



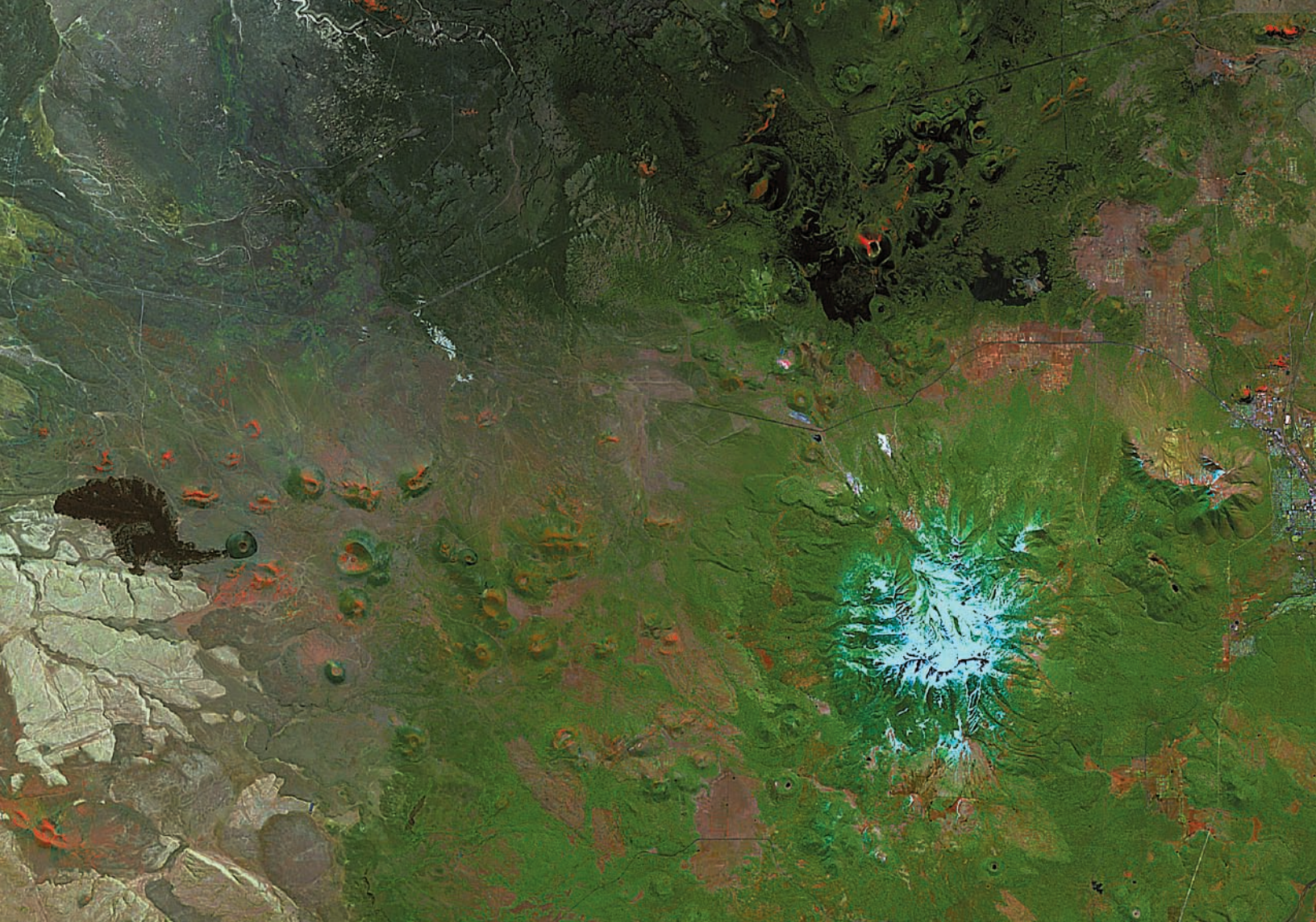
# 8

## Geologic Time

Some sciences deal with incredibly large numbers, others with great distances, still others with infinitesimally small particles. In every field of science, students must expand their conceptions of reality, a sometimes difficult, but very rewarding, adjustment to make. Geology students must expand their conceptions of the duration of time. Because life is short, we tend to think 20 years is a long time. A hundred years in most frames of reference is a very long time; yet, in studying Earth and the processes that operate on it, we must attempt to comprehend time spans of 1 million years, 100 million years, and even several billion years.

As a beginning student, you can see that rocks are records of time and begin to read this record. From the interrelationships of rocks, the events of Earth's history can be arranged in proper chronologic order. An area north (to the left) of Flagstaff, Arizona, and part of the Grand Canyon region is shown in the satellite panorama and is an excellent example. Several major geologic events are clearly expressed. The oldest obvious event is the deposition of a sequence of horizontal marine sedimentary rocks that form the tan to green plateau. The next event was the uplift of the rocks above sea level and the development of a series of





northeast (to the upper left) trending fractures that cut across the sedimentary rocks. Gradually, the deep canyon (on the far left) and other details of the landscape formed by stream erosion. The fractures were etched into long narrow valleys. Volcanic activity, evidenced by the dark lava flows, cinder cones, and vegetated lava domes (in false color on the far right), is obviously a younger event. Many different lava flows formed and filled stream valleys and fractures. The youngest eruption made the dark black lava flow and cinder cone near the center of the panorama. With this brief introduction, you can begin to appreciate the fact that rocks are records of time. We will have much more to say about telling time in the Grand Canyon later; remember that what is obvious here is only a fraction of the long history of the Grand Canyon region, which spans 1.7 billion (1,700,000,000) years.

How do scientists measure such long periods of time? Nature contains many types of time-measuring devices. Earth itself acts like a clock, rotating on its axis once every 24 hours. Fossils within a rock are a type of organic clock by which geologists can “tell time” and identify synchronous events in Earth’s history. Rocks also contain clocks that tick by systematic radioactive decay, which permit us to measure with remarkable accuracy the number of years that have passed since the minerals in a rock crystallized.

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*Courtesy of U.S. Geological Survey, Flagstaff, AZ.*





## MAJOR CONCEPTS

1. The interpretation of past events in Earth's history is based on the principle that the laws of nature do not change with time.
2. Relative dating (determining the chronologic order of a sequence of events) is achieved by applying the principles of (a) superposition, (b) faunal succession, (c) crosscutting relations, (d) inclusions, and (e) succession in landscape development.
3. The standard geologic column was established from studies of rock sequences in Europe. It is now used worldwide. Rocks were originally correlated from different parts of the world largely based on the fossils they contain. Today, radiometric dating can be used to correlate major rock sequences.
4. Numerical time designates a specific duration of time in units of hours, days, or years. In geology, long periods of numeric time can be measured by radiometric dating.

## THE DISCOVERY OF TIME

Time is measured by change. Because rocks are themselves records of change, they mark the passage of geologic time. The interpretation of rocks as products and records of events in Earth's history is based on the principle of uniformitarianism, which states that the laws of nature do not change with time.

We are all aware of change in the physical and biological worlds. Were things unchanging and motionless, we would not be aware of time. Time is measured by change, and change occurs on many scales of time and space. In the natural world, countless clocks are ticking at different rhythms, measuring different time spans. We are acutely aware of the changes in our daily world: night to day, the seasons, and cycles of life from birth to death. However, there is a scale of deep time, spanning millions and even billions of years, measured by clocks that are less obvious to the human experience. It is the rhythm of Earth's dynamics: continents moving, mountains uplifting and eroding, volcanoes erupting, and seas expanding and contracting. It is also the clock of species evolving and disappearing into the oblivion of extinction. Our planet has a vast natural archive that reveals past episodes of many of these changes.

The great abyss of time—geologic time—was discovered in Edinburgh in the 1770s by a small group of scholars led by James Hutton (1726–1797). These men challenged the conventional thinking of their day, in which the age of Earth was accepted to be 6000 years, as established by Bishop James Ussher's (1581–1656) summation of biblical chronology. Hutton and his friends studied the rocks along the Scottish coast and observed that every formation, no matter how old, was the product of erosion from other rocks, older still. Their discovery showed that the roots of time were far deeper than anyone had supposed. It was perhaps the most significant discovery of the eighteenth century because it changed forever the way we look at Earth, the planets, the stars, and, consequently, the way we look at ourselves.

### Uniformitarianism

The interpretation of rocks as products and records of events in Earth's history is based on a fundamental assumption of scientific inquiry: the principle of **uniformitarianism**, which states that *the laws of nature do not change with time*. We assume that the chemical and physical laws operating today have operated throughout all of time. The physical attraction between two bodies (gravity) acted in the past as it does today. Oxygen and hydrogen, which today combine under certain

conditions to form water, did so in the past under those same conditions. Although scientific explanations have improved and changed over the centuries, natural laws and processes are constant and do not change. All chemical and physical actions and reactions occurring today are produced by the same causes that produced similar events 100 years or 5 million years ago.

Hutton's principle of uniformitarianism was radical for the time and slow to be accepted. In the late eighteenth century, before modern geology had developed, the Western world's prevailing view of Earth's origin and history was derived from the biblical account of creation. Earth was believed to have been created in 6 days and to be approximately 6000 years old. Creation in so short a time was thought to have involved forces of tremendous violence, surpassing anything experienced in nature. This type of creation theory is known as **catastrophism**. Foremost among its proponents was Baron Georges Cuvier (1769–1832), a noted French naturalist. Cuvier, an able student of fossils, concluded that each fossil species was unique to a given sequence of rocks. He cited this discovery in support of the theory that each fossil species resulted from a special creation and was subsequently destroyed by a catastrophic event.

