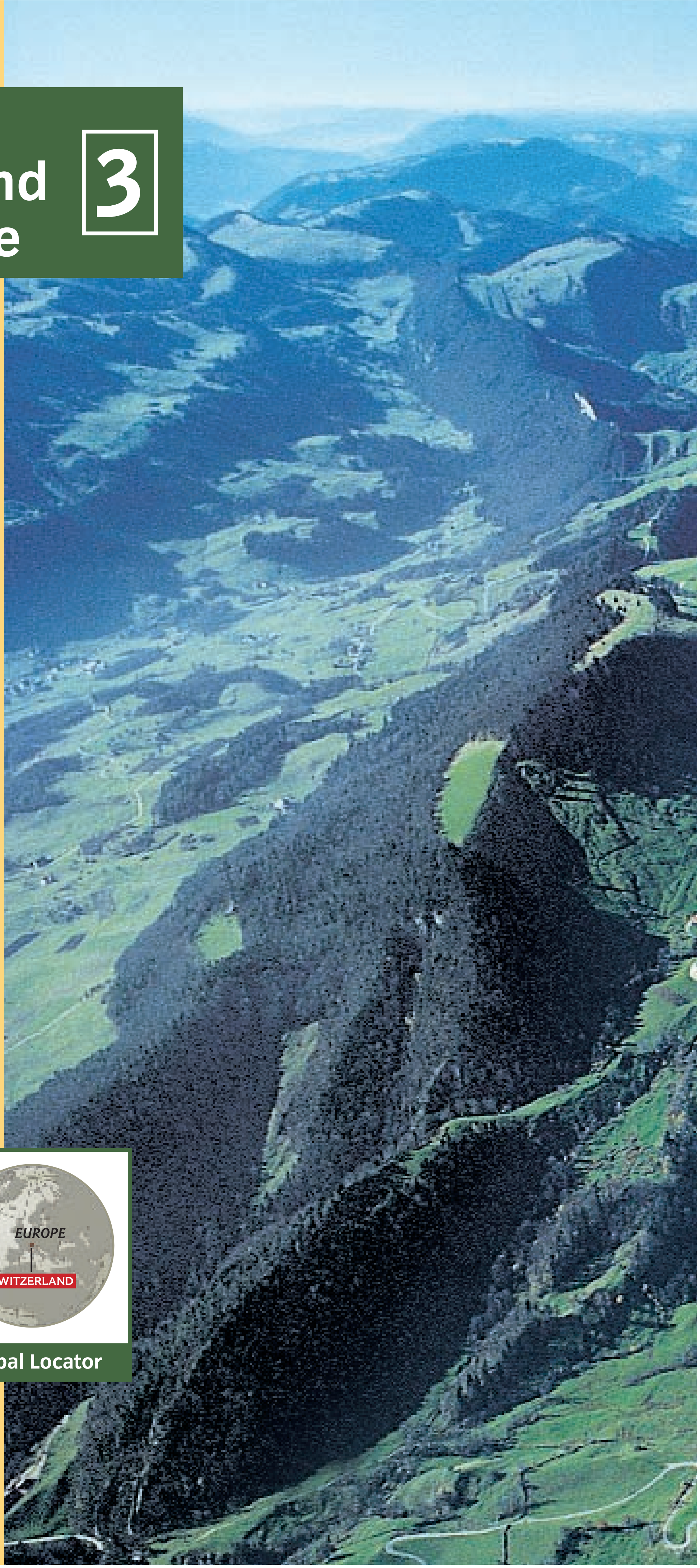
How Old Is Old? The Rock Record and Deep Geologic Time 3



What's in a name? Say the word "Jurassic" and most people probably think of *Jurassic Park*, the blockbuster movie by Steven Spielberg. Next, they would recall the stars of the movie—the terrifying Tyrannosaurus rex and the fast and wily velociraptors (whose real name is Deinonychus).

They probably wouldn't think about the Jura Mountains in Switzerland. These lushly wooded limestone hills contain millions of fossils of extinct sea creatures called ammonites, which lived in coiled seashells reminiscent of the modern nautilus. In the nineteenth century, geologists gradually realized that these creatures—and the rocks in which they were fossilized—all came from a particular period in the geologic past. They named it the Jurassic Period, after the mountain range where they found some of their best and most distinctive samples of ammonites. It is one of the delightful ironies of science that the fossil chosen to define the period was not a mighty dinosaur, but a humble sea creature.

(By the way, no tyrannosaurs or velociraptors lived in the Jurassic Period, though many other dinosaurs did. The name "Cretaceous Park" would have been more accurate.)

Fossils and rocks don't come with a date stamped on them. So how do geologists tell when an ancient animal lived, or when a particular layer of rocks was deposited? We will describe several methods in this chapter. It has taken geologists two centuries to piece together Earth's chronology, and they are still refining it.

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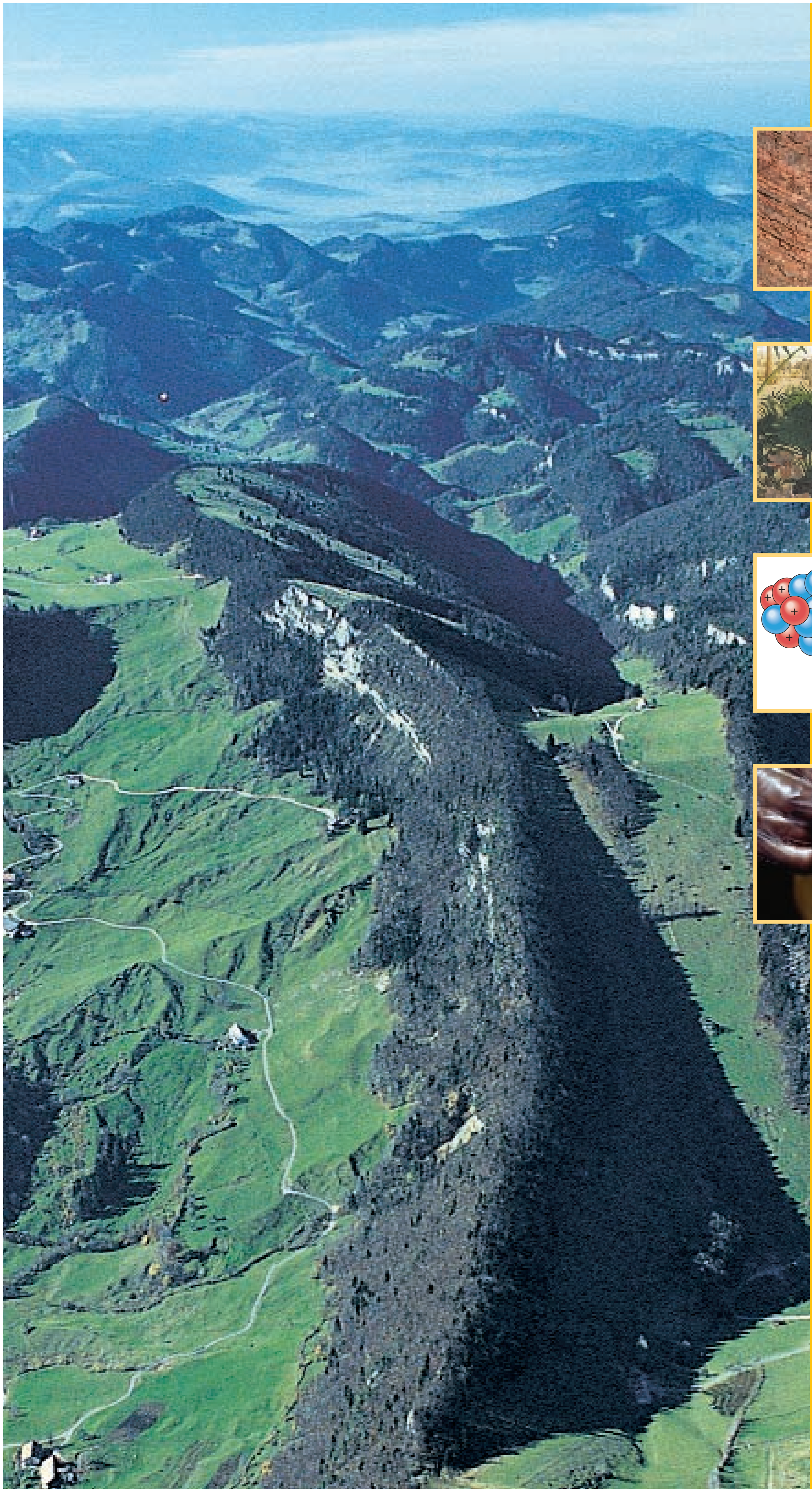

CHAPTER OUTLINE

Relative Age

Learning Objectives

Define relative and numerical ages.

Define stratigraphy and identify the three main principles involved.

Explain why gaps are common in the rock record.

Describe how fossils make it possible for geologists to correlate strata in different places.

The first scientific attempts to determine the extent of geologic time were made about two centuries ago. Geologists speculated that they might be able to estimate the time needed to erode away a mountain range by measuring the amount of sediment transported by streams. Their attempts were imprecise, but the inescapable conclusion was that Earth must be millions of years old because of the great thickness of sedimentary rocks. One of the founders of geology, a Scot named James Hutton, was so impressed by the evidence that in 1785 he wrote that for Earth there is "no vestige of a beginning, no prospect of an end."

The geologists who followed Hutton agreed with his conclusion that Earth must be very ancient, but they lacked a precise way to determine exactly how long ago a particular event occurred. The only thing they could do was figure out the sequence of past events. They could thus establish the **relative ages** of rock formations or other geologic features, which means that they could determine whether a particular formation or feature was older or younger than another formation or feature. By doing so, they took the essential first steps toward unraveling Earth's geologic history. Relative ages are derived from three basic principles of **stratigraphy**, discussed below.

relative age The age of a rock, fossil, or other geologic feature relative to another feature.

stratigraphy The science of rock layers and the process by which strata are formed.

STRATIGRAPHY

In places where you can find large exposed rock formations, such as the American Southwest, you will often see that the rocks have a banded appearance (see FIGURE 3.1). These bands are called **strata** (an individual band is called a *stratum*), from the Latin word for "layer." The bands are often horizontal, but it is not at all unusual to see them tilted or bent.

All of the rocks in a typical stratified formation are sedimentary, deposited over the eons by water. This observation leads to the first of three key principles of stratigraphy: the *principle of original horizontality*, which states that water-laid sediments are deposited in horizontal strata. You can test this principle yourself. Shake up a bottle of muddy water so that all of the particles are suspended. Let the bottle stand and then examine the result—the mud will be deposited at the bottom of the bottle in a horizontal layer. Therefore, whenever we observe water-laid strata that are bent, twisted, or tilted so that they are no longer horizontal, we know that some tectonic force must have disturbed the strata after they were deposited (see Figure 3.1B and C).

A second key to stratigraphy, which, like the first, is based on common sense, is the *principle of stratigraphic superposition*. This principle states that in any undisturbed sequence of strata, each stratum is younger than the stratum below it and older than the stratum above it (see What a Geologist Sees on page 46).

A third principle for determining relative ages, the *principle of cross-cutting relationships*, states that a stratum must always be older than any feature that cuts or disrupts it. If a stratum is cut by a fracture, for example, the stratum itself is older than the fracture that cuts across it, as shown in

Visualizing

Strata and the principle of horizontality FIGURE 3.1

All of these strata were originally deposited as horizontal layers; the strata in (B) and (C) were disrupted by later tectonic activity.

A Horizontal strata in Badlands State Park, South Dakota.

B Tilted strata in Telfer Gold Mine, Great Sandy Desert, Western Australia.

C Folded strata in Hamersley Gorge, Western Australia.

