Agassiz to hypothesize that a great ice age had occurred in response to a period of worldwide climate change and had affected large parts of the globe. Agassiz’s ideas eventually developed into our present-day glacial theory.

The proof of the glacial theory proposed by Agassiz and others constitutes a classic example of applying the principle of uniformitarianism. Realizing that certain landforms and other features are produced by no other known process but glacial activity, they were able to reconstruct the extent of now vanished ice sheets. Clearly, understanding the present was the key to deciphering the past.
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 demonstrates 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.”

**Geology Today**

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 geological 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’s processes vary in intensity, they still take a very long time to create or destroy major landscape features. 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 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 300 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 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.”

It is important to remember that although many features of our physical landscape may seem to be unchanging over our lifetimes, they are nevertheless changing, but on time scales of hundreds, thousands, or even many millions of years.

### Relative Dating—Key Principles

During the late 1800s and early 1900s, various attempts were made to determine the age of Earth. Although some of the methods appeared promising at the time, none proved reliable. What these scientists were seeking was a numerical date. Such dates specify the actual number of years that have passed since an event occurred—for example, the extinction of the dinosaurs about 65 million years ago. Today our understanding of radioactivity allows us to accurately determine numerical dates for rocks that represent important events in Earth’s distant past. We will study radioactivity later in this chapter. Prior to the discovery of radioactivity, geologists had no accurate and dependable method of numerical dating and had to rely solely on relative dating.

**Relative dating** means placing rocks in their proper sequence of formation—which ones formed first, second, third, and so on. Relative dating cannot tell us how long ago something took place, only that it followed one event and preceded another. The relative dating techniques that were developed are valuable and still widely used. Numerical dating methods did not replace these techniques; they simply supplemented them. To establish a relative time scale, a few basic principles or rules had to be discovered and applied. Although they may seem obvious to us today, they were major breakthroughs in thinking at the time, and their discovery and acceptance was an important scientific achievement.

### Students Sometimes Ask...

You mentioned early attempts at determining Earth’s age that proved unreliable. How did nineteenth-century scientists go about making such calculations?

One method that was attempted several times involved the rate at which sediment is deposited. Some reasoned that if they could determine the rate that sediment accumulates and could further ascertain the total thickness of sedimentary rock that had been deposited during Earth history, they could estimate the length of geologic time. All that was necessary was to divide the rate of sediment accumulation into the total thickness of sedimentary rock.

Estimates of Earth’s age varied each time this method was attempted. The age of Earth as calculated by this method ranged from 3 million to 1.5 billion years! Obviously this method was riddled with difficulties. Can you suggest what some might have been?
Law of Superposition
Nicolaus Steno, a Danish anatomist, geologist, and priest (1636–1686), is credited with being the first to recognize a sequence of historical events in an outcrop of sedimentary rock layers. Working in the mountains of western Italy, Steno applied a very simple rule that has come to be the most basic principle of relative dating—the law of superposition. The law simply states that in an undeformed sequence of sedimentary rocks, each bed is older than the one above it and younger than the one below. Although it may seem obvious that a rock layer could not be deposited unless it had something older beneath it for support, it was not until 1669 that Steno clearly stated the principle.

This rule also applies to other surface-deposited materials, such as lava flows and beds of ash from volcanic eruptions. Applying the law of superposition to the beds exposed in the upper portion of the Grand Canyon (Figure 10.2), you can easily place the layers in their proper order. Among those that are shown, the sedimentary rocks in the Supai Group must be the oldest, followed in order by the Hermit Shale, Coconino Sandstone, Toroweap Formation, and Kaibab Limestone.

Principle of Original Horizontality
Steno is also credited with recognizing the importance of another basic principle, called the principle of original horizontality. Simply stated, it means that layers of sediment are generally deposited in a horizontal position. Thus, if we observe rock layers that are flat, it means they have not been disturbed and thus still have their original horizontality. The layers in the Grand Canyon illustrate this in the chapter-opening photo and in Figure 10.2. But if they are folded or inclined at a steep angle, they must have been moved into that position by crustal disturbances sometime after their deposition (Figure 10.3).

Principle of Cross-Cutting Relationships
When a fault cuts through other rocks, or when magma intrudes and crystallizes, we can assume that the fault or intrusion is younger than the rocks affected. For example, in Figure 10.4, the faults and dikes clearly must have occurred after the sedimentary layers were deposited.

This is the principle of cross-cutting relationships. By applying the cross-cutting principle, you can see that fault A occurred after the sandstone layer was deposited, because it “broke” the layer. However, fault A occurred before the conglomerate was laid down, because that layer is unbroken.

We can also state that dike B and its associated sill are older than dike A, because dike A cuts the sill. In the same manner, we know that the batholith was emplaced after movement occurred along fault B, but before dike B was formed. This is true because the batholith cuts across fault B, and dike B cuts across the batholith.

Inclusions
Sometimes inclusions can aid the relative dating process. Inclusions are pieces of one rock unit that are contained within another. The basic principle is logical and straightforward. The rock mass adjacent to the one containing the inclusions must have been there first in order to provide the rock fragments. Therefore, the rock...
mass containing inclusions is the younger of the two. Figure 10.5 provides an example. Here the inclusions of intrusive igneous rock in the adjacent sedimentary layer indicate that the sedimentary layer was deposited on top of a weathered igneous mass rather than being intruded from below by magma that later crystallized.

Unconformities
When we observe layers of rock that have been deposited essentially without interruption, we call them conformable. Particular sites exhibit conformable beds representing certain spans of geologic time. However, no place on Earth has a complete set of conformable strata.