This theory was generally supported by scholars until 1785, when Hutton challenged it. He saw evidence that Earth had evolved by gradual processes over an immense span of time, and he developed the concept that became known as the principle of uniformitarianism. According to Hutton, past geologic events could be explained by the natural processes operating today, such as erosion by running water, volcanism, and the gradual uplift of Earth's crust. Hutton assumed that these processes occurred in the distant past just as they occur now. He saw that, in the vast abyss of time, enormous work could be achieved by what seemed small and insignificant processes. Rivers could completely erase a mountain range. Volcanism and Earth movements could form new ones. Based on his observations of the rocks of Great Britain, he visualized “no vestige of a beginning—no prospect of an end.” In a way, what Copernicus did for space, Hutton did for time. The universe does not revolve around Earth, and time is not measured by the life span of humans. Before Hutton, human history was all of history. Since Hutton, we know that we are but a tiny pinpoint on an extraordinarily long time line.

Sir Charles Lyell (1797–1875) based his *Principles of Geology* (1830–1833) on Hutton's uniformitarianism. Lyell's book established uniformitarianism as the method for interpreting the geologic and natural history of Earth. Charles Darwin (1809–1882) accepted Lyell's principles in formulating his theory of the origin of species and the descent of man. Modern science continues to make significant advances in understanding Earth, its long history, and how it was formed. As a result, the principle of uniformitarianism has been verified innumerable times.

The assumption of constancy of natural law is not unique to interpretations of geologic history; it is the logical essential in deciphering recorded history as well. We observe only the present and interpret past events on inferences based on present observations. We thus conclude that books or other records of history—such as fragments of pottery, cuneiform tablets, flint tools, temples, and pyramids—that were in existence before our arrival have all been the work of human beings, despite the fact that postulated past activities are outside the domain of any present-day observations. Having excluded supernaturalism, we draw these conclusions because humans are the only known agent capable of producing the effects observed. Similarly, in geology we conclude that ripple marks in a sandstone in the Appalachian Mountains were in fact formed by streams, or that coral fossils found in limestones exposed in the high Rocky Mountains are indeed the skeletons of corals that lived in a now-nonexistent sea.

Many features of rocks serve as records, or documents, of past events in Earth's history; for those who listen, the rocks still echo the past. Igneous rocks are records of thermal events; the texture and composition of an igneous rock show whether volcanic eruptions occurred or if the magma cooled beneath the surface. Sedimentary rocks record changing environments on Earth's surface—the rise and fall

**Why did scientists discard the idea of catastrophism as proposed by Cuvier?**



of sea level, changes in climate, and changes in life forms. A layer of coal is a record of lush vegetation growth, commonly in a swamp. Limestone, composed of fossil shells, indicates deposition in a shallow sea. Salt is precipitated from seawater or from saline lakes only in an arid climate, so a layer of salt carries specific climatic connotations. The list of examples could go on and on. For more than two centuries, geologists have extracted from the rocks a remarkably consistent record of events in Earth's history: a record of time.

## UNCONFORMITIES

Geologic time is continuous; it has no gaps. In any sequence of rocks, however, many major discontinuities (unconformities) reveal significant interruptions in rock-forming processes.



### Angular Unconformities

James Hutton was a very perceptive observer who recognized the historical implications of the relationships between rock bodies. He not only recognized the vastness of time recorded in the rocks of Earth's crust, but he also recognized breaks, or gaps, in the record. In 1788, Hutton, together with Sir James Hall and John Playfair, visited Siccar Point in Berwickshire, Scotland, and saw for the first time the Old Red Sandstone resting upon the upturned edges of the older strata (Figure 8.1). This exposure proved that the older rocks (primary strata) had been uplifted, deformed, and partly eroded away before the deposition of the "secondary strata." They soon discovered comparable relationships in other parts of Great Britain. This relationship between rock bodies became known as an **angular unconformity**.

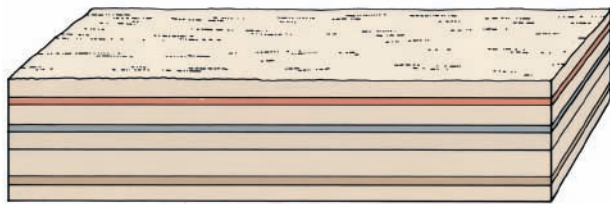


**FIGURE 8.1** Angular unconformity at Siccar Point, southeastern Scotland. It was here that the historical significance of an unconformity was first realized by James Hutton in 1788. Note that the older "primary" rocks are nearly vertical and that the younger "secondary" strata were deposited on the eroded surface formed on the older rocks.

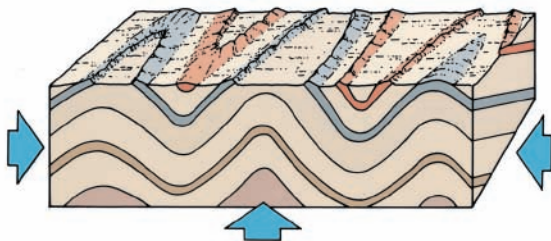
To appreciate the significance of an angular unconformity, consider what the angular discordance, or difference, implies by studying the sequence of diagrams in Figure 8.2. At least four major events are involved in the development of an angular unconformity: (1) an initial period of sedimentation during which the older strata are deposited in a near-horizontal position, (2) a subsequent period of deformation during which the first sedimentary sequence is folded, (3) development of an erosional surface on the folded sequence of rock, and (4) a period of renewed sedimentation and the development of a younger sequence of sedimentary rocks on top of the old erosional surface.

At first, only the most obvious stratigraphic breaks were recognized as unconformities, but with more field observations, other, more subtle, discontinuities were recognized. In Figure 8.3, for example, foliated metamorphic and igneous rocks are overlain by flat-lying sedimentary strata. This relationship, in which plutonic igneous or metamorphic rocks are overlain by sedimentary rocks, is a **nonconformity**. The deposition of sedimentary rocks on metamorphic or granitic rocks implies four major events: (1) the formation of an ancient sequence of rocks, (2) metamorphism or intrusion of granite, (3) uplift and erosion to remove the cover and expose the metamorphic rocks or granites at the surface, and (4) subsidence and deposition of younger sedimentary rocks on the eroded surface.

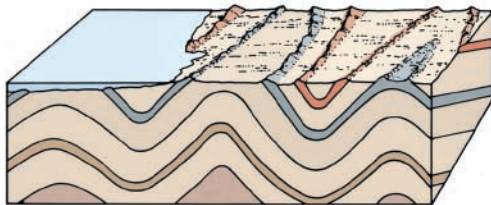
**Why is a major unconformity implied where sandstone is deposited on top of granite?**



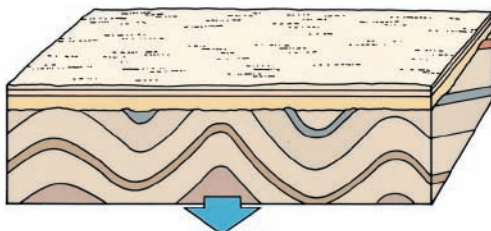
(A) Sedimentation: A sequence of rocks is deposited over time.



(B) Deformation: The sequence of rocks is deformed by mountain-building processes or by broad upwarps in Earth's crust, followed by erosion.



(C) Subsidence below sea level and renewed sedimentation.



(D) A new sequence of rocks is deposited on the eroded surface of the older deformed rocks.

**FIGURE 8.2** The geologic events implied from an angular unconformity represent a sequence of major events in the geologic processes operating within the area.



**FIGURE 8.3** A **nonconformity** is an unconformity in which sedimentary rocks were deposited on the eroded surfaces of metamorphic or intrusive igneous rocks. The metamorphic rocks and the igneous dikes shown in this photograph of the inner gorge of the Grand Canyon were formed at great depths in the crust. Subsequent uplift and erosion exposed them at the surface. Younger sedimentary layers were then deposited on the eroded surface of the igneous and metamorphic terrain.



An example of another type of stratigraphic break is shown in Figure 8.4. Here the rock strata above and below the erosion surface are parallel. Erosion may strip off the top of the older sequence and may cut channels into the older beds, but there is no structural discordance between the older, eroded rock body and the younger, overlying rock. This type of discordance is called a **disconformity**.

An unconformity is best seen in a vertical section exposed in a canyon wall, road cut, or quarry, where it appears as an irregular line. An unconformity is not a line, however, but a buried erosional surface. The present surface of Earth and especially its coastal plains are examples of what unconformable surfaces are like.



**FIGURE 8.4** **Disconformities** do not show angular discordance, but an erosion surface separates the two rock bodies. The channel in the central part of this exposure reveals that the lower shale units were deposited and then eroded before the upper units were deposited.

Channels cut by streams are responsible for many irregularities, and resistant rocks protruding above the surrounding surface can cause local relief of several hundred meters.

## RELATIVE AGES

Relative ages are determined by the chronologic order of a sequence of events. The most important methods of establishing relative ages are (1) superposition, (2) faunal succession, (3) crosscutting relations, and (4) inclusions.