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What a Geologist Sees

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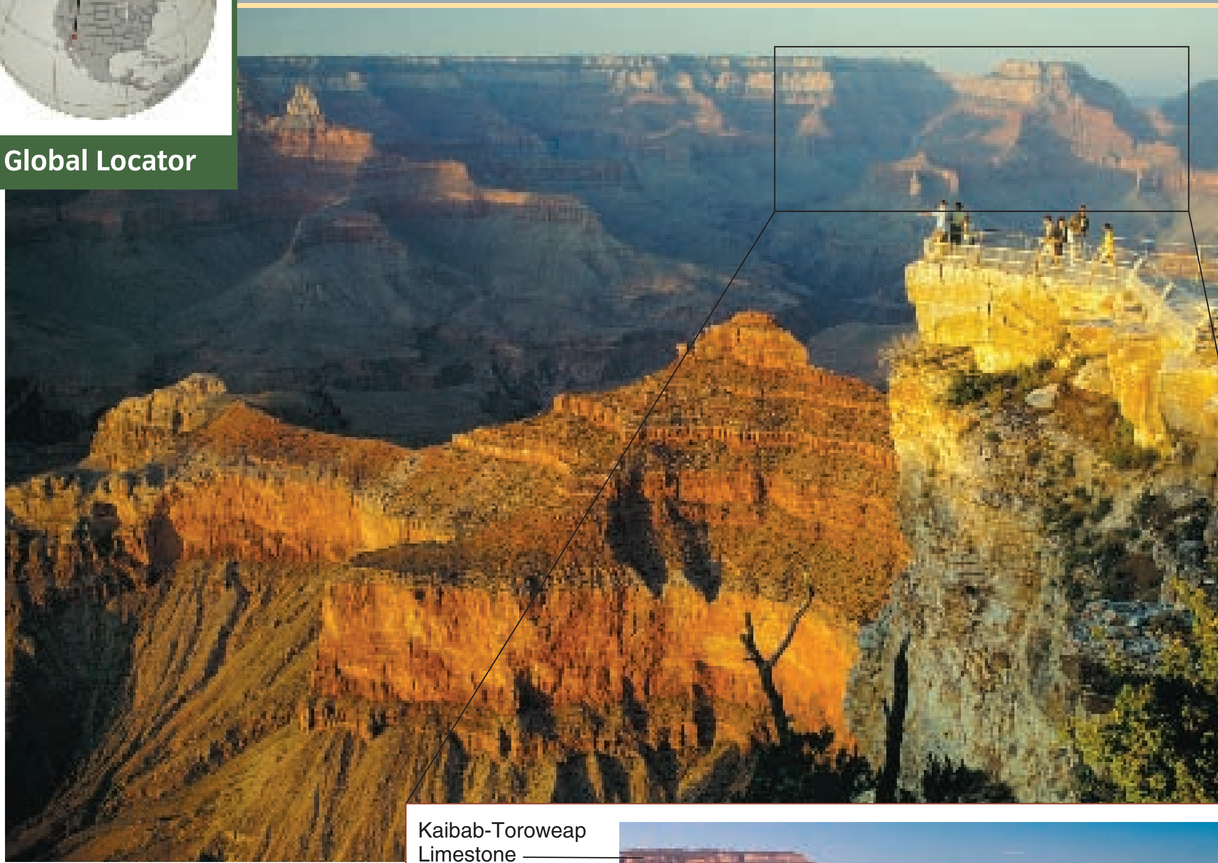

The Principle of Stratigraphic Superposition

The Grand Canyon is considered one of the natural wonders of the world—not surprising then, that nearly 5 million people visit the canyon every year. To a geologist, the Grand Canyon is more than just a scenic stop. It is also a beautiful example of the geologic record from millions of years ago to today.

A panoramic view of the Grand Canyon from the Toroweap Overlook shows a nearly 2-kilometer thickness of horizontal, sedimentary strata, lying on top of older strata that were tilted and tectonically deformed before the horizontal strata were deposited. According to the principle of stratigraphic superposition, each stratum is younger than the layer below it *(inset)*. Geologists can easily recognize the strata, and they have named each one after its predominant rock type and the location in the Grand Canyon where the best outcroppings occur (such as the Toroweap Overlook). The tilted strata, called the Grand Canyon Supergroup, are now known to be much older than the horizontal ones, but stratigraphy can only tell us the relative ages.

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FIGURE 3.2. When magma fills a fracture, the result is a vein of igneous rock that cuts across the strata. In this case, too, the sedimentary rocks must be older than the igneous vein.

GAPS IN THE RECORD

When nineteenth-century geologists had determined the relative ages of all the strata that they could see, they tried to estimate the **numerical age**—that is, the exact number of years that have elapsed since a given stratum was deposited. For example, a geologist might estimate that it would take 10 years for 1 inch of sediment to accumulate. If he was studying a layer of rock 300 feet (3600 inches) below the modern stratum at the top, then he would estimate the age of the layer in question to be 36,000 years old (3600 inches × 10 years per inch).

numerical age
The age of a rock or geological feature in years before the present.

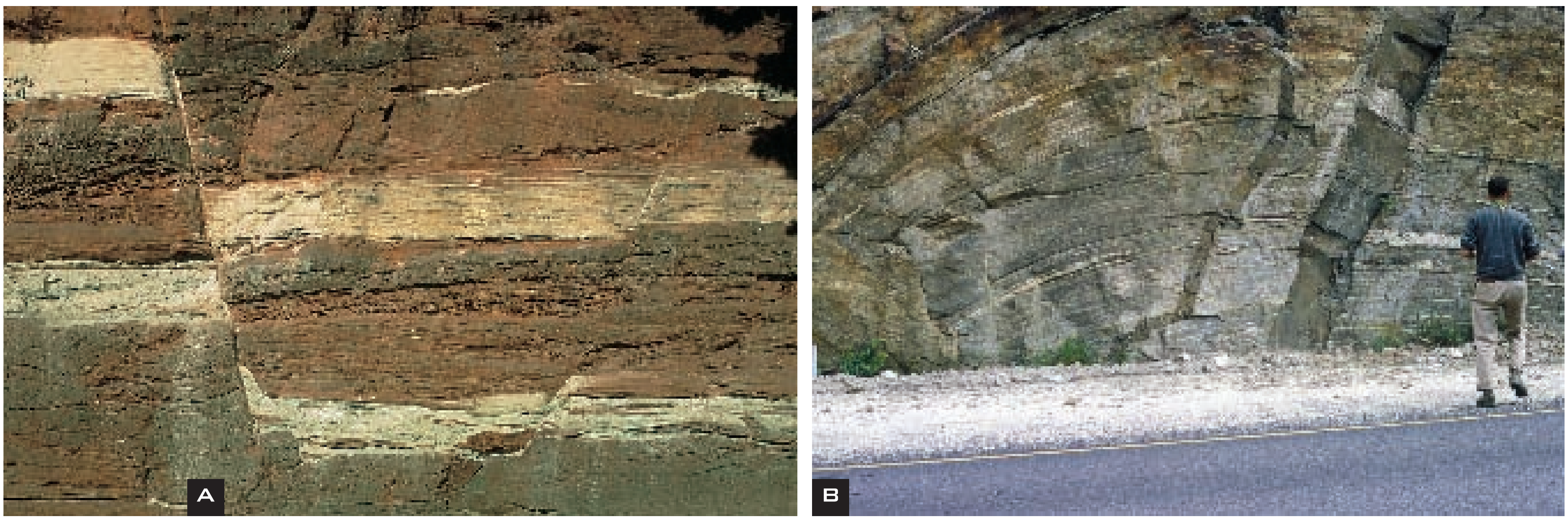
unconformity
A substantial gap in a stratigraphic sequence that marks the absence of part of the rock record.

At least three assumptions must be true for this method to work. First, the rate of sedimentation must have been constant during the entire time the layers were deposited. Second, the thickness of sediment must have been the same as the thickness of the sedimentary rock that eventually formed from it. Finally, all the strata must be *conformable*. This means that each layer must have been deposited on the one below it without any interruptions—in other words, there must not be any depositional gaps in the stratigraphic record.

There are problems with each of the assumptions. Rates of sedimentation vary greatly. Sediments are often compressed while they are turning into sedimentary rock, resulting in a much thinner stratum than was originally deposited. The conformity assumption also fails; gaps in the stratigraphic record, or **uncomformities**, are common and occur for several different reasons (see FIGURE 3.3 on the following page).

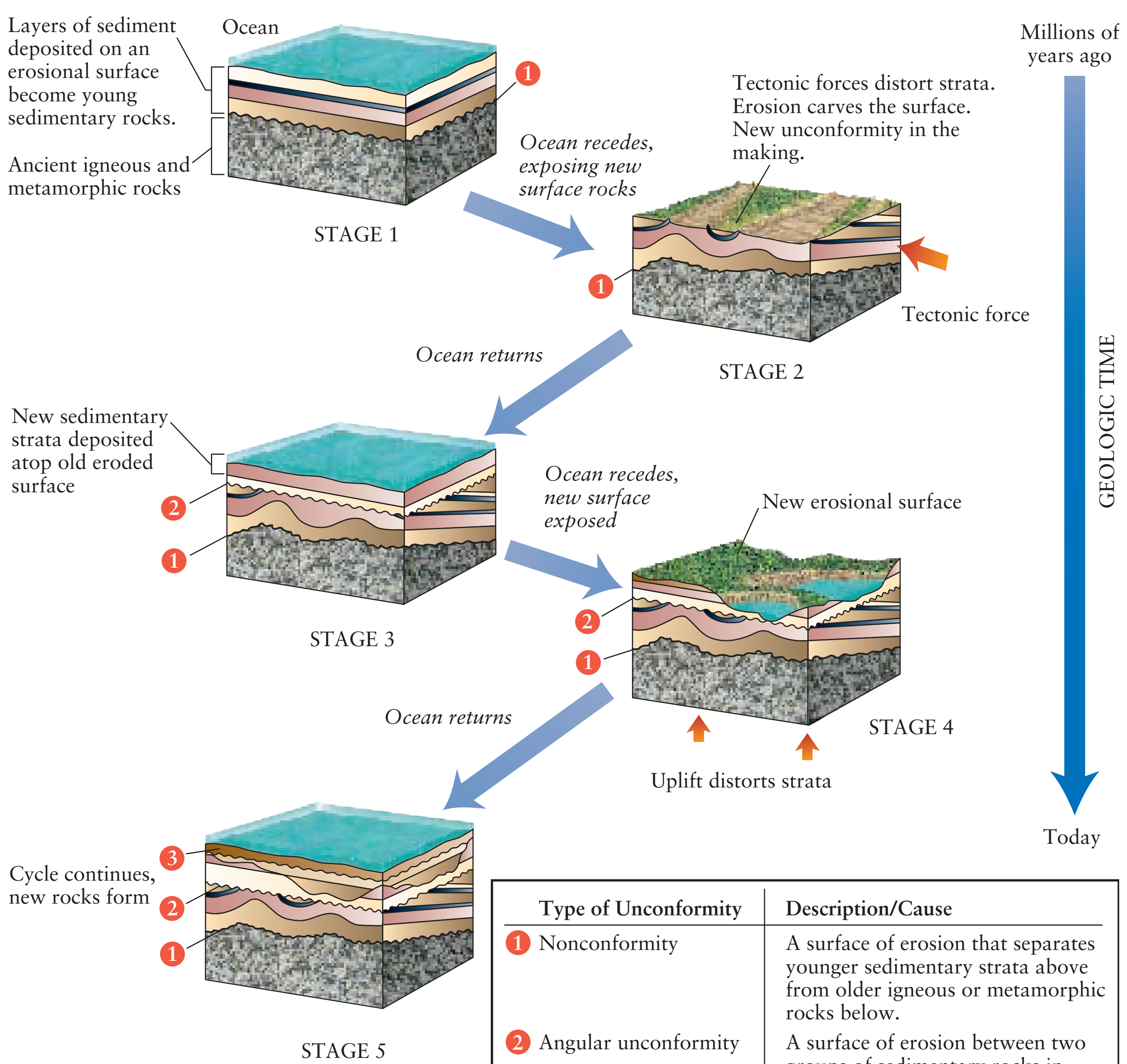
Principle of cross-cutting relationships FIGURE 3.2

A These fractures must be younger than the rock strata they cut, according to the principle of cross-cutting relationships. The fractures were found in a sequence of sandstone strata in Merseyside, United Kingdom. B At Three Valley Gap in Alberta, Canada, layers of metamorphic rock are sliced through by two igneous rock formations called dikes. A geologist sees three events: deposition of sedimentary strata; metamorphism and deformation of the strata into a rock called gneiss; intrusion of the dikes. By the principle of cross-cutting relations, the dikes must be the youngest feature.



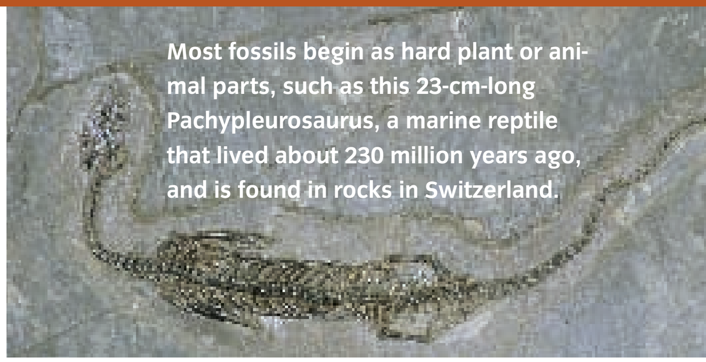
Unconformities: gaps in the rock record FIGURE 3.3

Any boundary that represents a gap in the sedimentary record is called an unconformity. This diagram illustrates the formation of three common types of unconformities: 1 nonconformity, 2 angular unconformity, and 3 disconformity.



Type of Unconformity	Description/Cause
1 Nonconformity	A surface of erosion that separates younger sedimentary strata above from older igneous or metamorphic rocks below.
2 Angular unconformity	A surface of erosion between two groups of sedimentary rocks in which the orientation of older strata, below, are at an angle to younger strata, above.
3 Disconformity	A surface of erosion in which the orientation of older strata, below, are parallel to younger strata, above.

Varieties of fossils FIGURE 3.4



Most fossils begin as hard plant or animal parts, such as this 23-cm-long Pachypleurosaurus, a marine reptile that lived about 230 million years ago, and is found in rocks in Switzerland.

These fossils, found in Sweden, record the slithering, sliding, and digging of some marine creatures, identity unknown, about 530 million years ago.

▲ Other fossils record the impressions of soft tissue on mud that later solidified. This lobe-finned fish (a Eusthenopteron), found in 380-million-year-old rocks in Quebec, had appendages that evolved into legs.

In sum, the estimates of numerical ages determined by early geologists from the thickness of stratigraphic sequences were not very accurate.