Throughout Earth history, the deposition of sediment has been interrupted again and again. All such breaks in the rock record are termed unconformities. An unconformity represents a long period during which deposition ceased, erosion removed previously formed rocks, and then deposition resumed. In each case uplift and erosion are followed by subsidence and renewed sedimentation. Unconformities are important features because they represent significant geologic events in Earth history. Moreover, their recognition helps us identify what intervals of time are not represented by strata and thus are missing from the geologic record.

The rocks exposed in the Grand Canyon of the Colorado River represent a tremendous span of geologic history. It is a wonderful place to take a trip through time. The canyon’s colorful strata record a long history of sedimentation in a variety of environments—advancing seas, rivers and deltas, tidal flats, and sand dunes. But the record is not continuous. Unconformities represent
An angular unconformity indicates that during the pause in deposition, a period of deformation (folding or tilting) and erosion occurred (Figure 10.7).

When James Hutton studied an angular unconformity in Scotland more than 200 years ago, it was clear to him that it represented a major episode of geologic activity (Figure 10.7E). He also appreciated the immense time span implied by such relationships. When a companion later wrote of their visit to the site, he stated that “the mind seemed to grow giddy by looking so far into the abyss of time.”

**Disconformity.** When contrasted with angular unconformities, disconformities are more common, but usually far less conspicuous because the strata on either side are essentially parallel. For example, look at the disconformities in the cross section of the Grand Canyon in Figure 10.6. Many disconformities are difficult to identify because the rocks above and below are similar and there is little evidence of erosion. Such a break often resembles an ordinary bedding plane. Other disconformities are easier to identify because the ancient erosion surface is cut deeply into the older rocks below.

**Nonconformity.** The third basic type of unconformity is a nonconformity. Here the break separates older metamorphic or intrusive igneous rocks from younger sedimentary strata (Figures 10.5 and 10.6). Just as angular unconformities and disconformities imply crustal movements, so too do nonconformities. Intrusive igneous masses and metamorphic rocks originate far below the surface. Thus, for a nonconformity to develop, there must be a period of uplift and the erosion of overlying rocks. Once exposed at the surface, the igneous or metamorphic rocks are subjected to weathering and erosion prior to subsidence and the renewal of sedimentation.

Using Relative Dating Principles

If you apply the principles of relative dating to the hypothetical geologic cross section in Figure 10.8 (p. 294), you can place in proper sequence the rocks and the events they represent. The statements within the figure summarize the logic used to interpret the cross section.

In this example, we establish a relative time scale for the rocks and events in the area of the cross section. Remember that this method gives us no indication as to how many years of Earth history are represented, for we have no numerical dates. Nor do we know how this area compares to any other.

Correlation of Rock Layers

To develop a geologic time scale that is applicable to the entire Earth, rocks of similar age in different regions must be matched up. Such a task is referred to as correlation.
Within a limited area, correlating the rocks of one locality with those of another may be done simply by walking along the outcropping edges. However, this might not be possible when the rocks are mostly concealed by soil and vegetation. Correlation over short distances is often achieved by noting the position of a distinctive rock layer in a sequence of strata. Or, a layer may be identified in another location if it is composed of very distinctive or uncommon minerals.

By correlating the rocks from one place to another, a more comprehensive view of the geologic history of a region is possible. Figure 10.9, for example, shows the correlation of strata at three sites on the Colorado Plateau in southern Utah and northern Arizona. No single locale exhibits the entire sequence, but correlation reveals a more complete picture of the sedimentary rock record.

Many geologic studies involve relatively small areas. Such studies are important in their own right, but their full value is realized only when the rocks are correlated with those of other regions. Although the methods just described are sufficient to trace a rock formation over relatively short distances, they are not adequate for matching rocks that are separated by great distances. When correlation between widely separated areas or between continents is the objective, geologists must rely on fossils.

**Fossils: Evidence of Past Life**

Fossils, the remains or traces of prehistoric life, are important inclusions in sediment and sedimentary rocks. They are important tools for interpreting the geologic past. Knowing the nature of the life forms that existed at a particular time helps researchers understand past environmental conditions. Further, fossils are important time indicators and play a key role in correlating rocks of similar ages that are from different places.

**Types of Fossils**

Fossils are of many types. The remains of relatively recent organisms may not have been altered at all. Such objects as teeth, bones, and shells are common exam-
Far less common are entire animals, flesh included, that have been preserved because of rather unusual circumstances. Remains of prehistoric elephants called mammoths that were frozen in the Arctic tundra of Siberia and Alaska are examples, as are the mummified remains of sloths preserved in a dry cave in Nevada.

Given enough time, the remains of an organism are likely to be modified. Often fossils become petrified (literally, “turned into stone”), meaning that the small internal cavities and pores of the original structure are filled with precipitated mineral matter (Figure 10.10A, p. 296). In other instances replacement may occur. Here the cell walls and other solid material are removed and replaced with mineral matter. Sometimes the microscopic details of the replaced structure are faithfully retained.

Molds and casts constitute another common class of fossils. When a shell or other structure is buried in sediment and then dissolved by underground water, a mold is created. The mold faithfully reflects only the shape and surface marking of the organism; it does not reveal any information concerning its internal structure. If these hollow spaces are subsequently filled with mineral matter, casts are created (Figure 10.10B).

A type of fossilization called carbonization is particularly effective in preserving leaves and delicate animal forms. It occurs when fine sediment encases the remains of an organism. As time passes, pressure squeezes out the liquid and gaseous components and leaves behind a thin residue of carbon (Figure 10.10C). Black shales deposited as organic-rich mud in oxygen-poor environments often contain abundant carbonized remains. If the film of carbon is lost from a fossil preserved in fine-grained sediment, a replica of the surface, called an impression, may still show considerable detail (Figure 10.10D).