An expanded conception of time is perhaps the main contribution of geology to the history of thought. Two different concepts of time, and hence two different but complementary methods of dating, are used in geology: relative time and numerical time. **Relative age** is simply determining the chronologic order of a sequence of events. Historians commonly use relative time when they place events in relation to ancient dynasties, reigns of kings, or major events such as wars. Geologists do the same with geologic time. Earth's history is divided into eons, eras, periods, and epochs by markers such as the existence of certain fossils (for example, the "age of dinosaurs") or major physical events (for example, Appalachian mountain building), although the actual dates of the events may be unknown.

Relative dating implies that no quantitative or numerical length of time in days or years is deduced. An event can only be interpreted to have occurred earlier or later than another. This can be done by applying several principles of remarkable simplicity and universality.



### Relative Dating

## The Principle of Superposition

The principle of **superposition** is the most basic guide in the relative dating of rock bodies. It states that in a sequence of undeformed sedimentary rock, the oldest beds are on the bottom and the higher layers are successively younger. The relative ages of rocks in a sequence of sedimentary beds can thus be determined from the order in which they were deposited.

In applying the principle of superposition, we make two assumptions: (1) Layers were essentially horizontal when they were deposited, and (2) the rocks have not been so severely deformed that the beds are overturned. (Many sedimentary rock sequences that have been overturned are generally easy to recognize by their sedimentary structures, such as cross-bedding, ripple marks, and mud cracks.)

**Why is the principle of superposition so important in geologic interpretations?**

## The Principle of Faunal Succession

Fossils are the actual remains of ancient organisms, such as bones and shells, or the evidence of their presence, such as trails and tracks. Their abundance and diversity are truly amazing. Some rocks (such as coal, chalk, and certain limestones) are composed almost entirely of fossils, and others contain literally millions of specimens. Invertebrate marine forms are most common, but even large vertebrate fossils of mammals and reptiles are plentiful in many formations. For example, it is estimated that more than 50,000 fossil mammoths have been discovered in Siberia, and many more remain buried.

The principle of **faunal succession** states that groups of fossil animals and plants occur in the geologic record in a definite chronologic order. Consequently, a period of geologic time can be recognized by its characteristic fossils. Thus, in addition to superposition, a sequence of sedimentary rocks has another independent element that can be used to establish the chronologic order of events.

Even before Darwin developed the theory of evolution by natural selection, the principle of faunal succession was recognized by William Smith (1769–1839),



a British surveyor and early geologist. Smith worked throughout much of southern England and carefully studied the fresh exposures of rocks in quarries, road cuts, and excavations. In a succession of interbedded sandstone and shale formations, he noted that several shales were very much alike, but the fossils they contained were not. Each shale layer had its own particular group (or assemblage) of fossils. By correlating types of fossils with rock layers, Smith developed a practical tool that enabled him to predict the location and properties of rocks beneath the surface. Soon after Smith announced that the fossil assemblages of England change systematically from the older beds to the younger, other investigators discovered the same to be true throughout the world.

**How can fossils be used to determine the relative age of a rock layer?**

By tracing the changing character of fossils in progressively younger rocks, you may appreciate the significance of these discoveries. The oldest rocks contain only traces of soft-bodied organisms. Progressively younger and younger sedimentary rocks contain marine invertebrates with shells, followed by the appearance of simple marine vertebrates like fish. Amphibians appear in even younger strata, followed in successively younger rocks by the first appearance of reptiles, birds, and mammals.

Today, the principle of faunal succession has been confirmed beyond doubt. It has been used extensively to find valuable natural resources, such as petroleum and mineral deposits. It is also the foundation for the standard geologic column, which divides geologic time into progressively shorter subdivisions called eons, eras, periods, epochs, and ages (see Figure 8.8).

### The Principle of Crosscutting Relations

The relative age of certain events is also shown by the principle of **crosscutting relations**, which states that igneous intrusions and faults are younger than the rocks they cut (Figure 8.5). Crosscutting relations can be complex, however, and careful observation may be required to establish the correct sequence of events. The scale of crosscutting features is highly variable, ranging from large faults, with displacements of hundreds of kilometers, to small fractures, less than a millimeter long.

### The Principle of Inclusion

The principle of **inclusion** states that a fragment of a rock incorporated or included in another is older than the host rock. The relative age of intrusive igneous rocks (with respect to the surrounding rock) is therefore commonly apparent if inclusions, or fragments, of surrounding rocks are included in the intrusion (Figure 8.6). As magma moves upward through the crust, it dislodges and engulfs large fragments of the surrounding material, which remain as unmelted foreign inclusions.

The principle of inclusion can also be applied to conglomerates in which large pebbles and boulders eroded from preexisting rocks have been transported and deposited in a new formation. The conglomerate is obviously younger than the formations from which the pebbles and cobbles were derived. In areas where superposition or other methods do not show relative ages, a limit to the age of a conglomerate can be determined from the rock formation represented in its pebbles and cobbles.

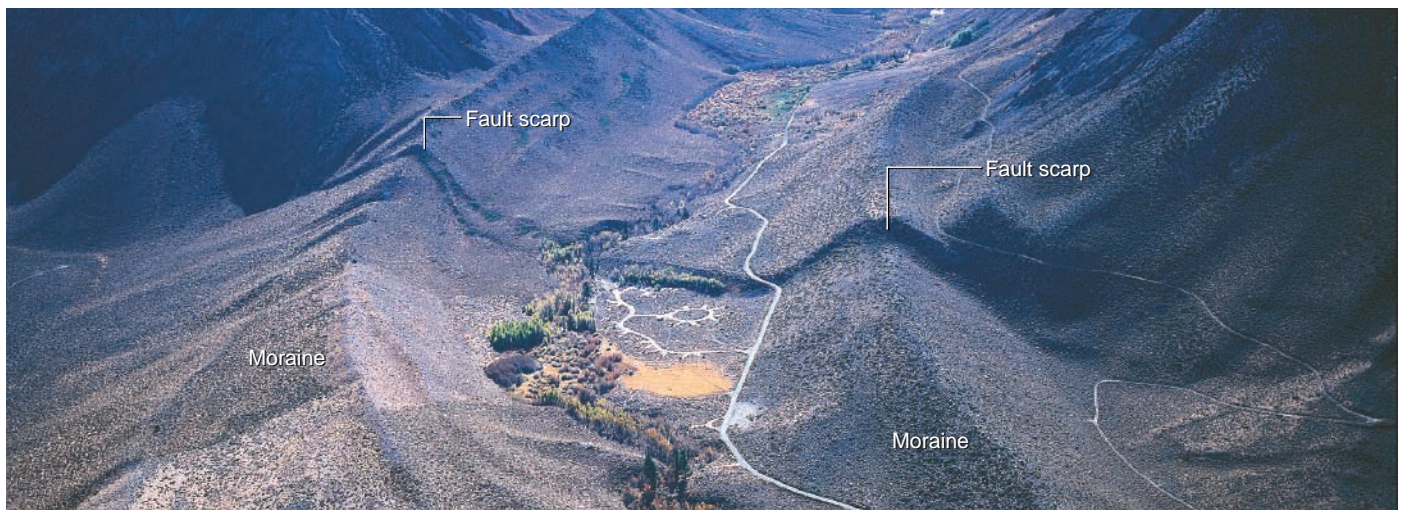
### Succession in Landscape Development

Surface features of Earth's crust are continually modified by erosion and commonly show the effects of successive events through time. Many landforms evolve through a series of stages, so a feature's relative age can be determined from the degree of erosion. This is especially obvious in volcanic features such as cinder cones and lava flows. These features are created during a period of volcanic activity and then subjected to the forces of erosion until they are completely destroyed or buried by erosional debris (Figure 8.7).





(A) Several generations of igneous dikes cut across the green metamorphic rock. The thick dike is the youngest because it cuts across all the other rock bodies. The green metamorphic rock is older than all of the dikes. Small fractures are younger than the dikes.



(B) This glacial moraine in the Sierra Nevada, California, is cut by a fault expressed as a low linear cliff (in shadow from left to right). The fault scarp is obviously younger than the moraine it cuts, indicating a tectonic event after deposition.

**FIGURE 8.5** Crosscutting relations indicate the relative ages of rock bodies and geologic structures.



**FIGURE 8.6** Inclusions of one rock in another provide a means of determining relative age. In this example fragments of granite are included in the basalt, clearly indicating that the granite is the older.



## THE STANDARD GEOLOGIC COLUMN

Using the principles of relative dating, geologists have unravelled the chronologic sequence of rocks throughout broad regions of every continent and have constructed a standard geologic time scale that serves as a calendar for the history of Earth.

Age **correlations** using fossils have made it possible to construct a diagram, called the **geologic column**, to show, in simple form, the major units of strata in Earth's crust (Figure 8.8). Most of the original geologic column was pieced together from strata studied in Europe during the mid-1800s. Major units of rock (such as the Cambrian, Ordovician, and Silurian) generally were named after geographic areas in Europe where they are well exposed. The rock units are distinguished from each other by major changes in rock type, unconformities, or different fossil assemblages. The original order of the units in the geologic column was based on the

**FIGURE 8.7** Ancient lava flows near St. George, Utah, now exist as long linear ridges with flat tops. When the lava was extruded, it flowed down stream valleys and displaced the stream to the margins of the flow. Subsequent erosion was then concentrated along the lava flow margins and developed a lava-capped ridge at the site of the original stream channel. These ridges are called inverted valleys. This flow is obviously older than other flows in the region that occupy the present drainage channels.