FOSSILS AND CORRELATION

Many strata contain remains of plants and animals that were incorporated into the sediment as it accumulated. **Fossils** usually consist of "hard parts" like shells, bones, or wood whose forms have been preserved in sedimentary rocks (see FIGURE 3.4). In some cases the imprints of soft animal tissues, like jellyfish, or the leaves and flowers of plants have been preserved. Even the preserved tracks and footprints of animals are considered to be fossils. Many fossils found in geologically young strata look similar to plants and animals living today (see FIGURE 3.5). The farther down in the stratigraphic sequence we go, the more likely we are to find fossils of extinct plants or animals, and the less familiar they seem.

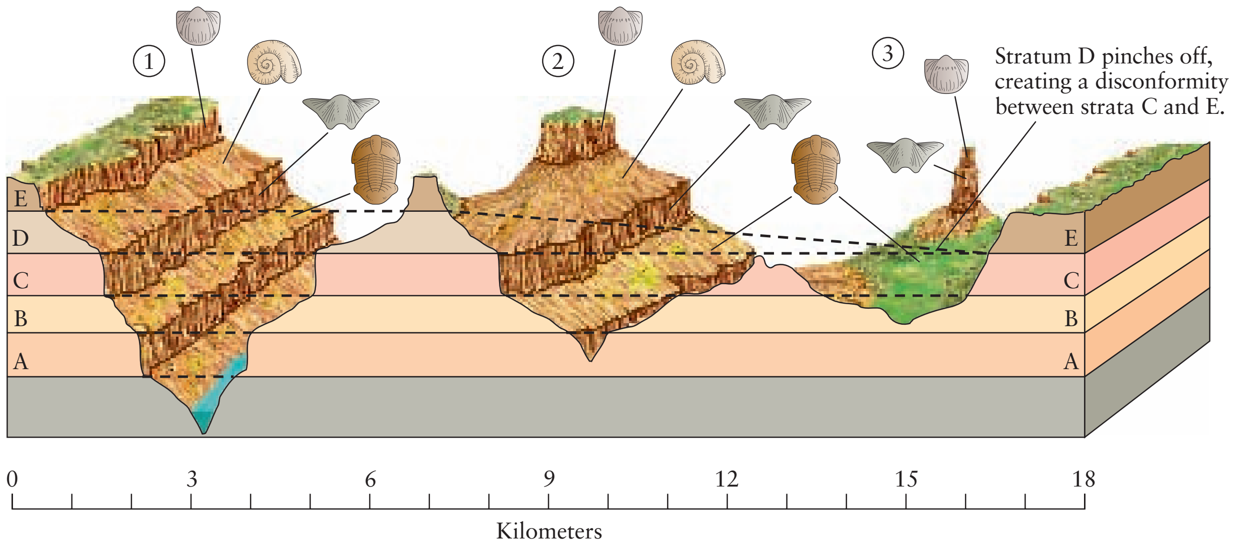
> **paleontology** The study of fossils and the record of ancient life on Earth; the use of fossils for the determination of relative ages.

Nicolaus Steno, whom we introduced in Chapter 2 in connection with crystals, was also one of the first scientists to conclude that fossils were the remains of ancient life. He published his ideas in a landmark paper in 1669, in which he also stated the principles of stratigraphic superposition and original horizontality. His conclusions were ridiculed at the time, but by the next century the idea of the plant and animal origin of fossils was widely accepted.

The study of fossils, called **paleontology**, is hugely important for understanding the history of life on

Ancient and modern FIGURE 3.5

A fossilized imprint of a Lebachia, a conifer that is found in rocks about 250 million years old, strongly resembles a modern Norfolk pine.



Fossils and correlation FIGURE 3.6

Geologists can use fossils to correlate strata at localities (1, 2, and 3) that are many kilometers apart. Strata B, C, D, and E have fossil assemblages that are different from one another, but consistent among the three sites. Note that stratum D is missing at locality 3, because E directly overlies C. Why?

Either D was never deposited there, or it was deposited and later removed by erosion. Either way, the boundary between C and E is a disconformity.

Earth, and we will have much more to say about it in Chapter 14. Aside from their biological interest, fossils also have great practical value to geologists. About the same time that James Hutton was working in Scotland, a young surveyor named William Smith was laying out canal routes in southern England. As the canals were excavated, Smith noticed that each group of strata contained a specific assemblage of fossils. In time, he could look at a specimen of rock from any sedimentary layer in southern England and name the stratum and its position in the sequence of strata. This skill enabled him to predict what kind of rock the canal excavators would encounter and how long it would take to dig through it. It also earned him the nickname "Strata."

The stratigraphic ordering of fossil assemblages is known as the principle of *faunal and floral succession.* Faunal means animals, floral means plants; succession means that new species succeed earlier ones as they evolve. William Smith's practical discovery turned out to be of great scientific importance. Geologists soon demonstrated that the faunal succession in northern France is the same as that found by Smith in southern England. By the middle of the nineteenth century, it had become clear that faunal succession is essentially the same everywhere. Thus Smith's practical observations led to a means of worldwide **correlation**, which is the most important way of filling the gaps in the geological record (see FIGURE 3.6).

correlation
A method of equating the ages of strata that come from two or more different places.

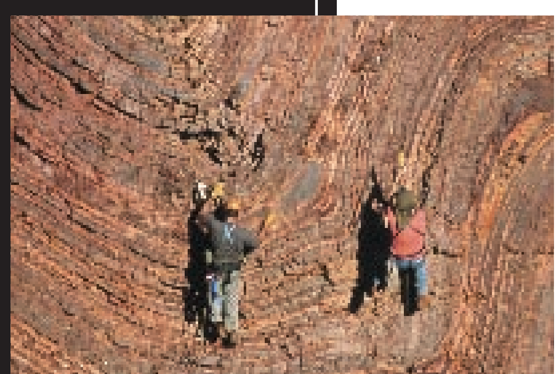
CONCEPT CHECK STOP

What are the three principles on which stratigraphy is based?

How can fossils provide information about the relative age of rocks?

How can the principles of stratigraphy be used to determine the relative age of strata?

What is the difference between conformable and unconformable strata?



The Geologic Column

LEARNING OBJECTIVES

Explain how worldwide observations of strata and the fossils they contain led to a single sequence of relative ages called the Geologic Column.

Distinguish four units of geologic time: eons, eras, periods, and epochs.

Explain how different eras and periods correspond to different fossil assemblages.

Worldwide stratigraphic correlation (see FIGURE 3.7) was one of the greatest successes of nineteenth-century science. It meant that a gap in the stratigraphic record in one place could be filled using evidence from somewhere else. Through worldwide correlation, nineteenth-century geologists assembled the **Geologic Column**, or *stratigraphic time scale*, a composite diagram showing the succession of all known strata, fitted together in chronological order, on the basis of their fossils and other evidence of relative age (see FIGURE 3.8 on the following page).

EONS AND ERAS

Even the most cursory inspection of the Geologic Column reveals how closely our understanding of strata is intertwined with the history of life. The vast majority of Earth's history is divided into three **eons** in which fossils are extremely rare or nonexistent, and in which geologic information is similarly sparse: the *Hadean* ("beneath the earth"), *Archean* ("ancient"), and *Proterozoic* ("early life") Eons. The Archean is roughly the period when single-celled life developed, and the Proterozoic is when multi-celled soft-bodied organisms first emerged. We now know that each eon spanned several hundred million years of time, as shown in Figure 3.8; however, the nineteenth-century geologists who first worked out the Geologic Column had no way of determining this information.

At the beginning of the fourth and current eon, called the *Phanerozoic* ("visible life"), the fossil record suddenly becomes much more detailed, thanks to the appearance of the first animals with hard shells and skeletons. Thus, geologists have divided the Phanerozoic eon into three shorter units called **eras**: the *Paleozoic* ("ancient life"), *Mesozoic* ("middle life"), and *Cenozoic* ("recent life"). These eras were separated by major extinction events, when more than 70 percent of the species on Earth perished (see FIGURE 3.9 on page 53).

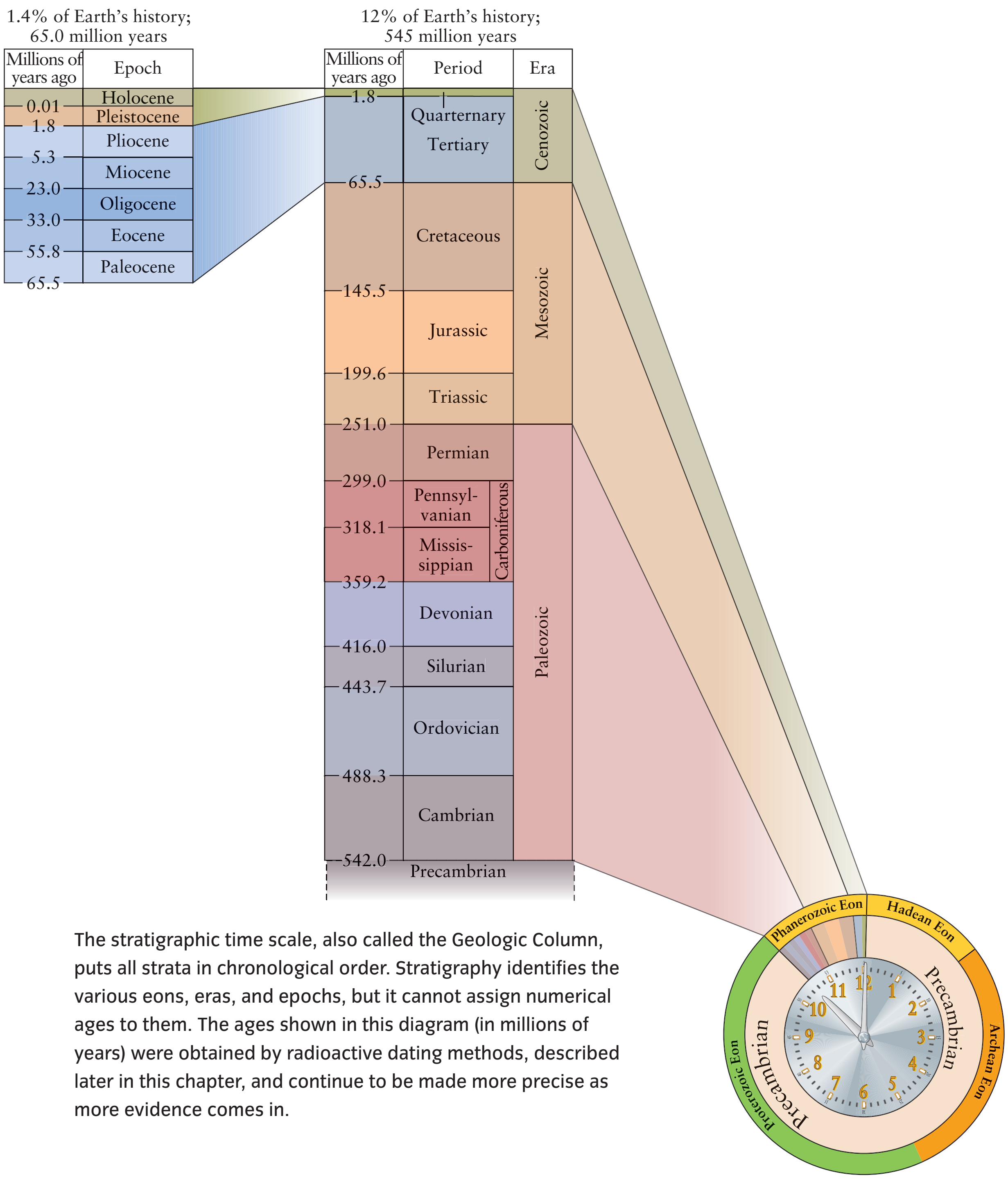
Geologic Column The succession of all known strata, fitted together in relative chronological order.

Markers of geologic time FIGURE 3.7

These ammonite fossils are encased in limestone and came from the Jura Mountains in Switzerland. Such fossils are typical of those used to correlate strata from place to place. Rocks anywhere in the world that contain the same species of ammonite can be reliably dated to the Jurassic Period (named after the Jura Mountains). Other species of marine invertebrates can be used to correlate rocks from other periods. While dinosaur and other vertebrate fossils may attract more attention, marine invertebrate fossils are the ones that have been most helpful in allowing scientists to reconstruct the history of our planet because they are more common and widely distributed than dinosaur fossils.

The Geologic Column in words

FIGURE 3.8

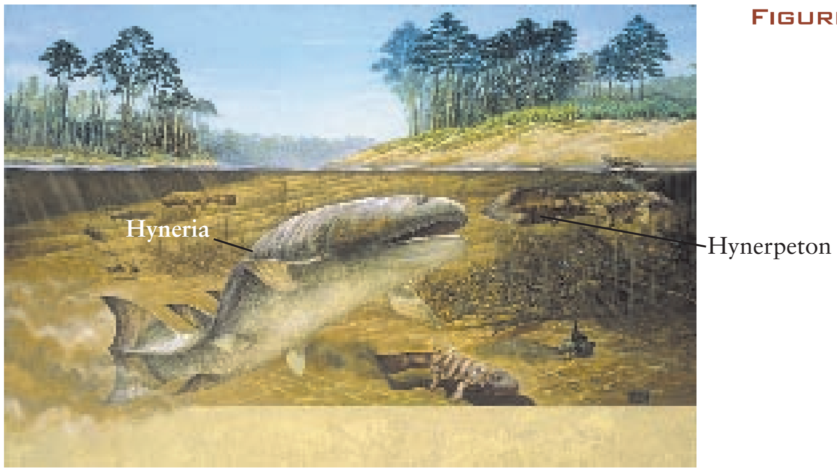


The stratigraphic time scale, also called the Geologic Column, puts all strata in chronological order. Stratigraphy identifies the various eons, eras, and epochs, but it cannot assign numerical ages to them. The ages shown in this diagram (in millions of years) were obtained by radioactive dating methods, described later in this chapter, and continue to be made more precise as more evidence comes in.