Delicate organisms, such as insects, are difficult to preserve, and consequently they are relatively rare in the fossil record. Not only must they be protected from decay but they must not be subjected to any pressure that would crush them. One way in which some insects have been preserved is in amber, the hardened resin of ancient trees. The fly in Figure 10.10E was preserved after being trapped in a drop of sticky resin. Resin sealed off the insect from the atmosphere and protected the remains from damage by water and air. As the resin hardened, a protective pressure-resistant case was formed.

In addition to the fossils already mentioned, there are numerous other types, many of them only traces of prehistoric life. Examples of such indirect evidence include:

1. Tracks—animal footprints made in soft sediment that was later lithified (Figure 10.10F).
2. Burrows—tubes in sediment, wood, or rock made by an animal. These holes may later become filled with mineral matter and preserved. Some of the oldest-known fossils are believed to be worm burrows.
Following the intrusion of sill D, the intrusion of dike F occurred. Because the dike cuts through beds A through E, it must be younger than all of them (principle of cross-cutting relationships). Further evidence that sill D is younger than beds C and E are the inclusions (arrows) in the sill of fragments from these beds. If this igneous mass contains pieces of adjacent strata, then the adjacent strata must have been there first. Applying the law of superposition, beds A, B, C, and E were deposited in that order. Finally, the irregular surface indicates that another gap in the rock record is being produced by erosion. Beds, G, H, I, J, and K were deposited in that order, again using the law of superposition. Although the lava flow (bed H) is not a sedimentary rock layer, it is a surface-deposited layer, and thus superposition may be applied. Next, the rocks were tilted and eroded. The tilting happened first because the upturned ends of the strata have been eroded. The tilting and erosion, followed by further deposition, produced an angular unconformity.

**Figure 10.8** Geologic cross section of a hypothetical region.

3. Coprolites—fossil dung and stomach contents that can provide useful information pertaining to food habits of organisms.
4. Gastroliths—highly polished stomach stones that were used in the grinding of food by some extinct reptiles.

**Conditions Favoring Preservation**

Only a tiny fraction of the organisms that have lived during the geologic past have been preserved as fossils. Normally the remains of an animal or plant are destroyed. Under what circumstances are they preserved? Two special conditions appear to be necessary: rapid burial and the possession of hard parts.

When an organism perishes, its soft parts usually are quickly eaten by scavengers or decomposed by bacteria. Occasionally, however, the remains are buried by sediment. When this occurs, the remains are protected from the environment, where destructive processes operate. Rapid burial therefore is an important condition favoring preservation.

In addition, animals and plants have a much better chance of being preserved as part of the fossil record if they have hard parts. Although traces and imprints of soft-bodied animals such as jellyfish, worms, and insects exist, they are not common. Flesh usually decays so rapidly that preservation is exceedingly unlikely. Hard parts such as shells, bones, and teeth predominate in the record of past life.
Because preservation is contingent on special conditions, the record of life in the geologic past is biased. The fossil record of those organisms with hard parts that lived in areas of sedimentation is quite abundant. However, we get only an occasional glimpse of the vast array of other life forms that did not meet the special conditions favoring preservation.

**Fossils and Correlation**

The existence of fossils had been known for centuries, yet it was not until the late 1700s and early 1800s that their significance as geologic tools was made evident. During this period an English engineer and canal builder, William Smith, discovered that each rock formation in the canals he worked on contained fossils unlike those in the beds either above or below. Further, he noted that sedimentary strata in widely separated areas could be identified and correlated by their distinctive fossil content.

Based on Smith’s classic observations and the findings of many geologists who followed, one of the most important and basic principles in historical geology was formulated: *Fossil organisms succeed one another in a definite and determinable order, and therefore any time period*
Figure 10.10  There are many types of fossilization. Six examples are shown here. A. Petrified wood in Petrified Forest National Park, Arizona. B. Natural casts of shelled invertebrates. C. A fossil bee preserved as a thin carbon film. D. Impressions are common fossils and often show considerable detail. E. Insect in amber. F. Dinosaur footprint in fine-grained limestone near Tuba City, Arizona. (Photo A by David Muench; Photos B, D, and F by E. J. Tarbuck; Photo C courtesy of the National Park Service; Photo E by Breck P. Kent)
can be recognized by its fossil content. This has come to be known as the principle of fossil succession. In other words, when fossils are arranged according to their age by applying the law of superposition to the rocks in which they are found, they do not present a random or haphazard picture. To the contrary, fossils show changes that document the evolution of life through time.

For example, an Age of Trilobites is recognized quite early in the fossil record. Then, in succession, paleontologists recognize an Age of Fishes, an Age of Coal Swamps, an Age of Reptiles, and an Age of Mammals. These “ages” pertain to groups that were especially plentiful and characteristic during particular time periods. Within each of the ages, there are many subdivisions based, for example, on certain species of trilobites and certain types of fish, reptiles, and so on. This same succession of dominant organisms, never out of order, is found on every continent.

Once fossils were recognized as time indicators, they became the most useful means of correlating rocks of similar age in different regions. Geologists pay particular attention to certain fossils called index fossils. These fossils are widespread geographically and are limited to a short span of geologic time, so their presence provides an important method of matching rocks of the same age. Rock formations, however, do not always contain a specific index fossil. In such situations, groups of fossils are used to establish the age of the bed. Figure 10.11 illustrates how an assemblage of fossils can be used to date rocks more precisely than could be accomplished by the use of only one of the fossils.

In addition to being important and often essential tools for correlation, fossils are important environmental indicators. Although much can be deduced about past environments by studying the nature and characteristics of sedimentary rocks, a close examination of any fossils present can usually provide a great deal more information.