EON	ERA	Duration in millions of years	Millions of years ago
PHANEROZOIC	CENOZOIC	65	65
	MESOZOIC	183	248
	PALEOZOIC	295	543
PRECAMBRIAN	PROTEROZOIC	LATE	357
		MIDDLE	700
		EARLY	900
	ARCHEAN	LATE	500
		MIDDLE	400
		EARLY	400
			800
	HADEAN		

Era	Period	Epoch	Duration in millions of years	Millions of years ago
CENOZOIC	Quaternary	Holocene	0.01	0.01
		Pleistocene	1.8	1.8
	Tertiary	Pliocene	3.5	5.3
		Miocene	18.5	23.8
		Oligocene	9.9	33.7
		Eocene	21.1	54.8
		Paleocene	10.2	65
MESOZOIC	Cretaceous		79	144
	Jurassic		62	206
	Triassic		42	248
PALEOZOIC	Permian		42	290
	Carboniferous	Pennsylvanian	33	323
		Mississippian	31	354
	Devonian		63	417
	Silurian		26	443
	Ordovician		47	490
	Cambrian		53	543
PRECAMBRIAN				

**FIGURE 8.8** The standard geologic column was developed in Europe in the 1800s, based on the principles of superposition and faunal succession. Later, radiometric dates on igneous rocks provided a numerical scale for absolute ages of the geologic periods.

**How are rock units on different continents correlated with one another?**

sequence of rock formations in their superposed order as they are found in Europe. In other areas of the world, rocks that contain the same fossil assemblages as a given part of the European succession are considered to be of the same age. The column is made of a hierarchy of relative time subdivisions of Earth's history. The longest units are called eons, and progressively shorter subdivisions are eras, periods, and epochs.

## The Precambrian Eon

**Precambrian** time is represented by a group of ancient rocks that form a large volume of the continental crust. Most of these are igneous and intensely deformed metamorphic rocks. To produce these rocks, great thicknesses of sedimentary and volcanic rocks were strongly folded and faulted, and then intruded with granitic rock. Precambrian rocks contain only a very few fossils of the more primitive forms of life. Without common fossils, age correlations of rock layers from continent to continent are difficult, if not impossible. Major progress in deciphering the Precambrian has been made using radiometric ages for igneous and metamorphic rocks (as discussed in the next section). The Hadean, Archean, and Proterozoic Eons, subdivisions of the Precambrian, are defined based on these radiometric ages and not on fossil successions.

## The Phanerozoic Eon

Rocks younger than the Precambrian are generally less deformed and contain many fossils, permitting geologists to identify and correlate them worldwide. The span of time since the end of the Precambrian is the **Phanerozoic Eon**—a term meaning “visible life” in Greek. The passage of time in this eon is chronicled by fossils that reveal the continual evolution of Earth's biosphere. The Phanerozoic is subdivided into three major eras, which are in turn subdivided into periods and into even shorter epochs (Figure 8.8).

**The Paleozoic Era.** The term Paleozoic means “ancient life.” **Paleozoic** rocks contain numerous fossils of invertebrate (no backbone) marine organisms and later vertebrates, such as primitive fish and amphibians. The era is subdivided into periods (Figure 8.8) distinguished largely according to the sequence of sedimentary rock formations of Great Britain.

**The Mesozoic Era.** Mesozoic means “middle life.” The term is used for a period of geologic time in which fossil reptiles, including dinosaurs, are present. Fossil invertebrates that were more like modern lifeforms dominate marine rocks. The **Mesozoic** Era includes three periods—the Triassic, Jurassic, and Cretaceous (Figure 8.8).

**The Cenozoic Era.** Cenozoic means “recent life.” Fossils in these rocks include many types closely related to modern forms, including mammals, plants, and invertebrates. The **Cenozoic** Era has two periods—the Tertiary and Quaternary (Figure 8.8).

The geologic column by itself shows only the relative ages of the major periods in Earth's history. It tells us nothing about the length of time represented by a period. With the discovery of the radioactive decay of uranium and other elements, new tools for measuring geologic time were invented. They greatly enhanced our understanding of time and of the history of Earth and provided numerical benchmarks for the standard geologic column.



## RADIOMETRIC MEASUREMENTS OF TIME

Radiometric dating provides a method for directly measuring geologic time in terms of a specific number of years (numeric age). It has been used extensively during the last 50 years to provide a numerical time scale for the events in Earth's history.

Unlike relative time, which specifies only a chronologic sequence of events, **numerical age** is measured in hours, days, and years. In other words, numeric dating specifies quantitative (or absolute) lengths of time. Numeric time can be measured using any regularly recurring event, such as the swing of a pendulum or the rotation of Earth. You are very familiar with the concept of numeric dating in that it is the way in which you record your own age. It is one matter to reveal that you are older than someone else (relative age) and something quite different to say that you are a specific number of years old (numeric age). Using appropriate numerical dating techniques, geologists can estimate the time span between two geologic events.

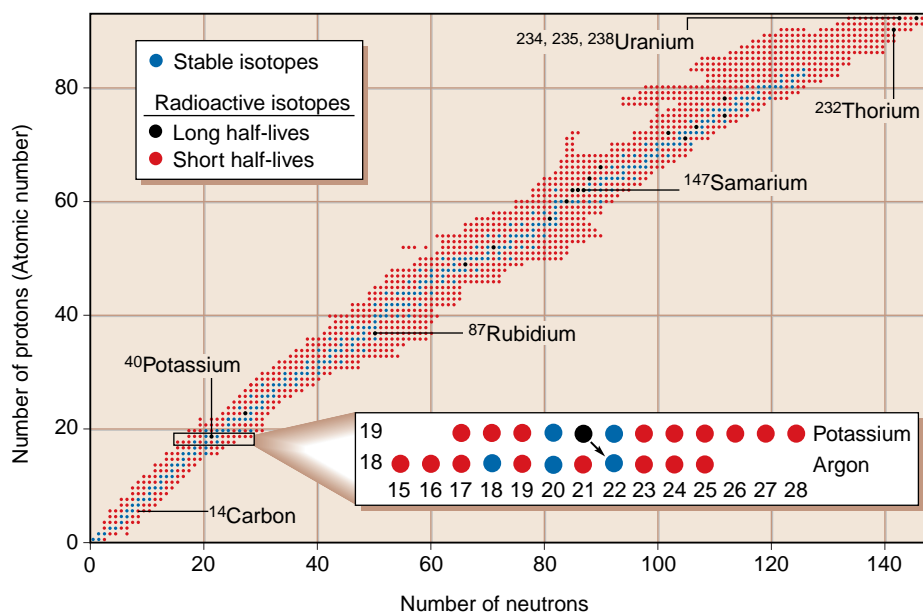
Before Hutton and Lyell, few people even thought about the age of Earth. After Hutton presented his arguments for uniformitarianism, and Lyell further developed the concept, much interest was generated in the magnitude of geologic time, and scientists explored several ways to estimate Earth's age. Early attempts included estimates based on how long it would take for the ocean to become salty (about 100 million years) or how long it would take to accumulate the known thicknesses of fossil-bearing sedimentary strata (about 500 million years). By the end of the 1800s, many geologists had come to accept an age for the Earth of about 100 million years. This was based on Lord Kelvin's estimate of how long it would take the planet to cool from an initially molten state.

In short, before the 1900s there was no reliable method for measuring long periods of geologic time, and there seemed to be little hope of finding the secret of Earth's age. Each method showed that Earth was far older than many had supposed based on a reading of the Bible (6000 y), but the true dimensions of time remained elusive. Then, a major breakthrough occurred when Henri Becquerel (1852–1908), a French physicist, discovered natural **radioactivity** in 1896 and opened new vistas in many fields of science. Among the first to experiment with radioactive substances was the distinguished British physicist Lord Rutherford (1871–1937). After defining the structure of the atom, Rutherford was the first to suggest that radioactive decay could be used to calculate a numerical age for geologic events (Figure 8.8).

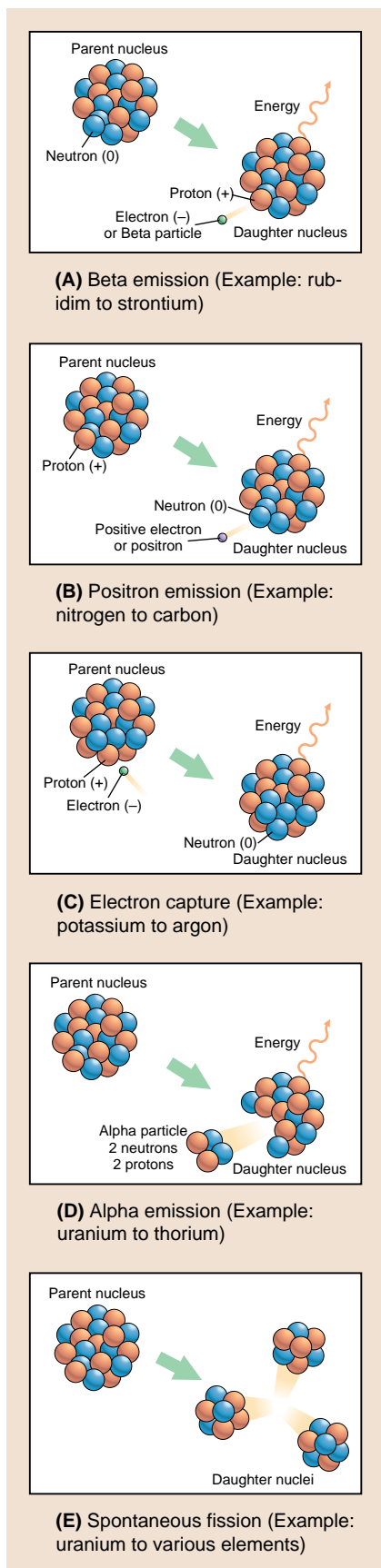
Have scientists always thought the Earth was billions of years old?