Visualizing
The Geologic Column

The Geologic Column in pictures

FIGURE 3.9

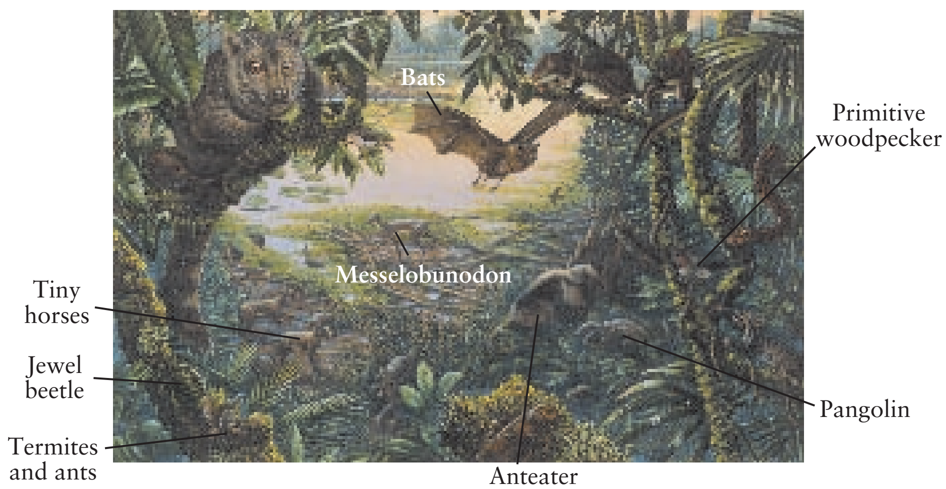


Paleozoic Era

During the Paleozoic Era, the evolution of life progressed from marine invertebrates (animals without backbones) to fish, amphibians, and reptiles. In this scene from 350 million years ago, a lobe-finned fish like the one in Figure 3.4 comes to life *(foreground)* along with some early amphibians whose fins have evolved into legs, but who still have a fishlike tail.

Mesozoic Era

The Mesozoic Era saw the rise of dinosaurs, which were the dominant vertebrates (animals with backbones) on land for many millions of years. If you look closely in the corners, you can see two harbingers of the future that first appeared in the Mesozoic Era: the first magnolia-like flowering plants *(lower left)* and the first shrew-like mammals *(lower right)*.



Cenozoic Era

In the Cenozoic Era, birds and mammals have flourished. In this scene from 15 million years ago, we can see recognizable ancestors of modern birds and primates.

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The Cambrian explosion FIGURE 3.10

Only the sketchiest remains are left of any life forms from Earth's earliest eons. But in the Cambrian Period, life suddenly exploded in a profusion of bizarre and now extinct forms, such as trilobites *(below),* Anomalocaris, and Opabinia.

Anomalocaris was the most fearsome predator of the Cambrian seas, a swimming creature up to a meter long.

Opabinia, which among other oddities had five eyes, was about 7 centimeters long and would have been a tasty morsel for Anomalocaris.

PERIODS AND EPOCHS

Geologists have divided the three eras of the Phanerozoic Eon into shorter units called **periods**. Some of them were also delineated by extinction events. Unfortunately, geologists named the periods in a somewhat haphazard way; with some periods named for geographic locations (e.g., Jurassic, from the Jura Mountains in Switzerland where this layer was first studied) and others named for the characteristics of their strata.

The earliest period of the Paleozoic Era, the Cambrian Period, is especially noteworthy. Not only is this when animals with hard shells first appeared in the geologic record, but in the opinion of many paleontologists it was a time of unparalleled diversity, a phenomenon called the "Cambrian Explosion" (see FIGURE 3.10). Rocks that formed before the Cambrian Period sometimes contain microscopic, soft-bodied fossils, but strata cannot be differentiated on the basis of the fossils they contain. Thus geologists often lump this enormous 4-billion-year swath of time and the rocks deposited then into one category, *Precambrian.*

Even periods, as we now know, lasted for tens of millions of years. Thus geologists find it helpful to split them into still smaller divisions called **epochs**. The names of the epochs of the Tertiary and Quaternary Periods are somewhat more familiar than others because humans and their ancestors emerged during these epochs, and the names sometimes appear in the popular press. These recent epochs are not defined by extinction events, but according to the percentage of their fossils that are represented by still-living species. Many plant and animal fossils found in Pliocene strata, for example, have still-living counterparts, but fossils in Eocene strata have few still-living counterparts.

CONCEPT CHECK STOP

What are the major subdivisions of the geologic time scale?

Why does the geologic time scale apply to rocks everywhere on Earth, not just those in one locality?

What major biological event distinguishes the Phanerozoic Eon from the previous (pre-Cambrian) eons?

Numerical Age

LEARNING OBJECTIVES

Describe how scientists finally arrived at a way of quantifying geologic time.

Describe the process of radioactive decay.

Explain how and why radioactive decay can be used to date igneous rocks.

Explain how magnetic polarity dating can be used to date both igneous and sedimentary rocks.

The scientists who worked out the Geologic Column were tantalized by the challenge of numerical time. They wanted to know Earth's age, how fast mountain ranges rise, how long the Paleozoic Era lasted, and most challenging of all, how long humans have inhabited Earth.

EARLY ATTEMPTS

Several methods for solving the problem of numerical time were proposed during the nineteenth century. All of them were unsuccessful, but the reasons for their failure are nonetheless quite illuminating—and they help explain where our currently accepted estimates came from (see FIGURE 3.11 on the following page). As previously mentioned, the earliest method involved estimating rates of sedimentation and multiplying by the thickness of stratigraphic sections. Unfortunately, the resulting estimates for Earth's age varied too widely to be useful, from 3 million to 1.5 billion years.

Early scientists recognized that rivers carry dissolved substances to the sea from the erosion of rocks on land. In 1715, Edmund Halley, for whom Halley's Comet is named, suggested that one could measure the rate at which salts are added to the sea by river input and calculate the time needed to transport all the salts now present in the sea. Halley did not carry out his own suggestion, and it was not until 1899 that John Joly made the necessary measurements and calculations. Joly estimated that the ocean was 90 million years old. Unfortunately, neither Halley nor Joly realized that the ocean, like other parts of the Earth system, is an open system. Salt is removed by reactions between seawater and volcanic rocks on the seafloor, as well as the evaporation of seawater in isolated basins. The addition and removal of salts have balanced each other for hundreds of millions (even billions) of years.

The nineteenth century also saw the publication of Charles Darwin's *On the Origin of Species* in 1859. The book intensified the ongoing debate over numerical ages. Darwin understood that the evolution of new species by natural selection must be a very slow process that needed vast amounts of time. The first edition of his book contained a rough estimate of Earth's age, based on the erosion rate of a mountain range, of at least 300 million years.

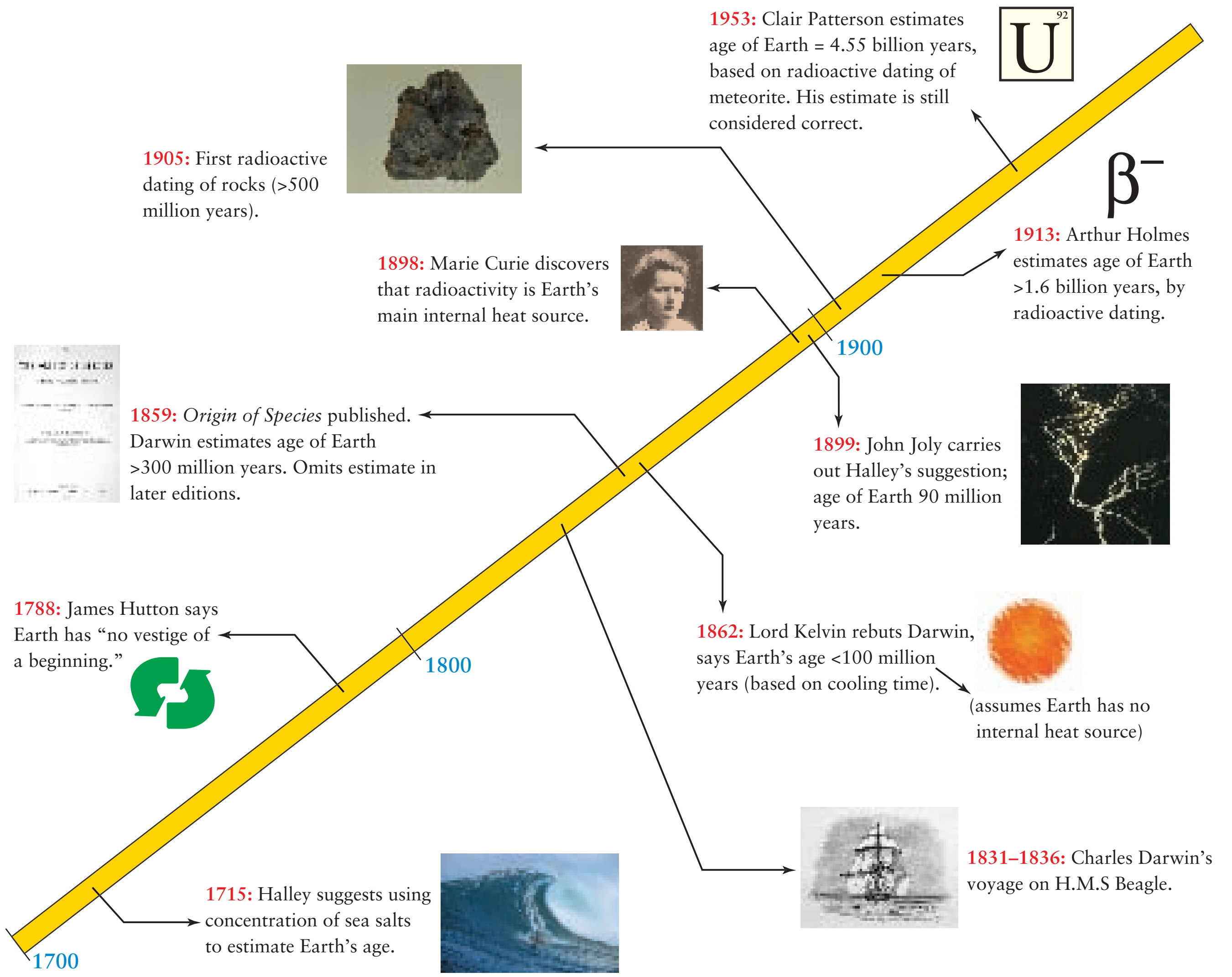
However, William Thomson (Lord Kelvin), a leading physicist and contemporary of Darwin, emphatically rejected Darwin's estimate. Kelvin used the laws of thermodynamics to calculate how long Earth has been a solid body. Kelvin made two assumptions: Earth was once completely molten, and no heat was added to it after it formed. Once it had cooled enough to form a solid outer layer, heat would escape only by conduction (the same way that heat moves through the wall of a coffee cup). Kelvin measured the current-day rate of heat loss and extrapolated backward to figure out the age of Earth's solid crust. He arrived at a figure of 20 million years. Even Darwin conceded, "Thomson's views on the recent age of the world have been for some time one of my sorest troubles," and removed his age estimate from later editions of *On the Origin of Species*.

Darwin died before geologists vindicated him. Kelvin's mistake was his assumption that no heat had

Visualizing

The debate over numerical age FIGURE 3.11

This timeline chronicles some of the major episodes in the long debate over how old Earth is. Note that even the unsuccessful attempts, such as Kelvin's or Joly's, were useful because they pointed out the incorrect assumptions that these scientists and others had made.



been added to Earth's interior since its formation. He did not know about **radioactivity**. Though Earth is a closed system (as we explained in Chapter 1), it does have inputs and outputs of energy, and Kelvin had missed a key input.

What was needed to solve the problem of numerical geologic time was a way to measure events by some process that runs continuously, is not reversible, is not influenced by such factors as chemical reactions and high temperatures, and leaves a continuous record without any gaps. The discovery of radioactivity not only proved that Kelvin's assumptions were wrong, but by fortunate chance, also provided the breakthrough needed to measure absolute time.

radioactivity A process in which an element spontaneously transforms into another isotope of the same element, or into a different element.

RADIOACTIVITY AND NUMERICAL AGES

To explain how radioactive dating works, we need to go back to the fundamentals of chemistry. Chapter 2 stated that most chemical elements have two or more *isotopes* that have the same number of protons per atom but a different number of neutrons per atom. To put it another way, each isotope of an element has the same atomic number but a different mass number.

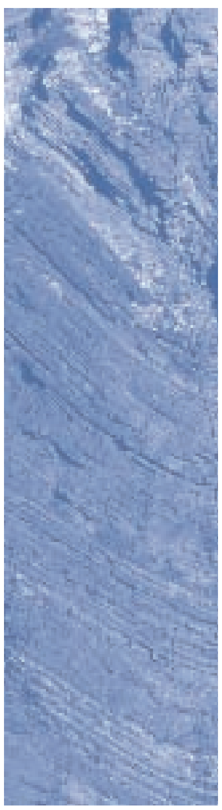
Most naturally occurring isotopes have stable nuclei. However, a few of them—such as carbon-14 and potassium-40—are unstable. They spontaneously release particles from their nuclei. In the process, they change their mass number, their atomic number, or both (see FIGURE 3.12). Any isotope that spontaneously undergoes such nuclear change is said to be *radioactive*, and the process of change is referred to as *radioactive decay*.