For example, when the remains of certain clam shells are found in limestone, the geologist can assume that the region was once covered by a shallow sea, because that is where clams live today. Also, by using what we know of living organisms, we can conclude that fossil animals with thick shells capable of withstanding pounding and surging waves must have inhabited shorelines. Conversely, animals with thin, delicate shells probably indicate deep, calm offshore waters. Hence, by looking closely at the types of fossils, the approximate position of an ancient shoreline may be identified.

**Figure 10.11** Overlapping ranges of fossils help date rocks more exactly than using a single fossil.
Further, fossils can indicate the former temperature of the water. Certain present-day corals require warm and shallow tropical seas like those around Florida and the Bahamas. When similar corals are found in ancient limestones, they indicate that a Florida-like marine environment must have existed when the corals were alive. These examples illustrate how fossils can help unravel the complex story of Earth history.

**Dating with Radioactivity**

In addition to establishing relative dates by using the principles described in the preceding sections, it is also possible to obtain reliable numerical dates for events in the geologic past. For example, we know that Earth is about 4.5 billion years old and that the dinosaurs became extinct about 65 million years ago. Dates that are expressed in millions and billions of years truly stretch our imagination because our personal calendars involve time measured in hours, weeks, and years. Nevertheless, the vast expanse of geologic time is a reality, and it is radiometric dating that allows us to measure it. In this section you will learn about radioactivity and its application in radiometric dating.

**Reviewing Basic Atomic Structure**

Recall from Chapter 1 that each atom has a nucleus containing protons and neutrons and that the nucleus is orbited by electrons. Electrons have a negative electrical charge, and protons have a positive charge. A neutron is actually a proton and an electron combined, so it has no charge (it is neutral).

The atomic number (each element’s identifying number) is the number of protons in the nucleus. Every element has a different number of protons and thus a different atomic number (hydrogen = 1, carbon = 6, oxygen = 8, uranium = 92, etc.). Atoms of the same element always have the same number of protons, so the atomic number stays constant.

Practically all of an atom’s mass (99.9%) is in the nucleus, indicating that electrons have virtually no mass at all. So, by adding the protons and neutrons in an atom’s nucleus, we derive the atom’s mass number. The
number of neutrons can vary, and these variants, or isotopes, have different mass numbers.

To summarize with an example, uranium’s nucleus usually has 92 protons, so its atomic number always is 92. But its neutron population varies, so uranium has three isotopes: uranium-234 \((\text{mass of protons + neutrons} = 234)\), uranium-235, and uranium-238. All three isotopes are mixed in nature. They look the same and behave the same in chemical reactions.

**Radioactivity**

The forces that bind protons and neutrons together in the nucleus usually are strong. However, in some isotopes, the nuclei are unstable because the forces binding protons and neutrons together are not strong enough. As a result, the nuclei spontaneously break apart (decay), a process called radioactivity.

What happens when unstable nuclei break apart? Three common types of radioactive decay are illustrated in Figure 10.12, and are summarized as follows:

1. Alpha particles (\(\alpha\) particles) may be emitted from the nucleus. An alpha particle consists of 2 protons and 2 neutrons. Consequently, the emission of an alpha particle means that the mass number of the isotope is reduced by 4 and the atomic number is decreased by 2.

2. When a beta particle (\(\beta\) particle), or electron, is given off from a nucleus, the mass number remains unchanged, because electrons have practically no mass. However, because the electron has come from a neutron (remember, a neutron is a combination of a proton and an electron), the nucleus contains one more proton than before. Therefore, the atomic number increases by 1.

3. Sometimes an electron is captured by the nucleus. The electron combines with a proton and forms an additional neutron. As in the last example, the mass number remains unchanged. However, as the nucleus now contains one less proton, the atomic number decreases by 1.

An unstable (radioactive) isotope of an element is called the parent. The isotopes resulting from the decay of the parent are the daughter products. Figure 10.13 provides an example of radioactive decay. Here it can be seen that when the radioactive parent, uranium-238 (atomic number 92, mass number 238), decays, it follows a number of steps, emitting 8 alpha particles and 6 beta particles before finally becoming the stable daughter product lead-206 (atomic number 82, mass number 206). One of the unstable daughter products produced during this decay series is radon. Box 10.2 examines the hazards associated with this radioactive gas.

Certainly among the most important results of the discovery of radioactivity is that it provided a reliable means of calculating the ages of rocks and minerals that contain particular radioactive isotopes. The procedure is called radiometric dating. Why is radiometric dating reliable? Because the rates of decay for many isotopes have been precisely measured and do not vary under the physical conditions that exist in Earth’s outer layers. Therefore, each radioactive isotope used for dating has been decaying at a fixed rate since the formation of the rocks in which it occurs, and the products of decay have been accumulating at a corresponding rate. For example, when uranium is incorporated into a mineral that crystallizes from magma, there is no lead (the stable daughter product) from previous decay. The radiometric “clock” starts at this point. As the uranium in this newly formed mineral disintegrates, atoms of the daughter product are trapped, and measurable amounts of lead eventually accumulate.

**Half-Life**

The time required for one half of the nuclei in a sample to decay is called the half-life of the isotope. Half-life is a common way of expressing the rate of radioactive disintegration. Figure 10.14 illustrates what occurs when a radioactive parent decays directly into its stable daughter product. When the quantities of parent and daughter are equal (ratio 1:1), we know that one half-life has transpired. When one-quarter of the original parent...
atoms remain and three-quarters have decayed to the daughter product, the parent/daughter ratio is 1:3 and we know that two half-lives have passed. After three half-lives, the ratio of parent atoms to daughter atoms is 1:7 (one parent for every seven daughter atoms).