Numerical Dating



**FIGURE 8.9** The chart of the nuclides shows the number of protons and neutrons in many of the almost 300 known isotopes. Most isotopes are radioactive and spontaneously decay to stable daughter isotopes that lie in the central band on the diagram. The elements that are commonly used in radiometric dating are labeled. The inset shows the decay of  $^{40}\text{K}$  to  $^{40}\text{Ar}$ . Some radioactive isotopes have such long half-lives that they can be found in rocks; others have half-lives of only fractions of a second and are not found naturally on Earth. Not all of these short-lived isotopes are shown.



**FIGURE 8.10** Several different modes of radioactive decay are important geologic clocks and important sources of heat.

The discovery of radioactive decay solved two problems at once. First it provided the means to calculate ages for igneous rocks. Second, the heat continually produced by radioactive decay explained why Earth was still hot billions of years after its formation.

## Radioactive Decay

Many atoms spontaneously change into other kinds of atoms through radioactive decay. You will remember from our discussion of the nature of atoms that the number of protons in the nucleus is the determining characteristic of an element. If the number of protons in the nucleus changes, the atom becomes a different element with its own set of distinctive physical and chemical properties. This happens in minerals when potassium (K) decays to form the noble gas argon (Ar). A loss of a proton in the nucleus of potassium changes it into argon (see the periodic table in Figure 3.3).

Of course, not all isotopes experience radioactive decay. To visualize the relationship between those isotopes that are radioactive and those that are not, refer to Figure 8.9. This chart shows the number of protons and the number of neutrons in the nuclei of most of the known isotopes. Remember, each isotope has a distinctive atomic weight—the sum of its protons and neutrons. Thus, one element can have many different isotopes, each with a different number of neutrons and different atomic weight, but the same number of protons. From this diagram, you can see that all of the stable isotopes lie in a diagonal band through the center of the diagram. Radioactive isotopes lie on either side. For example, you can see that potassium (K) has two stable isotopes ( $^{39}\text{K}$  and  $^{41}\text{K}$ ), one long-lived radioactive isotope ( $^{40}\text{K}$ ) that is found in rocks and minerals, and several short-lived isotopes that do not occur naturally on Earth.

All decay reactions move an unstable isotope on a path that ultimately ends in a stable nuclear configuration in the central part of the diagram. There are several types of radioactive decay (Figure 8.10), but all involve changes in the number of protons and neutrons in the nucleus of an unstable atom. The atom that decays is the **parent isotope** and the product is the **daughter isotope**. Many decay reactions are composed of several separate steps in a long decay chain involving as many as a dozen intermediate isotopes.

Radiogenic heat is also produced by radioactive decay reactions (along with other particles not listed in Figure 8.10). In fact, radioactive decay of potassium, uranium, and thorium is one of Earth's principal sources of heat. Radiogenic heating explains why Earth is still hot after all these years of cooling.

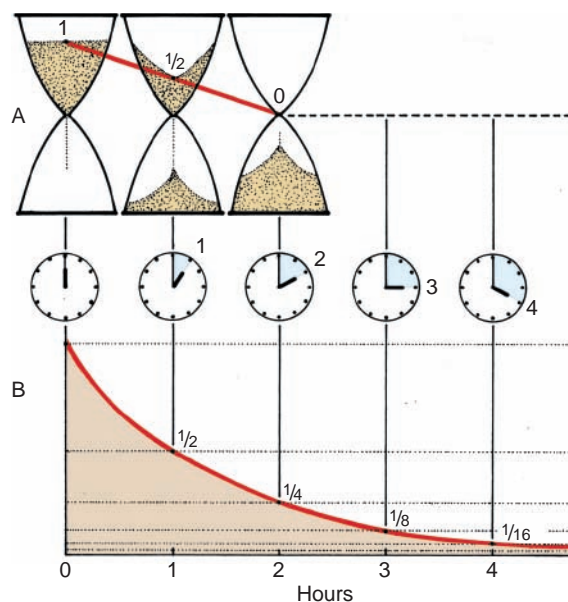
## Rates of Radioactive Decay

Each radioactive isotope disintegrates at its own distinctive rate. The rate of decay has been accurately and repeatedly measured for many radioactive isotopes. Unlike chemical reactions that only involve electrons, nuclear reactions are not affected by temperature or pressure, at least under the conditions found in the outer layers of Earth and other planets. Experimental measurements all show that decay follows a simple rule, under which half of the parent atoms present in a closed system decay to form daughter atoms in a fixed period of time known as a **half-life**. In other words, half the original atoms decay during one half-life. In a second half-life, half the remainder (or a quarter of the original atoms) decay. In a third half-life, half the remaining quarter decay, and so on (Figure 8.11).

Regular decay is the critical rhythm used in measuring radiometric dates. The time elapsed since the formation of a crystal containing a radioactive element can be calculated from the rate at which that particular element decays. For a simple decay reaction, the amount of the parent isotope remaining in the crystal can be compared with the amount of the daughter isotope.

Note that the fraction of atoms that decay during each half-life is always the same; one-half of the atoms change into another isotope. This means that the





**FIGURE 8.11 Rates of radioactive growth and decay are exponential.** (A) Many processes are characterized by uniform, straight-line depletion, like sand moving through an hourglass. If half of the sand is gone in 1 hour, all of it will be gone in 2 hours. (B) Radioactive decay, in contrast, is exponential. If half is depleted in 1 hour, half of the remainder, or one-fourth, will be depleted in 2 hours, leaving one-fourth. Rates of radioactive decay are expressed in half-lives; the time required for half of the remaining amount to be depleted. In this case, the half-life is 1 hour.

number of atoms that decay in a given time continually diminishes. Thus, the rate of decay actually declines over time. This declining rate is important in understanding radiometric dating, but it is also crucial for understanding why the amount of heat released by decay dramatically declines with the passage of time. Consequently, all of the planets have cooled with time.

The half-life for each unstable isotope is different. Most isotopes decay rapidly; that is, they have short half-lives and lose their radioactivity within a few days or years. Many of these short-lived isotopes may be formed naturally—in stellar interiors, for example. But they have such short half-lives compared with the age of the solar system that they have long since decayed away and are not found on Earth. However, other isotopes decay very slowly, with half-lives of hundreds of millions of years. These are the ones that can be used as atomic clocks for measuring long periods of time. The parent isotopes and their daughter products that are most useful for geologic dating are listed in Table 8.1.

## Radiometric Dating

The use of radioactive decay to measure the passage of time numerically has dramatically improved our understanding of Earth and its evolution. **Radiometric dating** of rocks and minerals uses a variety of elements that decay in different ways (Table 8.1). Commonly, the same rock can be dated by several different techniques, giving geologists important cross checks on their interpretations and lending a

**Why do some isotopes spontaneously decay to form other elements?**

**Do all radioactive isotopes decay at the same rate?**

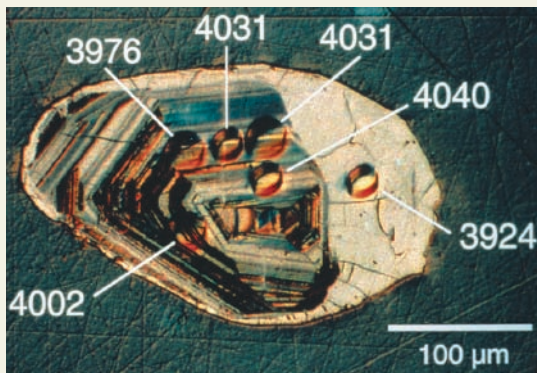
**TABLE 8.1 Radioactive Isotopes Commonly Used in Radiometric Dating**

Parent Isotope	Daughter Isotope	Half-life (years)
Uranium-238	Lead-206	4.5 billion
Uranium-235	Lead-207	704 million
Thorium-232	Lead-208	14.0 billion
Samarium-147	Neodymium-143	106 billion
Rubidium-87	Strontium-87	48.8 billion
Potassium-40	Argon-40	1.25 billion
Carbon-14	Nitrogen-14	5,730
Hydrogen-3	Helium-3	12.3

Many numerical dating techniques are based on the radioactive decay of one isotope into an isotope of a completely different element. One of the radioactive elements with a long half-life is uranium (Table 8.1). Uranium is found in fairly high concentrations in several minerals, including the mineral zircon ( $\text{ZrSiO}_4$ ), where uranium can substitute for zirconium because of its similar size and charge. Zircon is found in very small quantities in many igneous and metamorphic rocks. Because zircon equilibrates very slowly with its environment, it is difficult to reset the radiometric clock. The parent uranium isotopes and daughter lead isotopes are held tightly in the mineral's atomic structure. Geologists have found that zircon grains are windows into the geologic past.

A new type of sophisticated instrument is used to open these windows. Called a SHRIMP (for Sensitive High Resolution Ion MicroProbe), these expensive tools allow scientists to get numerical dates for extremely small spots only a fraction of a millimeter across. Thus, many dates can be obtained from a single grain (as shown in the photo above). In contrast, many other dating techniques require the use of tens to hundreds of grains to get a single date.