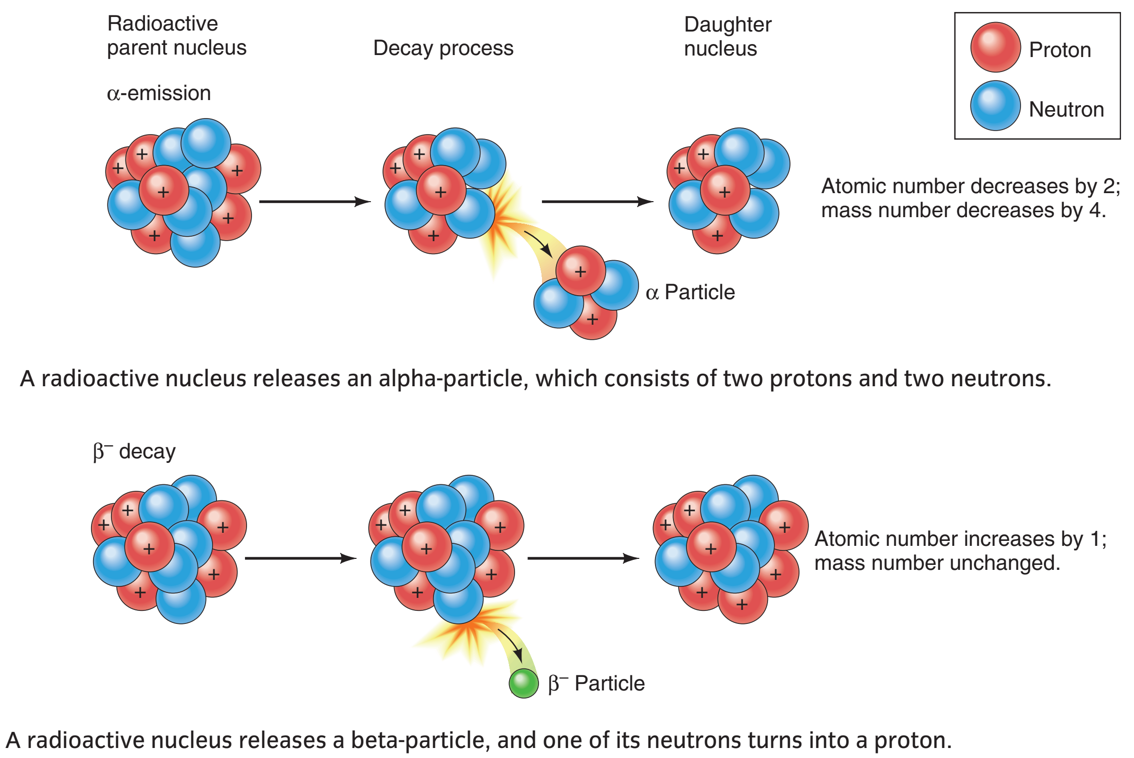
Because radioactive decay involves the nucleus, it is *not* a chemical process. In fact, it releases far more energy than any chemical reaction, which explains why it is still keeping Earth's interior hot after more than 4 billion years. The decay of radioactive isotopes is not influenced by any chemical process or by any conditions of heat or high pressure within Earth. Thus radioactive decay is a perfect built-in geologic clock, at least for rocks that contain radioactive isotopes. Furthermore, because each radioactive isotope has its own rate of decay, a rock that contains several different radioactive isotopes has numerous built-in clocks that can be checked against each other.

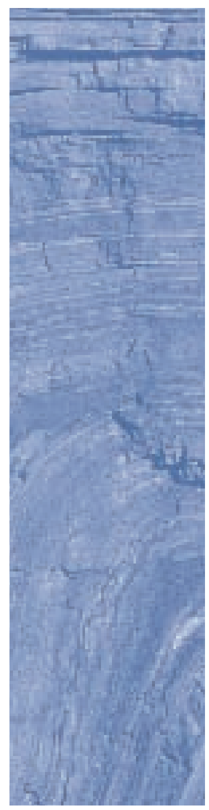
Rates of Decay

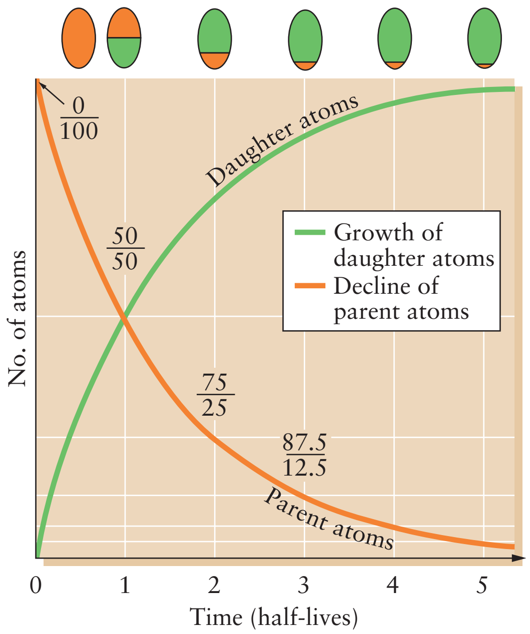
In any radioactive decay system, the number of radioactive parent atoms continuously decreases, while the number of nonradioactive daughter atoms continuously increases. For this reason, many of the radioactive isotopes that were present when Earth

Radioactive decay FIGURE 3.12









Radioactivity and time FIGURE 3.13

This graph illustrates the basic decay law of radioactivity. Suppose that a given isotope has a half-life of 1 hour. If we started with a sample consisting of 100 percent radioactive parent atoms, after an hour only 50 percent of the parent atoms would remain and an equal number of daughter atoms would have formed. At the end of the second hour, another half of the parent atoms would be gone, so there would be 25 percent parent atoms and 75 percent daughter atoms. After the third hour, another half of the parent atoms would have decayed, leaving 12.5 percent parent atoms and 87.5 percent daughter atoms. Note that the total number of atoms, parent plus daughter, remains constant. This fact is the key to the use of radioactivity to measure geologic time.

was formed have decayed away because they were short-lived. However, a few radioactive isotopes that decay very slowly are still present.

Regardless of how quickly or slowly they proceed, all decay rates follow the same basic law: The *proportion* of parent atoms that decay during each unit of time is always the same (see FIGURE 3.13). Proportion means a fraction, or percentage, not a whole number. The rate of radioactive decay is determined by the **half-life**.

Radiometric Dating: Not One Clock but Many

Radioactivity was discovered in 1896; the first estimates of the ages of rocks using radioactive decay were made in 1905. The long-hoped-for rock clock was finally available. The results were, and continue to be, remarkable. **Radiometric dating** has revolutionized the way we think about Earth and its long history.

A radioactive rock clock usually measures the amount of time that has elapsed since the minerals in the rock crystallized. When a new mineral grain forms—for example, a grain of feldspar in cooling lava—all the atoms in the grain become locked into the crystal structure and isolated from the environment outside the grain. In a sense, the atoms in the mineral grain, including any radioactive atoms, are sealed in an atomic time capsule. The trapped radioactive atoms decay to daughter atoms at a rate determined by the half-life.

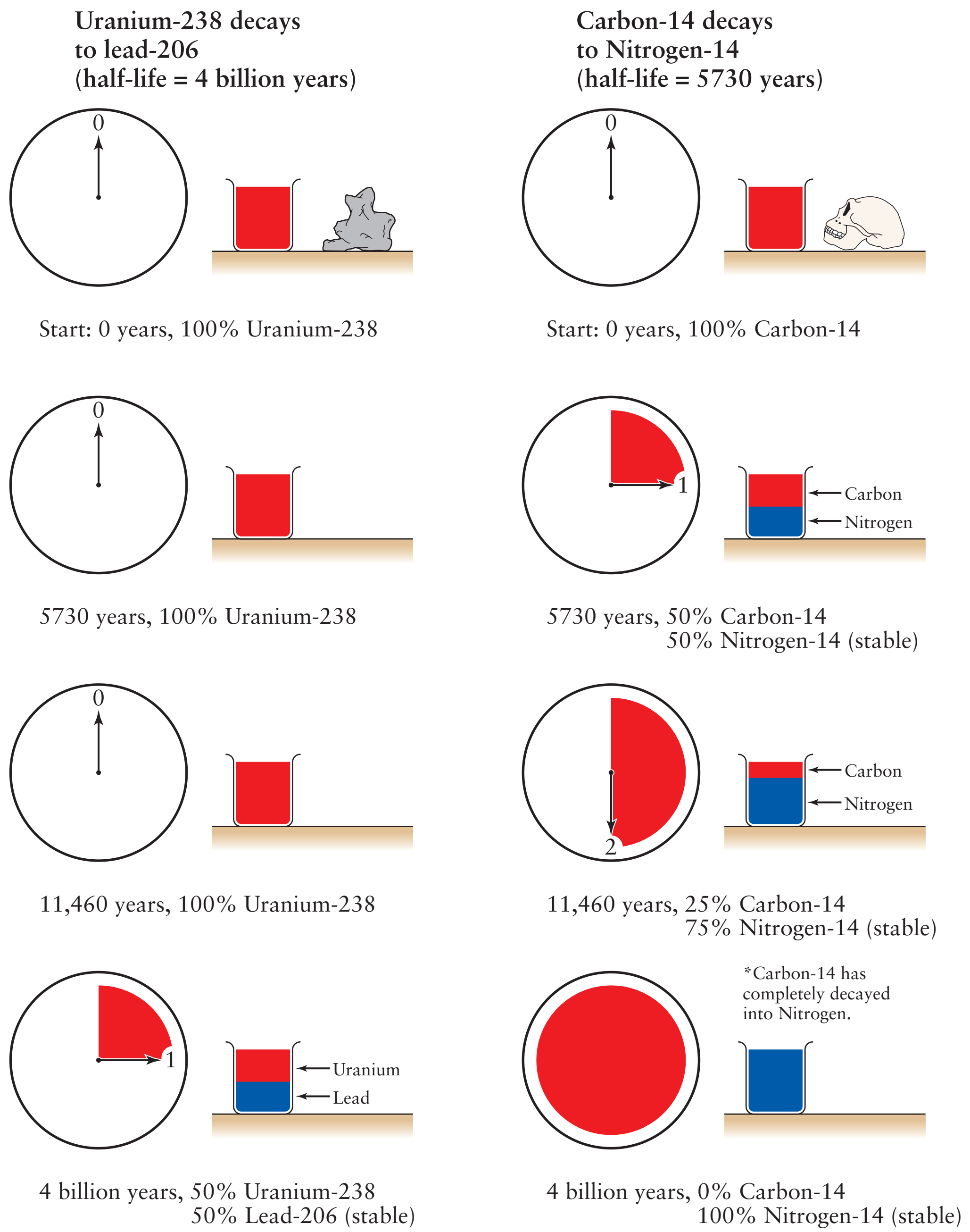
In the simplest case, if no daughter atoms were present in the mineral at the time of formation, we can use Figure 3.13 to work backward and determine how long ago the time capsule was sealed. If the mineral crystal contained some daughter atoms at the time of formation, the process is more difficult. Geologists have developed several ways to estimate the initial contamination of a sample by daughter atoms. Once that is done, and provided we know the half-life of the radioactive parent, it is a simple matter to calculate how long ago the mineral crystallized. Note that geologists use different isotopic systems to study rocks of different ages and compositions (see FIGURE 3.14).

Radiometric dating has been particularly useful for determining the ages of igneous rocks, because the mineral grains in an igneous rock form at the same time as the rock that contains them. On the other hand, most sedimentary rocks consist largely of mineral grains

half-life The time needed for a half of the atoms of a radioactive substance to decay into daughter atoms.

radiometric dating The use of naturally occurring radioactive isotopes to determine the numerical age of minerals or rocks.

Isotopes used in radiometric dating FIGURE 3.14



Long-lived isotopes such as uranium-238 are especially useful for dating ancient rocks. Short-lived isotopes such as carbon-14 are useless for dating samples that are millions of years old, including many of the rocks that are of interest to geologists. However, carbon-14 is very useful for dating geologically recent items, such as human artifacts. Geologists have also used it to date the latest Ice Age, by estimating the age of wood samples taken from trees killed by the advancing ice sheet.

that were formed long before the strata that contain them were deposited. Radiometric dating will tell how old the grains are but not when the strata were deposited. This makes it difficult to directly date most sedimentary rocks and to infer the numerical age of ancient life forms fossilized in the sediments.

Numerical Time and the Geologic Column

As geologists worked out the Geologic Column, they found many locations where layers of solidified lava and volcanic ash are interspersed with sedimentary strata. Through radiometric dating, they could determine the numerical ages of the lavas and volcanic ash and thereby bracket the ages of the sedimentary strata (see FIGURE 3.15).

Through a combination of geologic relations and radiometric dating, scientists have been able to fill in all the dates in the Geologic Column as shown in Figure 3.8. The scale is continually being refined, so the numbers given in the figure should be considered the best currently available. Further work will make the numbers more precise. It is a tribute to the work of geologists during the nineteenth century that the Geologic Column they established by ordering strata according to their relative ages has been fully confirmed by radiometric dating. At the same time, it is humbling to see how one wrong assumption caused Lord Kelvin to be more than 4 billion years off in his estimate of Earth's age.