If the half-life of a radioactive isotope is known and the parent/daughter ratio can be measured, the age of the sample can be calculated. For example, assume that the half-life of a hypothetical unstable isotope is 1 million years and the parent/daughter ratio in a sample is 1:15. Such a ratio indicates that four half-lives have passed and that the sample must be 4 million years old.

Radiometric Dating

Notice that the percentage of radioactive atoms that decay during one half-life is always the same: 50 percent. However, the actual number of atoms that decay with the passing of each half-life continually decreases. Thus, as the percentage of radioactive parent atoms declines, the proportion of stable daughter atoms rises, with the increase in daughter atoms just matching the drop in parent atoms. This fact is the key to radiometric dating.

Of the many radioactive isotopes that exist in nature, five have proved particularly useful in providing radiometric ages for ancient rocks (Table 10.1). Rubidium-87, thorium-232, and the two isotopes of uranium

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**Table 10.A Decay Products of Uranium-238**

<table>
<thead>
<tr>
<th>Some Decay Products of Uranium-238</th>
<th>Decay Particle Produced</th>
<th>Half-Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium-238</td>
<td>alpha</td>
<td>4.5 billion years</td>
</tr>
<tr>
<td>Radium-226</td>
<td>alpha</td>
<td>1600 years</td>
</tr>
<tr>
<td>Radon-222</td>
<td>alpha</td>
<td>3.82 days</td>
</tr>
<tr>
<td>Polonium-218</td>
<td>alpha</td>
<td>5.0 days</td>
</tr>
<tr>
<td>Lead-214</td>
<td>alpha</td>
<td>138 days</td>
</tr>
<tr>
<td>Bismuth-214</td>
<td>beta</td>
<td>3.1 minutes</td>
</tr>
<tr>
<td>Bismuth-214</td>
<td>beta</td>
<td>19.7 minutes</td>
</tr>
<tr>
<td>Polonium-214</td>
<td>beta</td>
<td>20.4 years</td>
</tr>
<tr>
<td>Lead-210</td>
<td>beta</td>
<td>1.6 x 10^-4 second</td>
</tr>
<tr>
<td>Polonium-210</td>
<td>alpha</td>
<td>26.8 minutes</td>
</tr>
<tr>
<td>Bismuth-210</td>
<td>none</td>
<td>stable</td>
</tr>
<tr>
<td>Lead-206</td>
<td>none</td>
<td>stable</td>
</tr>
</tbody>
</table>

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People and the Environment:
Radon—a Threat to Human Health

Richard L. Hoffman*

Radioactivity is defined as the spontaneous emission of atomic particles and/or electromagnetic waves from unstable atomic nuclei. For example, in a sample of uranium-238, unstable nuclei decay and produce a variety of radioactive progeny or “daughter” products as well as energetic forms of radiation (Table 10.A). One of its radioactive decay products is radon—a colorless, odorless, invisible gas.

Radon gained public attention in 1984 when a worker in a Pennsylvania nuclear power plant set off radiation alarms not when he left work, but when he first arrived. His clothing and hair were contaminated with radon decay products. Investigation revealed that his basement at home had a radon level 2800 times the average level in indoor air. The home was located along a geological formation known as the Reading Prong—a mass of uranium-bearing black rock that runs from near Reading, Pennsylvania, to near Trenton, New Jersey.

Originating in the radio decay of traces of uranium and thorium found in almost all soils, radon isotopes (Rn-222 and Rn-220) are continually renewed in an ongoing, natural process. Geologists estimate that the top six feet of soil from an average acre of land contains about 50 pounds of uranium (about 2 to 3 parts per million); some types of rocks contain more. Radon is continually generated by the gradual decay of this uranium. Because uranium has a half-life of about 4.5 billion years, radon will be with us forever.

Radon itself decays, having a half-life of only about four days. Its decay products (except lead-206) are all radioactive solids that adhere to dust particles, many of which we inhale. During prolonged exposure to a radon-contaminated environment, some decay will occur while the gas is in the lungs, thereby placing the radioactive radon progeny in direct contact with delicate lung tissue. Steadily accumulating evidence indicates radon to be a significant cause of lung cancer second only to smoking.

A house with a radon level of 4.0 picocuries per liter of air has about eight to nine atoms of radon decaying every minute in every liter of air. The EPA suggests indoor radon levels be kept below this level. EPA risk estimates are conservative; they are based on an assumption that one would spend 75 percent of a 70-year time span (about 52 years) in the contaminated space, which most people would not.

Once radon is produced in the soil, it diffuses throughout the tiny spaces between soil particles. Some radon ultimately reaches the soil surface, where it dissipates into the air. Radon enters buildings and homes through holes and cracks in basement floors and walls. Radon’s density is greater than air, so it tends to remain in basements during its short decay cycle.

The source of radon is as enduring as its generation mechanism within Earth; radon will never go away. However, cost-effective mitigation strategies are available to reduce radon to acceptable levels, generally without great expense.
are used only for dating rocks that are millions of years old, but potassium-40 is more versatile. Although the half-life of potassium-40 is 1.3 billion years, analytical techniques make possible the detection of tiny amounts of its stable daughter product, argon-40, in some rocks that are younger than 100,000 years.

It is important to realize that an accurate radiometric date can be obtained only if the mineral remained a closed system during the entire period since its formation. A correct date is not possible unless there was neither the addition nor loss of parent or daughter isotopes. This is not always the case. In fact, an important limitation of the potassium-argon method arises from the fact that argon is a gas, and it may leak from minerals, throwing off measurements. Cross-checking of samples, using two different radiometric methods, is done where possible to ensure accurate age determinations.