The essence of this technique is to bombard a polished grain surface with a narrow beam of energetic ions (usually

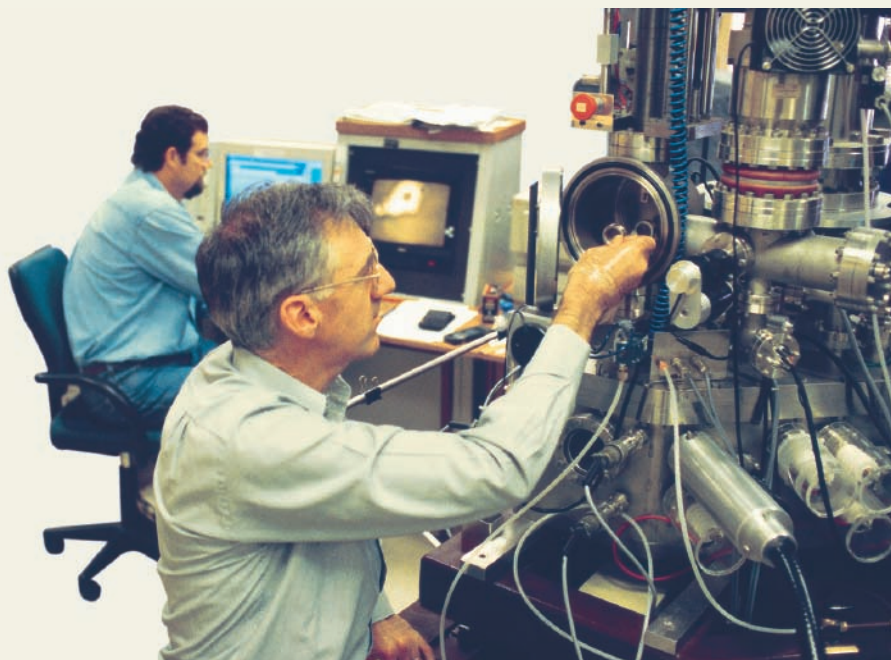


(Courtesy of I. S. Williams, Australian National University)

argon). These ions drill a small crater into the grain's surface and eject ionized atoms from the grain. These ions are swept into a mass spectrometer where the ratio of the parent isotope and the daughter isotope can be measured. (See page 415 for more information on how mass spectrometers work.) For zircon, this means measuring the amount of uranium and its radiogenic daughter lead. By using this ratio and the known decay rate of uranium, a crystallization age for this small spot on the mineral can be calculated.

After moving the crystal a small distance, another micro-hole is drilled and another age is calculated. The result is a map that shows the crystallization history of a single tiny grain of zircon (ages given in millions of years).

This technique shows that some gneisses have zircon grains that first crystallized in a magma, were then metamorphosed, and later still incorporated into a different hot magma without ever completely dissolving or even reaching equilibrium with the new molten environment. Each event is recorded by the crystallization of a rim (colored bands) of new zircon around the old core. In the photo you can see that the rim of the grain is about 80 million years younger than the core. Even more exciting results have come from dating zircons from the ancient rocks of the shields. The oldest rocks found on Earth so far are gneisses that crystallized about 4.0 billion years ago in what is now northern Canada.



(Courtesy of I. S. Williams, Australian National University)



firm foundation to our measurements of geologic time. Let us review several important systems for measuring radiometric dates.

**Potassium-Argon (K-Ar) Clock.** The potassium-argon method of radiometric dating is one of the most widely applied techniques. Because potassium is incorporated in common minerals, such as feldspars, micas, and amphiboles, this method is widely used to date igneous and metamorphic rocks. Although the half-life of  $^{40}\text{K}$  is about 1.25 billion years (Table 8.1), rocks as young as a few hundred thousand years have been successfully dated. Fortunately, the potassium-argon clock is one of the easiest to understand.  $^{40}\text{Ar}$ , the decay product of  $^{40}\text{K}$ , is a noble gas and does not form chemical bonds with other ions in mineral structures. Thus, when a  $^{40}\text{K}$ -bearing mineral crystallizes from hot magma, it contains very little or no  $^{40}\text{Ar}$ . Once the rock cools,  $^{40}\text{Ar}$  steadily accumulates as  $^{40}\text{K}$  decays by electron capture. As long as the mineral is cool, less than a few hundred degrees Celsius, the  $^{40}\text{Ar}$  will remain trapped within the mineral's crystalline structure, just as the grains of sand accumulate in the bottom of an hourglass. If this igneous rock is collected and the  $^{40}\text{K}$  and  $^{40}\text{Ar}$  contents are precisely measured, the crystallization age of the mineral can be calculated because the half-life of  $^{40}\text{K}$  is accurately known.

It is important to keep in mind that a radiometric age is the time of crystallization of the mineral that is dated. These techniques tell us nothing about the time at which the elements themselves formed; most elements formed in the interiors of ancient stars billions of years before Earth was created. Moreover, this technique works best when used to date mineral grains that crystallized over very short periods of time and at the same time that the rock formed. Consequently, potassium-argon dating is best used to date metamorphic and igneous rocks, particularly quickly cooled volcanic rocks. It is nearly useless in dating clastic sedimentary rocks because argon may have been accumulating in the individual mineral grains for a very long time before the grains were transported and deposited to form a sedimentary rock.

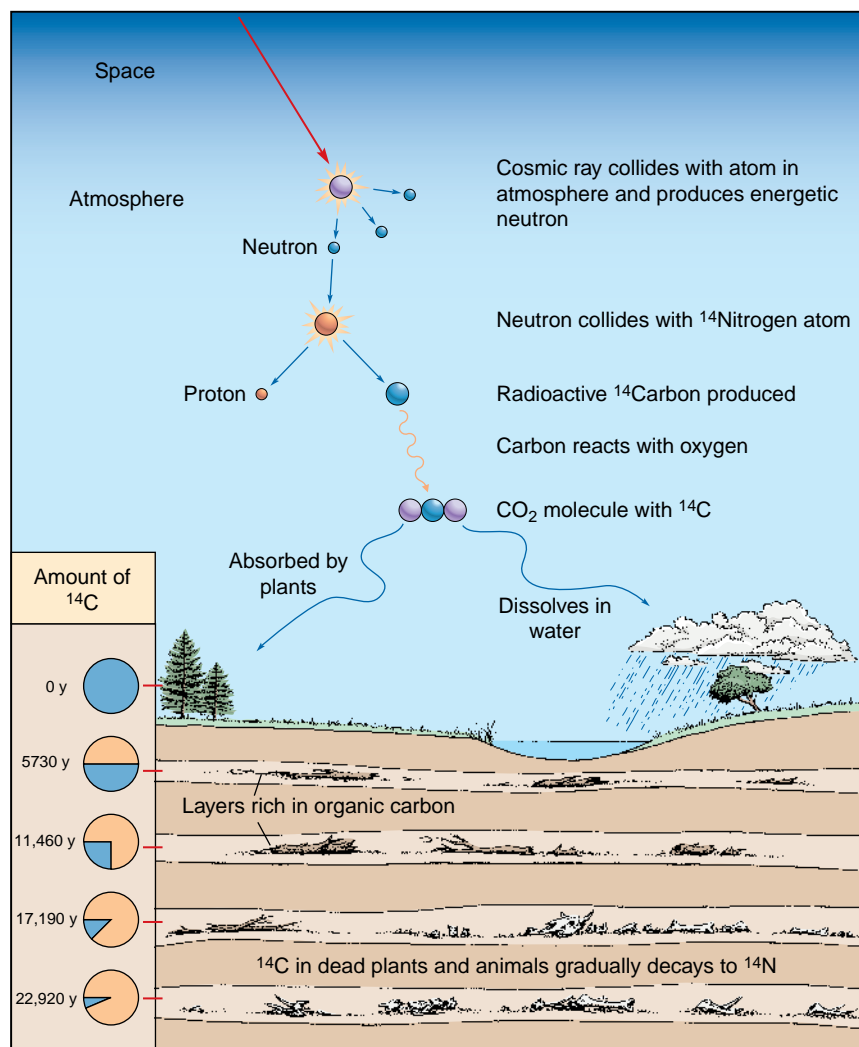
To understand other potential complications in radiometric dating, imagine that a  $^{40}\text{K}$ -bearing mineral grain leaks a little of the  $^{40}\text{Ar}$  already produced by radioactive decay. If we collect and analyze this grain, its calculated age will be lower than the real crystallization age of the mineral. In the same way, an underestimate of the passage of time would occur if we used an hourglass that had an undetected crack through which sand grains in the lower chamber escaped from the once-closed system. Leakage of  $^{40}\text{Ar}$  can occur in real minerals if, for example, they are heated during metamorphic processes or if they are weathered by reactions with air and water at Earth's surface. Radiometric dating only works if the mineral has remained a *closed system*, with no loss or gain of the parent or daughter isotopes. Therefore, it is extremely important for the geologist to collect fresh, unaltered rocks for geochronologic work.

On the other hand, the fact that the potassium-argon clock can be partially or completely reset allows these techniques to be used to study the thermal histories of rocks, not just the time when they crystallized. A simple example is the metamorphism of an old granite to form gneiss. Here, all of the  $^{40}\text{Ar}$  may be expelled from the igneous minerals as they become hot, effectively resetting the clock completely. Such a gneiss would then yield a K-Ar age that corresponds to the age of metamorphism. With increasingly sophisticated techniques, we are now able to look at the timing of even more subtle temperature changes, such as those that occur when sedimentary rocks are buried or when mountain belts are uplifted.