MAGNETIC POLARITY DATING

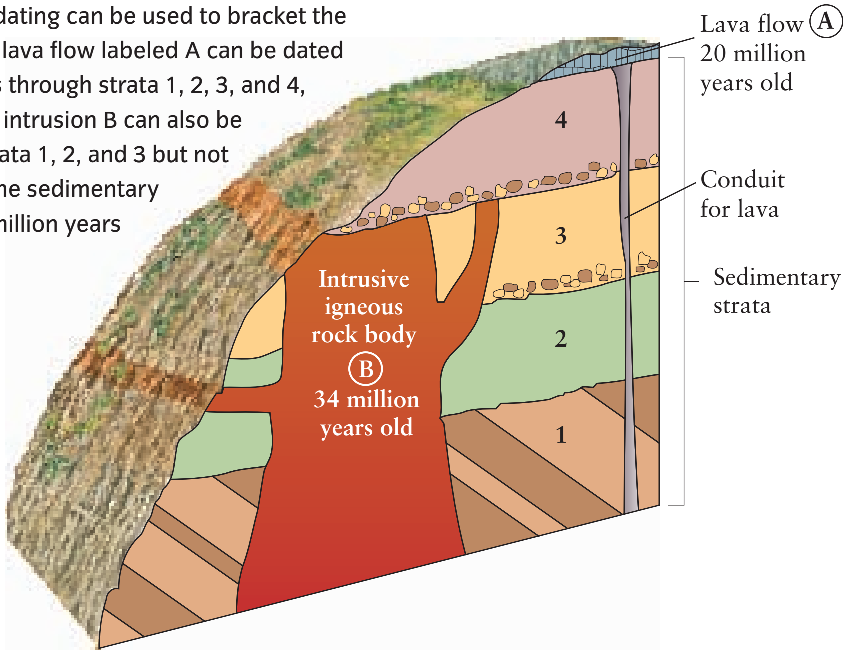
Time is so central to the study of Earth that geologists are always seeking new ways to estimate ages. An exciting newer method of dating, developed in the 1960s, involves **paleomagnetism**, the study of Earth's past magnetic field (FIGURE 3.16). Both igneous and sedimentary rocks "lock in" information about the magnetic field at their time of formation.

> **paleomagnetism** The study of rock magnetism in order to determine the intensity and direction of Earth's magnetic field in the geologic past.

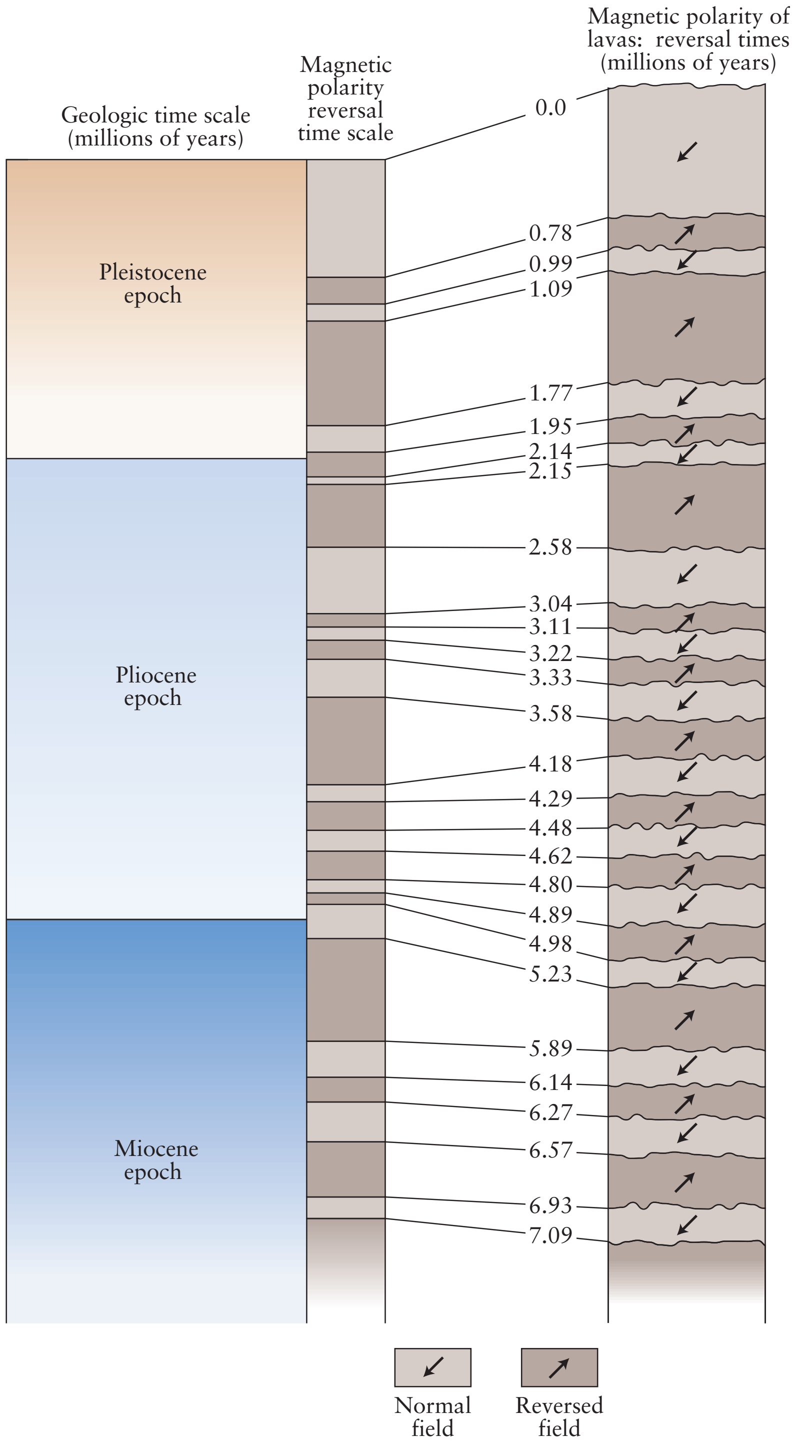
Earth's magnetic field reverses its polarity at irregular intervals, but on average, about once every half million years. This means that the magnetic pole that had

Radiometric dating and the Geologic Column FIGURE 3.15

This idealized drawing shows how radiometric dating can be used to bracket the ages of sedimentary strata. The conduit for the lava flow labeled A can be dated directly by radiometric means. The conduit cuts through strata 1, 2, 3, and 4, so it must be younger than all of them. Igneous intrusion B can also be dated by radiometric means. It cuts through strata 1, 2, and 3 but not 4, and hence must be older than layer 4. Thus the sedimentary rocks in layer 4 are between 20 million and 34 million years old.



Magnetic reversal time scale FIGURE 3.16



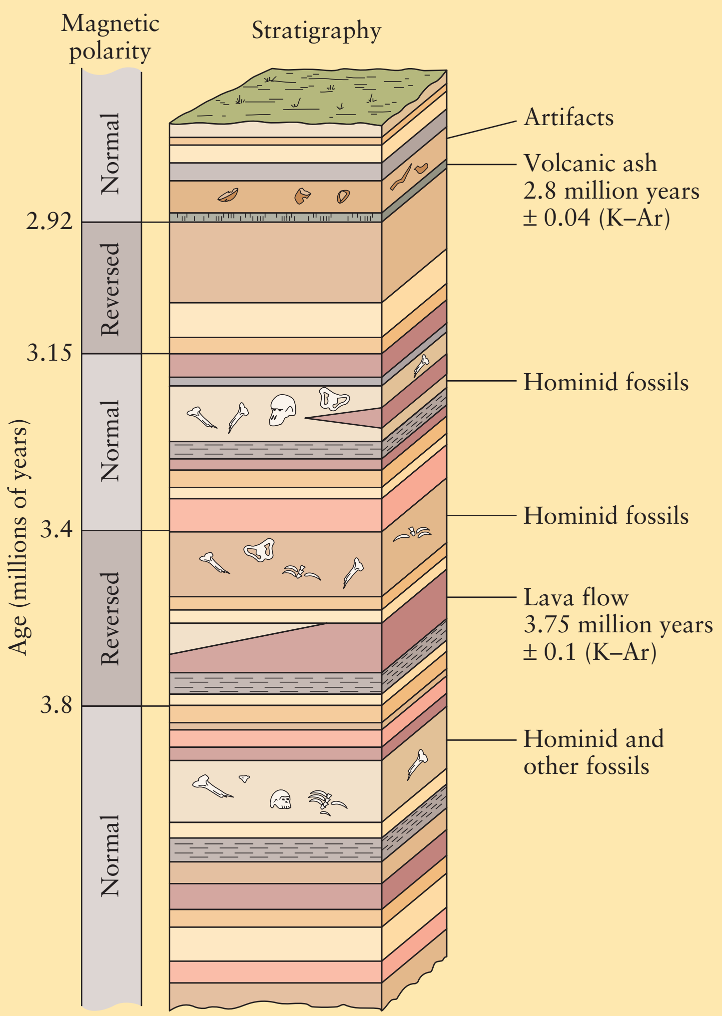
Periods of normal polarity, as today, and periods of reversed polarity have been identified and dated, using radiometric dating of lavas, back to the beginning of the Jurassic Period, about 200 million years ago. This figure shows the most recent 7 million years.

CASE STUDY

Dating Human Ancestors

The Haddar region of northern Ethiopia has been a fertile site for finding fossils of ancient human ancestors, part of a larger group called *hominids*. Many of the fossils have been found in ancient stream gravels, where they were tumbled and battered by long-ago floodwaters. The fossil-bearing gravels are interlayered with sediments that give good magnetic signals.

The problem is to know where in the magnetic polarity time scale the Haddar sediment falls. Geologists answered this question by dating a lava flow that lay below some of the hominid fossils and a layer of volcanic ash that lay above them. The two radiometric dates determined the magnetic reversal ages unambiguously and indicated that early hominids lived in the region until about 3.15 million years ago, during the Pliocene Epoch. Through many studies like this, it is slowly becoming clear that the hominid genus *Homo* (which includes our own species, *Homo sapiens*) evolved a little more than 2 million years ago from an older genus called *Australopithecus*. (Two reconstructed Australopithecus skulls are shown at bottom right.)



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magnetic reversal A period of time in which Earth's magnetic polarity reverses itself.

been in the northern hemisphere moves to a position near Earth's south pole, and the magnetic pole that had been in the south moves to the north. Note, however, that Earth's geographic North and South poles of rotation do not change position. Scientists are still working out details of how or why **magnetic reversals** happen. The two important points are that the reversal happens quickly by geologic time standards, and any iron-bearing mineral in a sedimentary or igneous rock retains or "remembers" the magnetic polarity of Earth at the time that the rock was formed—that is, a change in the magnetic field does not affect already formed minerals. Through a combination of radiometric dating and magnetic polarity measurements, it has been possible to establish a time scale of magnetic polarity reversals dating back to the Jurassic Period (see Figure 3.16). Still earlier reversals are a subject of ongoing research.

Correlation on the basis of magnetic reversals differs from other geologic correlation methods. One magnetic reversal looks just like any other in the rock record. When evidence of a magnetic reversal is found in a sequence of rocks, the problem lies in knowing which of the many reversals it actually represents. When a continuous record of reversals can be found, starting with the present, it is simply a matter of counting backward. But if not, the technique must be combined with stratigraphic and radioactive dating techniques (see Case Study on page 62). Chapter 4 discusses how magnetic polarity dating played a crucial role in the development of plate tectonic theory.

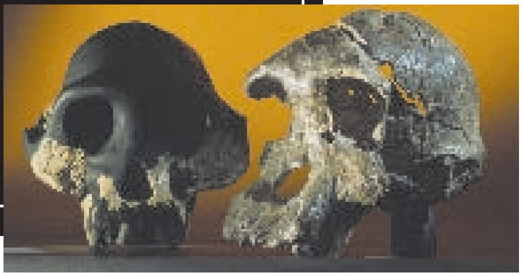
CONCEPT CHECK STOP

What were some of the early attempts to calculate the age of Earth? Why were they inaccurate?

Why is radioactive decay useful as a "geological clock"?

What geological materials are most useful for obtaining numerical ages through radiometric techniques? Which are the least useful, and why?

Why can magnetic polarity dating sometimes provide more detailed age information than radiometric dating?



The Age of Earth

Learning Objectives

Explain why the age of the oldest rocks is not necessarily the age of the planet.

Explain why scientists currently believe Earth is about 4.56 billion years old.

Throughout this book, we mention examples of actual rates of geologic processes. This would not be possible without the numerical dates obtained through radiometric dating and other numerical age methods. In fact, more than any other contribution by geologists, the ability to determine numerical dates has changed the way humans think about the world and the immensity of geologic time.

Now that we know how to determine the numerical ages of rocks, can we determine Earth's age? It's not as easy as you might think. The continual recycling of Earth's surface by erosion and plate tectonics means that very few, if any, remnants of Earth's

Earth's oldest rocks FIGURE 3.17

The Acasta gneiss in northern Canada was formed 4.0 billion years ago. It is the most ancient body of rock so far discovered on Earth.

original crust remain. Of the many radiometric dates obtained from Precambrian rocks, the oldest is about 4.0 billion years (see FIGURE 3.17). Although no older rocks than this have been found, an individual mineral grain from a sedimentary rock in Australia has been dated to 4.4 billion years, so it is conceivable that igneous rocks older than 4.0 billion years may someday be located.