### Table 10.1 Radioactive isotopes frequently used in radiometric dating.

<table>
<thead>
<tr>
<th>Radioactive Parent</th>
<th>Stable Daughter Product</th>
<th>Currently Accepted Half-Life Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium-238</td>
<td>Lead-206</td>
<td>4.5 billion years</td>
</tr>
<tr>
<td>Uranium-235</td>
<td>Lead-207</td>
<td>713 million years</td>
</tr>
<tr>
<td>Thorium-232</td>
<td>Lead-208</td>
<td>14.1 billion years</td>
</tr>
<tr>
<td>Rubidium-87</td>
<td>Strontium-87</td>
<td>47.0 billion years</td>
</tr>
<tr>
<td>Potassium-40</td>
<td>Argon-40</td>
<td>1.3 billion years</td>
</tr>
</tbody>
</table>

### Dating with Carbon-14

To date very recent events, carbon-14 is used. Carbon-14 is the radioactive isotope of carbon. The process is often called radiocarbon dating. Because the half-life of carbon-14 is only 5730 years, it can be used for dating events from the historic past as well as those from very recent geologic history. In some cases carbon-14 can be used to date events as far back as 75,000 years.

Carbon-14 is continuously produced in the upper atmosphere as a consequence of cosmic-ray bombardment. Cosmic rays, which are high-energy particles, shatter the
nuclei of gas atoms, releasing neutrons. Some of the neutrons are absorbed by nitrogen atoms (atomic number 7), causing their nuclei to emit a proton. As a result, the atomic number decreases by 1 (to 6), and a different element, carbon-14, is created (Figure 10.15A). This isotope of carbon quickly becomes incorporated into carbon dioxide, which circulates in the atmosphere and is absorbed by living matter. As a result, all organisms contain a small amount of carbon-14, including yourself.

While an organism is alive, the decaying radiocarbon is continually replaced, and the proportions of carbon-14 and carbon-12 remain constant. Carbon-12 is the stable and most common isotope of carbon. However, when any plant or animal dies, the amount of carbon-14 gradually decreases as it decays to nitrogen-14 by beta emission (Figure 10.15B). By comparing the proportions of carbon-14 and carbon-12 in a sample, radiocarbon dates can be determined.

Although carbon-14 is useful in dating only the last small fraction of geologic time, it has become a very valuable tool for anthropologists, archaeologists, and historians, as well as for geologists who study very recent Earth history. (Box 10.3 explores another method of studying and dating recent events.) In fact, the de-

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**Figure 10.15** A. Production and B. decay of carbon-14. These sketches represent the nuclei of the respective atoms.

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**UNDERSTANDING EARTH:** Using Tree Rings to Date and Study the Recent Past

If you look at the top of a tree stump or at the end of a log, you will see that it is composed of a series of concentric rings. Each of these tree rings becomes larger in diameter outward from the center (Figure 10.B). Every year in temperate regions trees add a layer of new wood under the bark. Characteristics of each tree ring, such as size and density, reflect the environmental conditions (especially climate) that prevailed during the year when the ring formed. Favorable growth conditions produce a wide ring; unfavorable ones produce a narrow ring. Trees growing at the same time in the same region show similar tree-ring patterns.

Because a single growth ring is usually added each year, the age of the tree when it was cut can be determined by counting the rings. If the year of cutting is known, the age of the tree and the year in which each ring formed can be determined by counting back from the outside ring.* This procedure can be used to determine the dates of recent geologic events. For example, the minimum number of years since a new land surface was created by a landslide or a flood. The dating and study of annual rings in trees is called dendrochronology.

To make the most effective use of tree rings, extended patterns known as ring chronologies are established. They are produced by comparing the patterns of rings among trees in an area. If the same pattern can be identified in two samples, one of which has been dated, the second sample can be dated from the first by matching the ring pattern common to both. This technique, called cross dating, is illustrated in Figure 10.C. Tree-ring chronologies extending back for thousands of years

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*Scientists are not limited to working with trees that have been cut down. Small, nondestructive core samples can be taken from living trees.
development of radiocarbon dating was considered so important that the chemist who discovered this application, Willard F. Libby, received a Nobel prize.

**Importance of Radiometric Dating**

Bear in mind that although the basic principle of radiometric dating is simple, the actual procedure is quite complex. The analysis that determines the quantities of parent and daughter must be painstakingly precise. In addition, some radioactive materials do not decay directly into the stable daughter product. As you saw in Figure 10.13, uranium-238 produces 13 intermediate unstable daughter products before the fourteenth and final daughter product, the stable isotope lead-206, is produced.

Radiometric dating methods have produced literally thousands of dates for events in Earth history. Rocks from several localities have been dated at more than 3 billion years, and geologists realize that still older rocks exist. For example, a granite from South Africa has been dated at 3.2 billion years, and it contains inclusions of quartzite. (Remember that inclusions are older than the rock containing them.) Quartzite itself is a metamorphic rock that originally was the sedimentary rock sandstone. Sandstone, in turn, is the product of the lithification of sediments produced by the weathering of existing rocks. Thus, we have a positive indication that much older rocks existed.

Radiometric dating has vindicated the ideas of James Hutton, Charles Darwin, and others who inferred that geologic time must be immense. Indeed, modern dating methods have proved that there has been enough time for the processes we observe to have accomplished tremendous tasks.

**The Geologic Time Scale**

Geologists have divided the whole of geologic history into units of varying magnitude. Together they comprise the **geologic time scale** of Earth history (Figure 10.16). The major units of the time scale were delineated during the nineteenth century, principally by scientists working in Western Europe and Great Britain. Because radiometric dating was unavailable at that time, the entire time scale was created using methods of rela-

![Figure 10.C](image)

*Figure 10.C*  Cross dating is a basic principle in dendrochronology. Here it was used to date an archaeological site by correlating tree-ring patterns for wood from trees of three different ages. First, a tree-ring chronology for the area is established using cores extracted from living trees. This chronology is extended further back in time by matching overlapping patterns from older, dead trees. Finally, cores taken from beams inside the ruin are dated using the chronology established from the other two sites.

have been established for some regions. To date a timber sample of unknown age, its ring pattern is matched against the reference chronology.