**Carbon-14 Clock.** Another important radiometric clock uses the decay of **carbon-14** ( $^{14}\text{C}$ ), which has a half-life of 5730 years (Figure 8.12). If this isotope has such a short half-life, why is there any left at all? Carbon-14 is produced continually in Earth's upper atmosphere by cosmic rays—high-energy nuclear particles that arise from the Sun and elsewhere in space. Cosmic rays fragment the nuclei of gases in the atmosphere to produce free particles, including protons and neutrons.

**What processes can reset the K-Ar clock to zero age?**

**Why can't we use carbon-14 to date old metamorphic rocks like those in the shields?**



**FIGURE 8.12** The  $^{14}\text{C}$  radiometric clock is based on the production of  $^{14}\text{C}$  from nitrogen in the atmosphere, the incorporation of the radioactive carbon into living plants and animals, and the regular decay of the  $^{14}\text{C}$  after organisms die and stop absorbing carbon from the atmosphere. The short half-life of  $^{14}\text{C}$  allows this system to be used to date events from a few hundred to as much as 40,000 years old.

If one of these neutrons hits  $^{14}\text{N}$ , with seven protons, the nucleus gives up a proton and unstable  $^{14}\text{C}$ , with only six protons, is formed. The formation of  $^{14}\text{C}$  is in balance with its decay, so the proportion of  $^{14}\text{C}$  in atmospheric carbon dioxide ( $\text{CO}_2$ ) is essentially constant.

The newly formed radioactive carbon becomes mixed with ordinary carbon atoms in atmospheric carbon dioxide. Plants use this radioactive carbon dioxide in photosynthesis, and animals also incorporate radioactive carbon by eating the plants. Both plants and animals thus maintain a fixed proportion of  $^{14}\text{C}$  while they are alive. After death, however, no additional  $^{14}\text{C}$  can replenish what is lost by radioactive decay. The  $^{14}\text{C}$  steadily reverts to  $^{14}\text{N}$  by beta decay. The time elapsed since an organism died can therefore be determined by measuring how much  $^{14}\text{C}$  remains. The longer the time elapsed since death, the less  $^{14}\text{C}$ . Because the isotope's half-life is 5730 years, the amount of  $^{14}\text{C}$  remaining in organic matter older than 50,000 years is too small to be measured accurately. This method is therefore useful for dating very young geologic events involving organic matter and for dating archeological material.

There are several complications in using the  $^{14}\text{C}$  system for age determinations. An important difficulty lies in the fact that the production rate of  $^{14}\text{C}$  in the atmosphere has not been constant. Changes in the rate of cosmic-ray bombardment and in the strength of Earth's magnetic field, which can deflect cosmic rays, are probably the most important reasons why  $^{14}\text{C}$  production changes. However, this error amounts to only 1% to 4%, when compared with ages obtained by other numeric dating techniques, such as tree ring dating. In addition, the short half-life limits  $^{14}\text{C}$  dating to

**Can all rocks be accurately dated using radiometric techniques?**



very young materials. Another possible drawback comes from carbon's mobility at Earth's surface and the fact that it may be added to or subtracted from an organism's remains after death.

### Problems in Radiometric Dating

The principles of radiometric dating may be simple enough, but the laboratory procedures are complex. Most radioactive elements are found in only trace quantities in rocks and minerals. They do not form their own minerals but are impurities in common rock-forming minerals. For example, uranium and thorium have concentrations of only a few parts per million in most rocks. Consequently, the principal difficulty lies in the precise measurement of minute amounts of parent and daughter isotopes. Modern instruments are capable of accurate measurements at the parts per billion level. The accuracy of a date also depends on the accuracy with which the half-life of the radioactive element is known. For example, measurements of the half-life for the decay of  $^{235}\text{U}$  to  $^{207}\text{Pb}$  are considered accurate within 1%. Other errors are the result of the movement of parent and daughter isotopes after the radiometric clock has been started, as described previously for the K-Ar system. Isotopic systems can become open, or leaky, as a result of weathering and alteration, or by heating, burial, and uplift. By understanding these problems, one can minimize their effects by carefully collecting samples and using precise instruments in the laboratory.

Many rocks cannot be dated by radiometric methods. Some rocks are too young to have accumulated sufficient daughter products for analysis. Other rocks are too old and all of the parent isotopes have decayed away. Some rocks lack sufficient quantities of radioactive elements in the first place. For example, quartz does not accommodate radioactive elements in its crystal structure and is rarely useful for radiometric dating.

To safeguard against these problems, geologists constantly check and recheck radiometric ages. Several radioactive isotopes are suitable for numerical dating, so one obvious test is to determine the age of a mineral or a rock by more than one method. If the results agree, the probability is high that the age is reliable. If the results differ significantly, additional methods must be used to decide which age, if either, is correct. Another independent check can be made by comparing the radiometric age with the relative age of the rocks, determined from such evidence as superposition and fossils. Through this system of tests and cross-checks, many very reliable radiometric ages have been determined.

## OTHER METHODS TO MEASURE NUMERICAL TIME

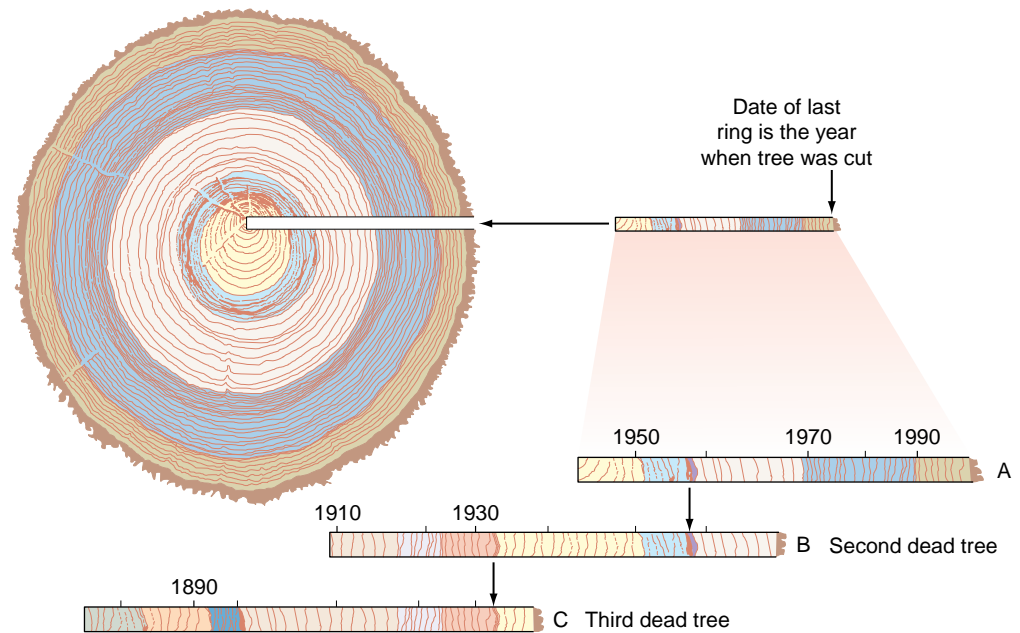
Some natural processes produce records that can be used to calculate numerical ages. Some of the most important are tree rings, varves, and ice layers. Most of these methods can be used to understand the last few tens of thousands of years of Earth's history.

### Tree Rings

The annual growth rings of trees found in temperate climates provide a simple way to measure the age of a tree (Figure 8.13). The thickness and texture of each ring are records of the environment—temperature, humidity, precipitation, insect infestations, and even fires will create distinctive patterns recorded in all of the trees in one area. Consequently, by comparing the pattern of rings from one tree to another tree, or even to ones that have died, the chronology of a forested region can be accurately deduced. By overlapping sections of rings from many different trees, scientists have been able to link together unbroken tree ring records that extend as far back as 8000 years in some localities.

**What kinds of rocks are most useful for radiometric dating?**

**Why can't we count tree rings to find out when dinosaurs lived on Earth?**



**FIGURE 8.13** Tree rings can be used to determine the numerical ages of some very young geologic events. The patterns of annual growth rings can be matched from living to dead trees to form a record extending back several thousand years in some locations.

Because the rings are so sensitive to the climate, **tree ring dating** is an ideal tool to date and explain many of Earth's most recent climate changes. Moreover, tree rings have been used to examine slumping and mass movement on hillsides and also disturbances caused by earthquakes. Pollutants from power plants, smelters, nuclear testing, and waste disposal sites are transported in wind and water and become incorporated in an annual ring. Consequently, both the extent and timing of these environmental perturbations are recorded as the tree grows.