However, geologists believe that there is still a gap between the age of these oldest mineral grains and the age of Earth. There is strong evidence that Earth formed at the same time as the Moon, the other planets, and meteorites. Through radiometric dating, it has been possible to determine the ages of meteorites and of "moon dust" brought back by astronauts. The *Apollo* astronauts found rocks and individual grains of Moon dust that are believed to be pieces of the Moon's original crust. Such rocks should be abundant because the Moon has been geologically much less active than Earth.

Meteorite ages are especially valuable because some meteorites have remained frozen since the formation of the solar system. (Recall that melting resets the radiometric clock.) For example, the Allende Meteorite, which fell to Earth in the Mexican state of Chihuahua on February 8, 1969, belongs to a rare category called *carbonaceous chondrites*, which are believed to contain unaltered material from the formation of the solar system. It is "carbonaceous" because it contains tiny amounts of carbon (about 3 parts per 1000). Some of the carbon is in chemical compounds called amino acids—organic components that are

A cosmic interloper FIGURE 3.18

The Allende Meteorite, which fell to Earth in Mexico, is one of the most famous meteorites in history. Note the white spots on the meteorite. Some of these inclusions, which are slightly older than the black carbonaceous material around them, are more than 4.6 billion years old, making them the oldest objects of any kind ever found on Earth.

essential for life. The dark, fine-grained part of the meteorite is mostly olivine, with a few flecks of metallic iron and some carbon. The clumps of white material are oxide and silicate minerals of calcium and aluminum and are thought to be the first matter to condense in the gas cloud that formed the Solar System (FIGURE 3.18). The white clumps are older than Earth itself.

The ages of many of these objects cluster closely around 4.56 billion years. Planetary scientists therefore believe that Earth, and indeed the Sun's entire planetary system, formed at that time.

Today, two centuries after Hutton, it is widely agreed that Earth was formed about 4.56 billion years ago. When will it cease to exist? Astronomers tell us that billions of years in the future, the Sun will become a red giant, at which point it will expand and engulf Earth. However, Hutton is still correct in one sense: from geologic evidence there is no prospect of an end to Earth's existence.

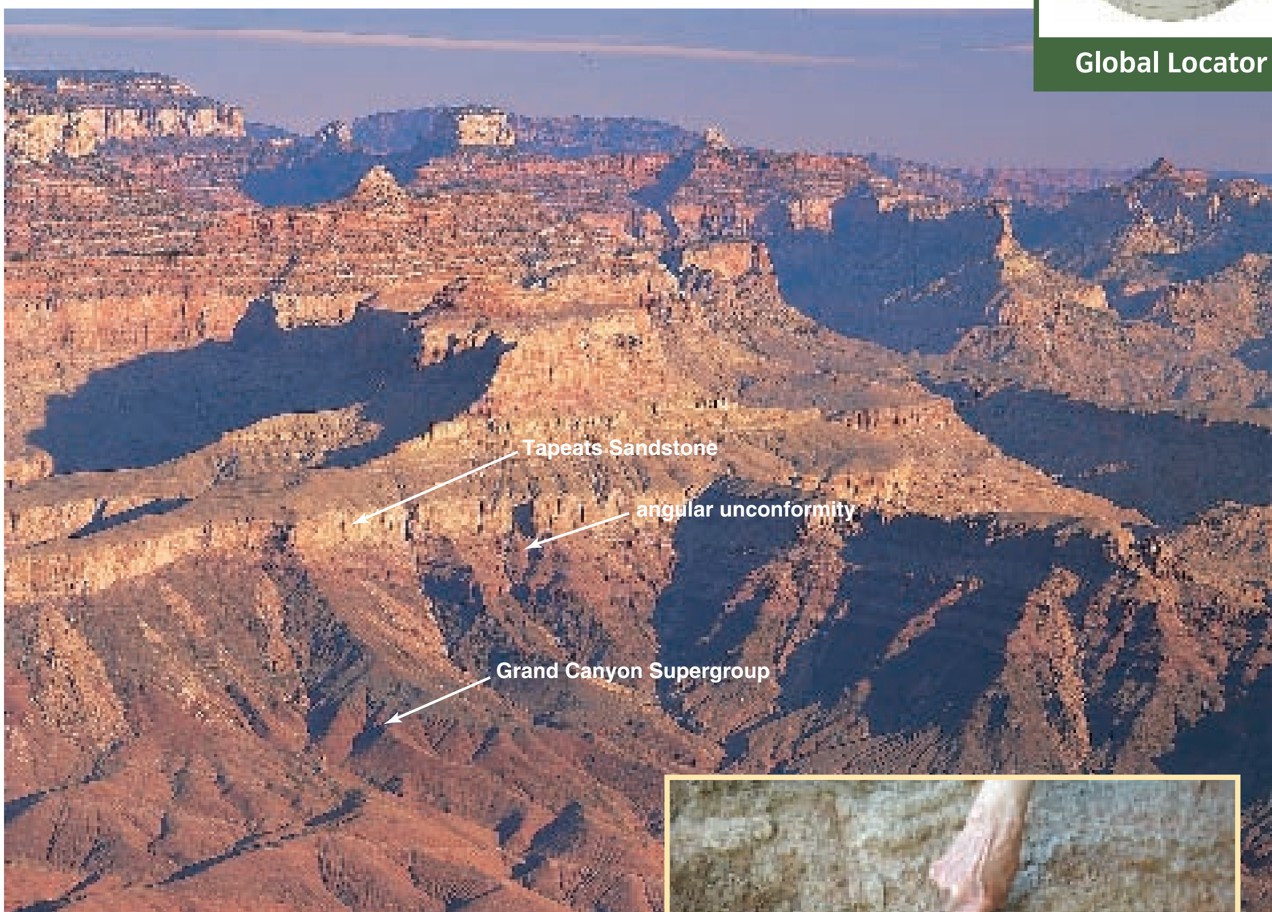
CONCEPT CHECK STOP

What is the oldest age that has been obtained from material found of Earth? Does this match the presumed age of Earth? Why or why not?

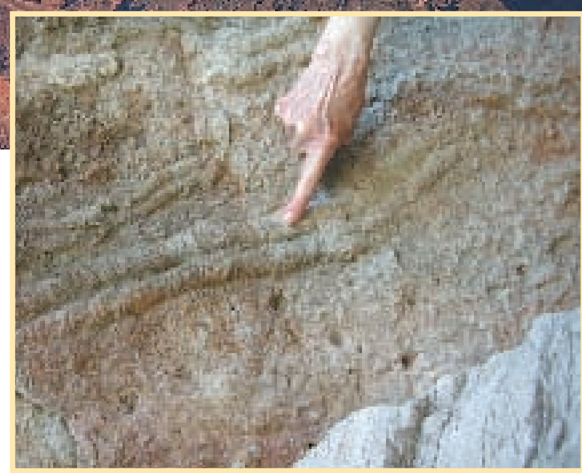
How have meteorites and rocks from the Moon helped determine the age of Earth?

Amazing Places: The Grand Canyon

Global Locator



Standing at the rim of the Grand Canyon, you can see more than 2 billion years of Earth's history, preserved in the rocks. All three kinds of unconformities can be found here. The upper layers in this photograph were all deposited during the Paleozoic Era. Some of the contacts between different-colored parallel strata are disconformities, and they record the rising and ebbing of seas over this part of the North American continent. Below the Tapeats Sandstone (arrow) you can see an angular unconformity, which also represents a major time gap between Precambrian rocks (deposited about 825 million years ago) and Cambrian rocks (deposited less than 545 million years ago). Finally, there is a nonconformity (not visible in the photo) between the lowermost sedimentary layer of the Grand Canyon Supergroup, the Bass Limestone, and the Vishnu Formation, a foundation of metamorphic and igneous rocks that once lay at the base of an ancient mountain range that eroded away long before the Rocky Mountains came into existence.



As a geology student you owe it to yourself not to stop at the rim, as most tourists do, but to descend to the river level and get a close-up look at 2 billion years of Earth's history. You might be lucky and see trilobite tracks, like these, in the Tapeats Sandstone. The tracks were made when trilobites (like the one shown in Figure 3.10) extended their legs sideways, pulled in mud, then, under the safety of their hard shells, picked over the mud for food.

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CHAPTER SUMMARY

1 Relative Age

1. Geologists study the chronology sequence of geologic events, that is, their **relative age**. Relative age is derived from **stratigraphy**, the study of rock layers and how those layers are formed.

2. There are three basic principles of stratigraphy. **Strata**, or sedimentary rock layers, are horizontal when they are deposited as water-laid sediment *(principle of original horizontality)*. Strata accumulate in sequence, from the oldest on the bottom to the youngest on the top *(principle of superposition)*. The final principle for finding relative age is that a rock stratum is always older than any geologic feature, such as a fracture, that cuts across it *(principle of cross-cutting relationships)*.

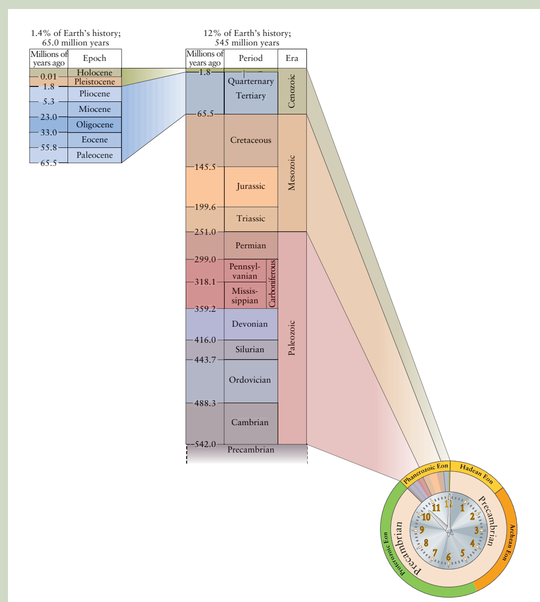
3. **Numerical age**, the exact number of years of a geologic feature, is more difficult to find. One difficulty that arises is that the sequence of strata in any particular location is not necessarily continuous in time. An **unconformity** is a break or gap in the normal stratigraphic sequence. It usually marks a period during which sedimentation ceased and erosion removed some of the previously laid strata. The three common types of unconformities are nonconformities, angular unconformties, and disconformities.

4. **Correlation** of strata is the establishment of the time equivalence of strata in different places. **Fossil** assemblages, usually consisting of hard shells, bones, and wood, have been the primary key to correlation of strata across long distances. The study of fossils and the record of ancient life on Earth is called **paleontology**. The principle of *faunal and floral successions* (plants and animals, respectively) is the stratagraphic ordering of fossil assemblages.

2 The Geologic Column

1. The **Geologic Column**, a *stratigraphic time scale*, is a composite diagram that shows the succession of all known strata, arranged in chronological order of formation, based on fossils and other age criteria.

2. The Geologic Column is divided into several different units of time, called **eons**, **eras**, **periods**, and **epochs**. The majority of Earth's history is divided into three eons, in which fossils are very rare or nonexistent. Those eons, each spanning several hundred million years, are the *Hadean*, *Archean*, and *Proterozoic*. The fourth and most recent eon, the *Phanerozoic*, is the only eon in which fossils are abundant. Very dramatic changes in fossil assemblages occur between the three eras of the Phanerozoic eon—the *Paleozoic*, *Mesozoic*, and *Cenozoic*—which were separated by major extinction events. The earliest period of the Paleozoic era is especially important, as this was a time of unique diversity. This period is known as the "Cambrian Explosion." Rocks formed before the Cambrian period cannot be differentiated by the fossil record; these rocks are considered to be *Precambrian*.



CHAPTER SUMMARY

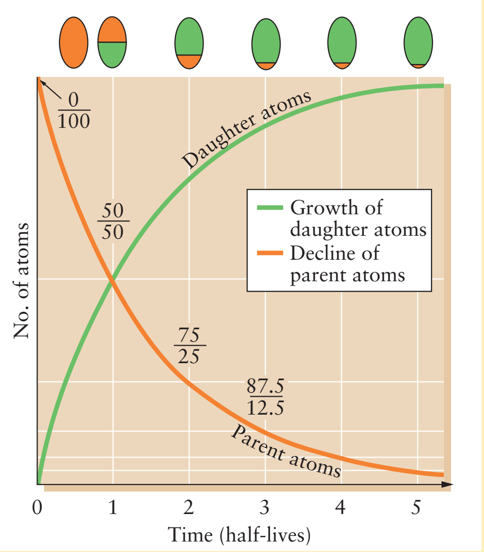
3 Numerical Age

1. Finding the age of Earth contined to be of interest to many scientists. Different theories were proposed by Halley, Joly, Darwin, Lord Kelvin, and several other prominent scientists of the later 1800s and early 1900s. Though many of these theories were proved to be incorrect, each was an important step in finding a method of numerical dating.

2. **Radioactivity** is the process in which an element transforms itself into another *isotope* of the same element, or into a different element, through the release of particles and heat energy. The *radioactive decay* of isotopes of chemical elements provides a basis for radiometric dating, which gives values for the numerical ages (age in years) of rock units and thus values for numerical dates of geologic events. Because radioactive decay is not influenced by chemical processes or by heat and high pressure in Earth, it is an extremely accurate gauge of numerical age.