Tree-ring chronologies are unique archives of environmental history and have important applications in such disciplines as climate, geology, ecology, and archaeology. For example, tree rings are used to reconstruct climate variations within a region for spans of thousands of years prior to human historical records. Knowledge of such long-term variations is of great value in making judgments regarding the recent record of climate change.

In summary, dendrochronology provides useful numerical dates for events in the historic and recent prehistoric past. Moreover, because tree rings are a storehouse of data, they are a valuable tool in the reconstruction of past environments.
Radiometric dating. It was only in the twentieth century that radiometric dating permitted numerical dates to be added.

Structure of the Time Scale
The geologic time scale subdivides the 4.5-billion-year history of Earth into many different units and provides a meaningful time frame within which the events of the geologic past are arranged. As shown in Figure 10.16, eons represent the greatest expanses of time. The eon that began about 540 million years ago is the Phanerozoic, a term derived from Greek words meaning visible life. It is an appropriate description because the rocks and deposits of the Phanerozoic eon contain abundant fossils that document major evolutionary trends.

Another glance at the time scale reveals that the Phanerozoic eon is divided into eras. The three eras within the Phanerozoic are the Paleozoic (paleo = ancient, zoe = life), the Mesozoic (meso = middle,
As the names imply, the eras are bounded by profound worldwide changes in life forms. Each era is subdivided into periods. The Paleozoic has seven, the Mesozoic three, and the Cenozoic two. Each of these 12 periods is characterized by a somewhat less profound change in life forms as compared with the eras.

Finally, periods are divided into still smaller units called epochs. As you can see in Figure 10.16, seven epochs have been named for the periods of the Cenozoic. The epochs of other periods, however, are not usually referred to by specific names. Instead, the terms early, middle, and late are generally applied to the epochs of these earlier periods.

Precambrian Time

Notice that the detail of the geologic time scale does not begin until about 540 million years ago, the date for the beginning of the Cambrian period. The more than 4 billion years prior to the Cambrian is divided into three eons, the Hadean, the Archean, and the Proterozoic. It is also common for this vast expanse of time to simply be referred to as the Precambrian. Although it represents about 88 percent of Earth history, the Precambrian is not divided into nearly as many smaller time units as is the Phanerozoic eon.

The quantity of information geologists have deciphered about Earth’s past is somewhat analogous to the detail of human history. The further back we go, the less we know. Certainly more data and information exist about the past 10 years than for the first decade of the twentieth century; the events of the nineteenth century have been documented much better than the events of the first century A.D., and so on. Thus it is with Earth history. The more recent past has the freshest, least disturbed, and most observable record. The further back in time the geologist goes, the more fragmented the record and clues become.

Difficulties in Dating the Geologic Time Scale

Although reasonably accurate numerical dates have been worked out for the periods of the geologic time scale (see Figure 10.16), the task is not without difficulty. The primary problem in assigning numerical dates to units of time is the fact that not all rocks can be dated by radiometric methods. Recall that for a radiometric date to be useful, all minerals in the rock must have formed at about the same time. For this reason, radioactive isotopes can be used to determine when minerals in an igneous rock crystallized and when pressure and heat created new minerals in a metamorphic rock.

However, samples of sedimentary rock can only rarely be dated directly by radiometric means. A sedimentary rock may include particles that contain radioactive isotopes, but the rock’s age cannot be accurately determined because the grains making up the rock are not the same age as the rock in which they occur. Rather, the sediments have been weathered from rocks of diverse ages.

Radiometric dates obtained from metamorphic rocks may also be difficult to interpret, because the age of a particular mineral in a metamorphic rock does not necessarily represent the time when the rock initially formed. Instead, the date may indicate any one of a number of subsequent metamorphic phases.

If samples of sedimentary rocks rarely yield reliable radiometric ages, how can numerical dates be assigned to sedimentary layers? Usually the geologist must relate them to datable igneous masses, as in Figure 10.17. In
this example, radiometric dating has determined the ages of the volcanic ash bed within the Morrison Formation and the dike cutting the Mancos Shale and Mesaverde Formation. The sedimentary beds below the ash are obviously older than the ash, and all the layers above the ash are younger (principle of superposition). The dike is younger than the Mancos Shale and the Mesaverde Formation but older than the Wasatch Formation because the dike does not intrude the Tertiary rocks (cross-cutting relationships).

From this kind of evidence, geologists estimate that a part of the Morrison Formation was deposited about 160 million years ago, as indicated by the ash bed. Further, they conclude that the Tertiary period began after the intrusion of the dike, 66 million years ago. This is one example of literally thousands that illustrates how datable materials are used to bracket the various episodes in Earth history within specific time periods. It shows the necessity of combining laboratory dating methods with field observations of rocks.

**Chapter Summary**

- During the seventeenth and eighteenth 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.

- The two types of dates used by geologists to interpret Earth history are (1) relative dates, which put events in their proper sequence of formation, and (2) numerical dates, which pinpoint the time in years when an event took place.

- Relative dates can be established using the law of superposition, principle of original horizontality, principle of cross-cutting relationships, inclusions, and unconformities.

- Correlation, the matching up of two or more geologic phenomena in different areas, is used to develop a geologic time scale that applies to the entire Earth.

- Fossils are the remains or traces of prehistoric life. The special conditions that favor preservation are rapid burial and the possession of hard parts such as shells, bones, or teeth.

- Fossils are used to correlate sedimentary rocks from different regions by using the rocks’ distinctive fossil content and applying the principle of fossil succession. It 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.

- Each atom has a nucleus containing protons (positively charged particles) and neutrons (neutral particles). Orbiting the nucleus are negatively charged electrons. The atomic number of an atom is the number of protons in the nucleus. The mass number is the number of protons plus the number of neutrons in an atom’s nucleus. Isotopes are variants of the same atom, but with a different number of neutrons and hence a different mass number.

- Radioactivity is the spontaneous breaking apart (decay) of certain unstable atomic nuclei. Three common types of radioactive decay are (1) emission of alpha particles from the nucleus, (2) emission of beta particles (electrons) from the nucleus, and (3) capture of electrons by the nucleus.

- An unstable radioactive isotope, called the parent, will decay and form stable daughter products. The length of time for half of the nuclei of a radioactive isotope to decay is called the half-life of the isotope. If the half-life of the isotope is known and the parent/daughter ratio can be measured, the age of a sample can be calculated.

- The geologic time scale divides Earth’s history into units of varying magnitude. It is commonly presented in chart form, with the oldest time and event at the bottom and the youngest at the top. The principal subdivisions of the geologic time scale, called eons, include the Hadean, Archean, Proterozoic (together, these three eons are commonly referred to as the Precambrian), and, beginning about 540 million years ago, the Phanerozoic. The Phanerozoic (meaning “visible life”) eon is divided into the following eras: Paleozoic (“ancient life”), Mesozoic (“middle life”), and Cenozoic (“recent life”).

- A significant problem in assigning numerical dates to units of time is that not all rocks can be dated radiometrically. A sedimentary rock may contain particles of many ages that have been weathered from different rocks that formed at various times. One way geologists assign numerical dates to sedimentary rocks is to relate them to datable igneous masses, such as dikes and volcanic ash beds.

**Key Terms**

- angular unconformity (p. 291)
- catastrophe (p. 287)
- Cenozoic era (p. 305)
- conformable (p. 290)
- correlation (p. 291)
- cross-cutting relationships, principle of (p. 289)
- disconformity (p. 291)
- eon (p. 304)
- epoch (p. 305)
- era (p. 304)
- fossil (p. 292)
- fossil succession, principle of (p. 297)
- geologic time scale (p. 303)
- half-life (p. 299)
- inclusions (p. 289)
- index fossil (p. 297)
- Mesozoic era (p. 304)
- nonconformity (p. 291)
- numerical date (p. 288)
- original horizontality, principle of (p. 289)
- Paleozoic era (p. 304)
- period (p. 305)
Review Questions

1. Contrast catastrophism and uniformitarianism. How did the proponents of each perceive the age of Earth?

2. Distinguish between numerical and relative dating.

3. What is the law of superposition? How are cross-cutting relationships used in relative dating?

4. When you observe an outcrop of steeply inclined sedimentary layers, what principle allows you to assume that the beds became tilted after they were deposited?

5. Refer to Figure 10.4 to answer the following questions:
   (a) Is fault A older or younger than the sandstone layer?
   (b) Is dike A older or younger than the sandstone layer?
   (c) Was the conglomerate deposited before or after fault A?
   (d) Was the conglomerate deposited before or after fault B?
   (e) Which fault is older, A or B?
   (f) Is dike A older or younger than the batholith?

6. A mass of granite is in contact with a layer of sandstone. Using a principle described in this chapter, explain how you might determine whether the sandstone was deposited on top of the granite or the granite was intruded from below after the sandstone was deposited.

7. Distinguish among angular unconformity, disconformity, and nonconformity.

8. What is meant by the term correlation?

9. List and briefly describe at least five different types of fossils.

10. List two conditions that improve an organism’s chances of being preserved as a fossil.

11. Why are fossils such useful tools in correlation?

12. In addition to being important aids in dating and correlating rocks, how else are fossils helpful in geologic investigations?

13. If a radioactive isotope of thorium (atomic number 90, mass number 232) emits 6 alpha particles and 4 beta particles during the course of radioactive decay, what are the atomic number and mass number of the stable daughter product?

14. Why is radiometric dating the most reliable method of dating the geologic past?

15. Assume that a hypothetical radioactive isotope has a half-life of 10,000 years. If the ratio of radioactive parent to stable daughter product is 1:3, how old is the rock containing the radioactive material? What if the ratio were 1:15?

16. To make calculations easier, let us round the age of Earth to 5 billion years.
   (a) What fraction of geologic time is represented by recorded history (assume 5000 years for the length of recorded history)?
   (b) The first abundant fossil evidence does not appear until the beginning of the Cambrian period (approximately 550 million years ago). What percentage of geologic time is represented by abundant fossil evidence?

17. What subdivisions make up the geologic time scale? What is the primary basis for differentiating the eras?

18. Briefly describe the difficulties in assigning numerical dates to layers of sedimentary rock.

Examining the Earth System

1. Figure 10.10A is a large petrified log in Arizona’s Petrified Forest National Park. Describe the transition of this tree from being part of the biosphere to being a component of the solid Earth. How might the hydrosphere and/or atmosphere have played a role in the transition?

2. The famous angular unconformity at Scotland’s Siccar Point was originally studied by James Hutton in the late 1700s (see Figure 10.7E, p. 293). Can you describe in a general way what occurred to produce this feature? Could all of the spheres of the Earth system have been involved? The Earth system is powered by energy from two sources. How are both sources represented here?

Web Resources

- Online review quizzes.
- Web-based critical thinking and writing exercises.
- Links to chapter-specific Web resources.
- Internet-wide key term searches.

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