3. **Radiometric dating** is based on the principle that in any sample containing a radioactive isotope, half of its atoms of that isotope will change to daughter atoms in a specific length of time, called the **half-life**. (The *proportion* of parent atom decay during a unit of time is always the same.) Radioactive isotopes with a long half-life, such as uranium, are most useful for dating rocks. Carbon-14, which has a much shorter half-life, is most useful for dating organic materials of relatively recent origin (less than 70,000 years).

4. Though radiometric dating is primarily useful for igneous rocks, a complementary technique called magnetic polarity dating works for sedimentary rocks, too. Magnetic polarity dating involves **paleomagnetism**, the study of reversals in Earth's magnetic field. As yet, **magnetic reversals**, or periods of time in which Earth's magnetic polarity reverses itself, are not fully understood.



4 The Age of Earth

1. Through measures of numerical age, it has become clear that most of Earth's history took place in Precambrian time. The oldest Earth rocks discovered are about 4.0 billion years old.

2. Because radiometric clocks are reset by melting, Earth is not a good place to look for the oldest rocks in the solar system. Samples from the Moon and from meteorites indicate that the solar system formed about 4.56 billion years ago, and by inference this is also the age of Earth.

KEY TERMS

- **relative age** p. 44
- **stratigraphy** p. 44
- **numerical age** p. 47
- **unconformity** p. 47
- **paleontology** p. 49
- **correlation** p. 50
- **Geologic Column** p. 51
- **radioactivity** p. 56
- **half-life** p. 58
- **radiometric dating** p. 58
- **paleomagnetism** p. 60
- **magnetic reversal** p. 63

CRITICAL AND CREATIVE THINKING QUESTIONS

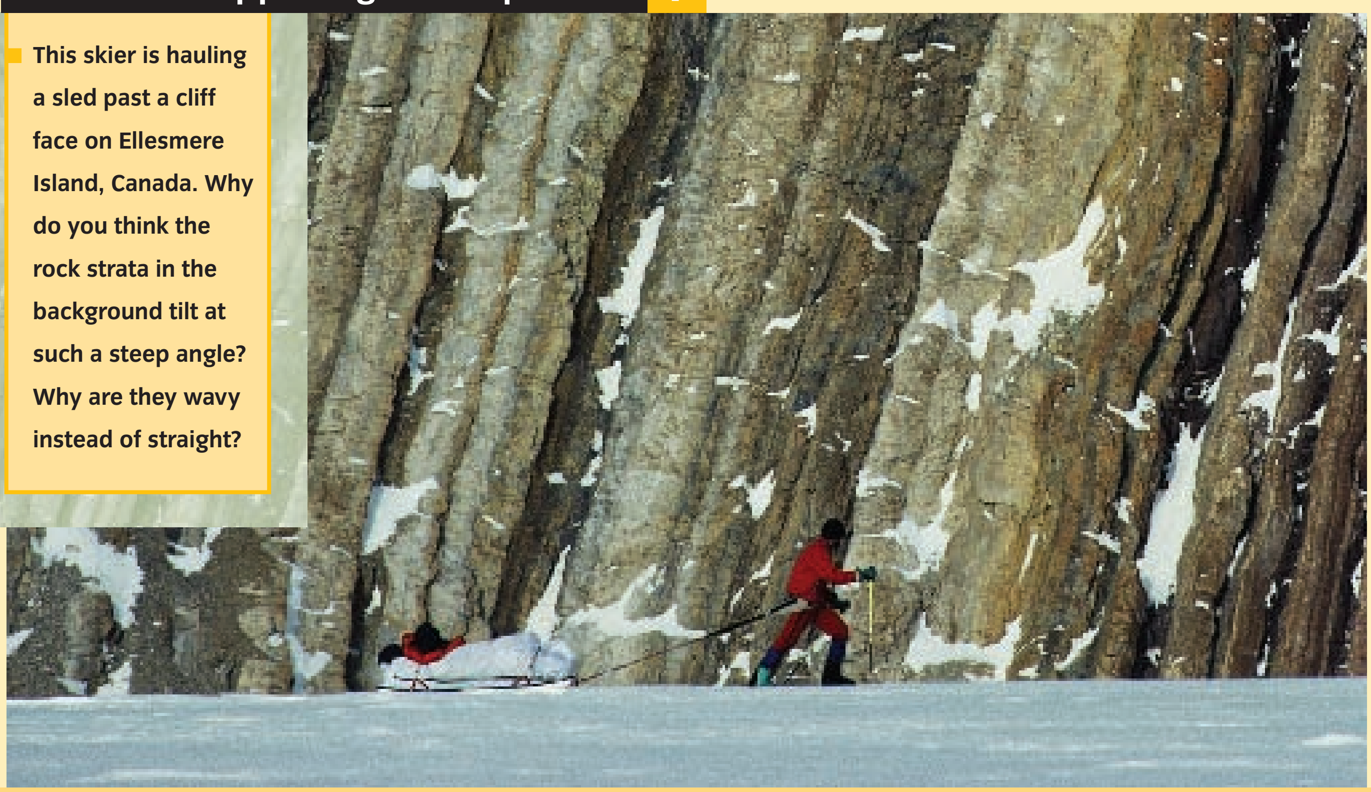
1. Do the same principles of stratigraphy apply on the Moon as they do on Earth? Bear in mind that the geologic processes on the Moon have been very different from those on Earth. If you had to determine the relative age of features on the Moon, based entirely on satellite photographs, what would you look for and how might you proceed?

2. Check the area in which you live to see if there is an excavation—perhaps one associated with a new building or road repair. Visit the excavation and note the various layers, the paving (if the excavation is in a road), and the soil below the surface. Is any bedrock exposed beneath the soil?

3. How old are the rock formations in the area where you live and attend college or university? How can you find out the answer to this question?

4. Choose one of the geologic periods or epochs listed in Figure 3.8 and find out all you can about it: How are rocks from that period identified? What are its most characteristic fossils? Where are the best samples of rocks from your chosen period found?

What is happening in this picture ?



- This skier is hauling a sled past a cliff face on Ellesmere Island, Canada. Why do you think the rock strata in the background tilt at such a steep angle? Why are they wavy instead of straight?

SELF-TEST: THE ROCK RECORD AND DEEP GEOLOGIC TIME

1. A _______________ is the age of a one rock unit or geologic feature compared to another.

a. relative age
b. numerical age

2. The principle of cross-cutting relationships says that

a. water-borne sediments are deposited in nearly horizontal layers.
b. a sediment or sedimentary rock layer is younger than the layers below it and older than the layers that lie above.
c. a rock unit is older than a feature that disrupts it, such as a fault or igneous intrusion.
d. a sediment or sedimentary rock layer is older than the layers below it and younger than the layers that lie above.

3. The _______________ states that water-borne sediments are deposited in nearly horizontal layers.

a. law of superposition
b. principle of faunal succession
c. principle of original horizontality
d. principle of cross-cutting relationship

4. In a conformable sequence

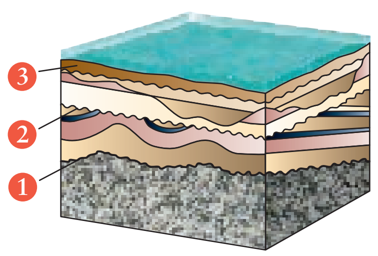
a. Each layer must have been deposited on the one below it without any interruptions.
b. There must not be any depositonal gaps in the stratigraphic record.
c. Both a. and b.
d. None of the above

5. An unconformity represents

a. a gap in the stratigraphic record.
b. a period of erosion or nondeposition.
c. Both a. and b.
d. None of the above.

6. For the figure below label each unconformity as one of following:

nonconformity
angular unconformity
disconformity



7. Fossils found in strata

a. are the records of ancient life.
b. allow the correlation of strata separated by many miles.
c. have been useful to geologists in creating the Geologic Column.
d. All of the above statements are correct.
e. None of the above statements are correct.

8. The three eras that make up the Phanerozoic Eon are the

a. Hadean, Archean, and Proterozoic.
b. Paleozoic, Mesozoic, and Cenozoic.
c. Triassic, Jurassic, and Cretaceous.
d. Pliocene, Pliestocene, and Holocene.

9. The most distinctive changes in the fossil record occur across the boundaries between

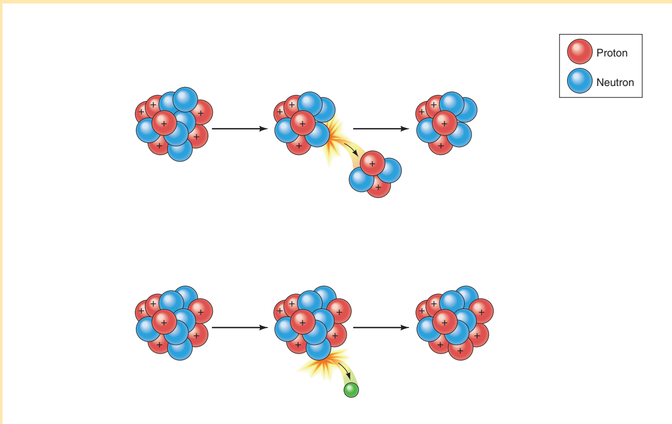
a. periods.
b. eras.
c. epochs.

10. The dinosaurs were dominant during the _______________.

a. Cenozoic
b. Mesozoic
c. Paleozoic
d. Precambrian

11. Label the two decay sequences depicted in this illustration as either alpha emission or beta decay. For each decay sequence, also label the following:

parent nucleus	alpha particle
daughter nucleus	beta particle



12. Potassium 40 is a naturally occurring radioisotope that decays to Argon 40 and is common in many rocks of the continental crust. The half-life of Potassium 40 is 1.3 billion years. Assuming no contamination, what would be the age of a sample that contained a 3:1 ratio of Potassium 40 to Argon 40?

a. 1.3 billion years.
b. 650 million years.
c. 2.6 billion years.
d. 325 million years.

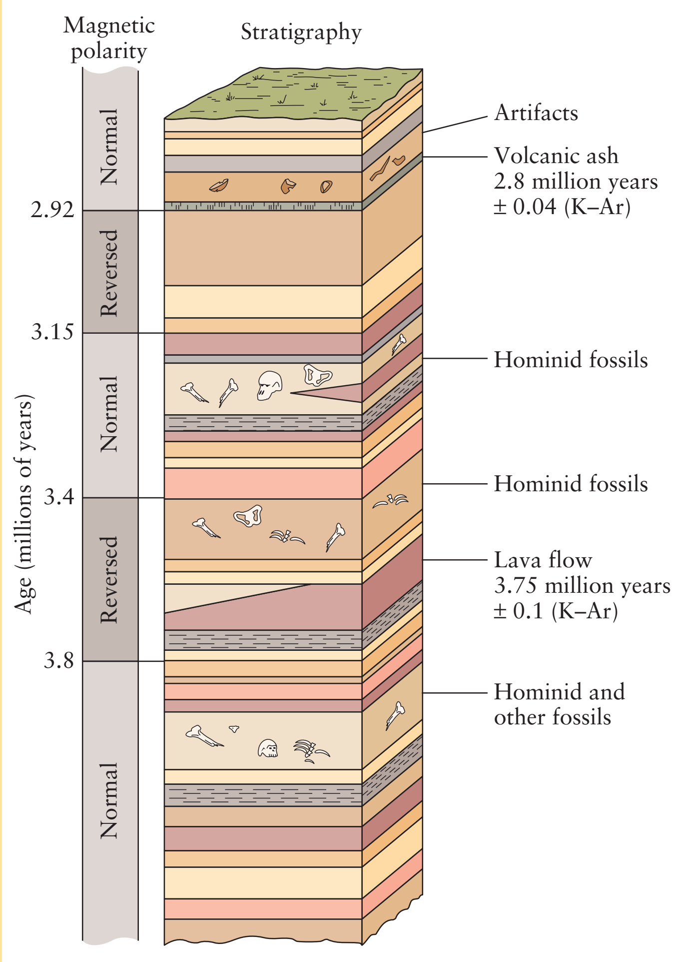
13. If the sample indicated above showed evidence that it had been heated by contact with a more recent lava flow, what would be the likely error in the determined age?

a. The sample would appear too young.
b. The sample would appear too old.
c. Rocks are a "closed system"; there would be no error.

14. A gravel deposit containing an important hominid tooth fossil is found in a field location in Northern Ethiopia. The gravel deposit has fragments of volcanic rocks dated at 3.75 million years ± 0.1 (K-Ar) and is known from stratigraphy to be younger than a 2.8 million year ± 0.06 (K-Ar) volcanic ash deposit. Sediments interlayered with the fossil-bearing gravels have good magnetic signals and have a normal polarity. Given the figure in the second column for the region, what is the most likely date for the hominid fossil?

a. Between 3.8 and 3.4 million years.
b. Between 3.4 and 3.15 million years.
c. Exactly 3.75 million years.
d. Younger than 2.92 million years.

Question 14



15. Earth is not considered a good place to look for the oldest rocks in the solar system because

a. contamination from atmospheric tests of nuclear weapons have contaminated the crust of Earth.
b. Earth's magnetic field interferes with the radiometric clocks in most igneous rocks.
c. melting has reset radiometric clocks in the rocks of Earth's crust.