### Varves

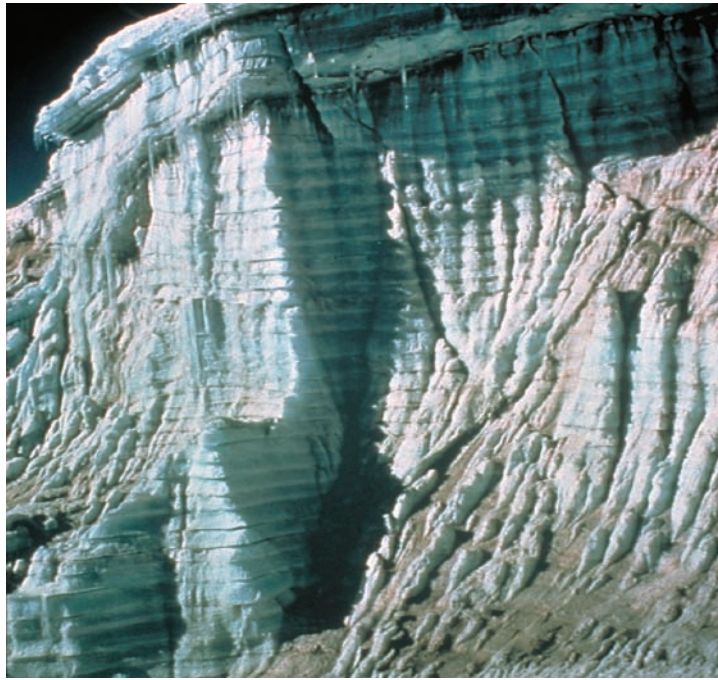
In some geologic settings, rhythmic changes in a sedimentary environment create a type of clock based on successions of thin sediment beds. Some of these rhythms correspond to the annual cycle of the seasons. For example, thin layers of clay, known as **varves**, accumulate in the still waters of some glacial lakes (see Figure 14.22B). Each graded layer represents one year and was created by seasonal variations in the amount of sediment-laden meltwater that flowed into a lake. By carefully counting these layers, geologists have pieced together a record that extends back about 20,000 years in the glaciated region around the Baltic Sea of northern Europe. Some varves can also be dated by  $^{14}\text{C}$  techniques if they contain sufficient organic material.

In many other areas, thick sequences of laminated sedimentary rocks exist, but without a knowledge of the numerical age of the first or last bed, we can only decipher the total length of time that passed during their deposition, not the numerical age of each layer. One famous section from the shales of the Green River Formation of Wyoming is built of layers 2 mm thick that accumulated into a sequence almost 1 km thick (see Figure 5.5C). If each bed represents a single year, then the shales were deposited over a period of about 5 million years, a result in accord with what is known about the radiometric age of the formation.

### Ice Layers

A distinctive type of rhythmic sediment accumulates in Earth's high mountains and in its polar regions—ice sheets (Figure 8.14). Seasonal changes in the amount of snowfall and subsequent snowmelt create thin layers in glacial ice sheets. Drill





**FIGURE 8.14** Annual layers of ice form in many glaciers. Many layers can be seen in this South American glacier. Layers of wind-blown dust deposited in the summer help define the layers. In some deep drill cores, these layers can be counted back for tens of thousands of years. (Courtesy of L Thompson)

cores obtained from both the Greenland and Antarctic ice sheets show that these layers can be counted to obtain a nearly continuous record almost 65,000 years long. Ice older than this is present in the ice sheets, but the annual layers have been destroyed by flowage of the ice. Some of these cores are 3000 m long. Independent confirmation of the age of the ice layers can be obtained from radiometric dates of thin beds of volcanic ash preserved in the ice. Volcanoes in Iceland, Mount St. Helens in the United States, and even some volcanoes as far away as Mexico have erupted ash that is preserved in the Greenland ice cap.

These ice layers are rich storehouses of climatic information. Besides the information in their thickness, the isotopic and chemical composition of the ice tell when changes in the environment occurred. Contaminants in the ice reveal the widespread changes that accompanied the industrial revolution, including the introduction of lead and copper from smelting operations and the buildup of carbon dioxide trapped in bubbles. Moreover, by carefully examining the oxygen isotopic composition of the ice, scientists can calculate the temperature of the polar regions.

**What segment of geologic time can be dated using ice layers?**

## CALIBRATION OF THE GEOLOGIC TIME SCALE

Numerical ages of many geologic events have been determined from thousands of specimens throughout the world. These, in combination with the standard geologic column, provide a radiometric time scale from which the numerical age of other rock units and geologic events can be estimated.

Unfortunately, radiometric dates cannot be used to determine the age of every rock. Many sedimentary rocks do not contain minerals suitable for accurately dating the time of deposition. In most cases, a radiometric date of a sedimentary rock indicates when the mineral grains within the rock crystallized—not the time when the sediment was deposited. Radiometric dating can be used effectively to determine when igneous rocks crystallized or when new minerals formed in metamorphic rocks because, in these cases, the mineral and the rock formed together. The problem in developing a reliable numeric time scale is the placement of the radiometric dates of igneous and metamorphic rocks in their proper positions in the relative time scale established by relative dating of sedimentary rocks.

## Layered Volcanic Rocks

The best reference points for the radiometric time scale are probably volcanic ash falls and lava flows. Both are deposited instantaneously, as far as geologic time is concerned. Because they commonly are interbedded with fossiliferous sediments, their exact positions in the geologic column can be determined.

For example, thin beds of volcanic ash are common in some richly fossiliferous shales and limestones of the western interior of the United States. Here, several different fossil species permit us to determine precisely the position of thin units in which the fossils occur within the geologic column. Comparisons with fossils found on other continents are also possible, so that their Late Cretaceous age is well established. The sequence of interbedded volcanic ash layers can be dated very precisely by radiometric means. Therefore, a numerical age for each successive fossil zone can be established. In this case, individual fossil zones have radiometric ages known within about 1% and provide tight constraints on the numerical ages of several important parts of the geologic time scale.

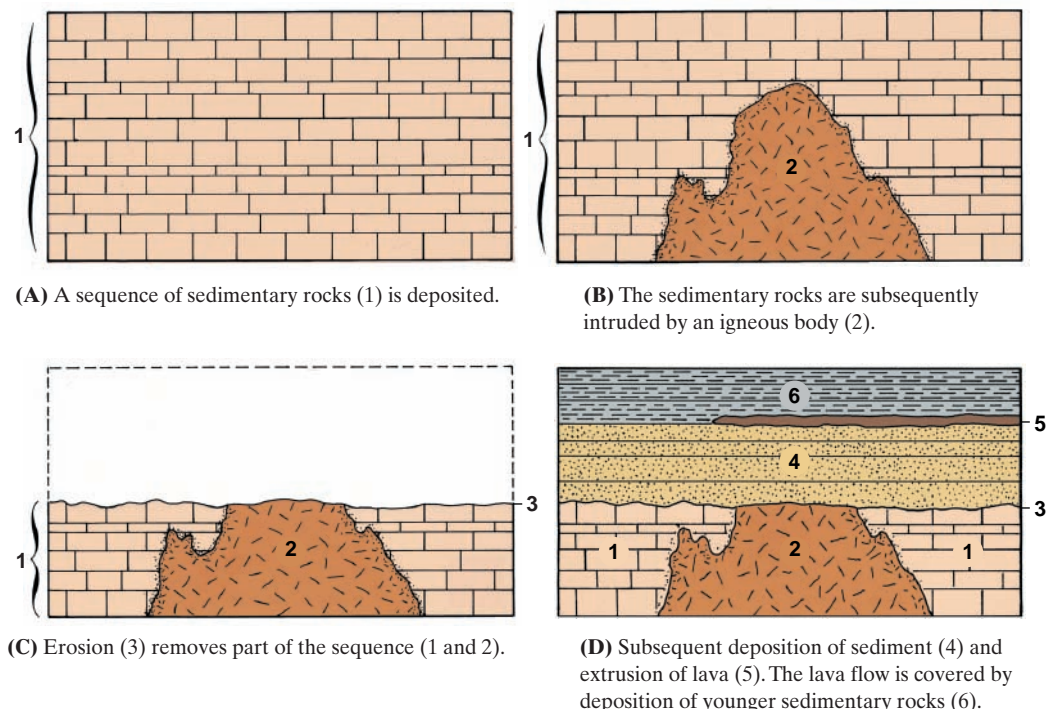
In other formations, sedimentary rocks lack fossils that are diagnostic of a certain period of geologic time. For example, the Morrison Formation of the western United States is famous for its abundant and distinctive dinosaur fauna, including stegosaurs, allosaurs, and apatosaurs, but it has few fossils that identify its exact position in the standard geologic column. Estimates of its age ranged from Jurassic to Cretaceous. However, volcanic ash beds are common in this unit, and careful radiometric dating has established that the Morrison Formation and its dinosaur remains range from 155 to 148 million years old. They are thus Late Jurassic in age (Figure 8.8).

**How are igneous rocks used to calibrate the relative time scale?**

## Bracketed Intrusions

As shown in Figure 8.15, molten rock can cool within Earth's crust without ever breaking out to the surface. Subsequent erosion may expose this rock at the surface. Later, younger sediments may be deposited on top. In some cases, the entire sequence of events takes only a few million years. In others, a much longer time may pass. The relative age of the igneous rock is bracketed between the ages

**FIGURE 8.15 Radiometric dating of igneous rocks** can be used in developing a numerical time scale, but the relationship between rock bodies must be considered. In these diagrams, major geologic events are numbered. Radiometric dating of the intrusion (2) indicates that the granite cooled 355 million years ago and that the lava flow (5) cooled 288 million years ago. These two dates place certain constraints on the absolute age of all units. (1) is older than 355 million years; (3) and (4) formed between 355 and 288 million years ago; and (6) is younger than 288 million years.





of the older sediments (1) and the younger sediments (4). Such a rock body is therefore known as a bracketed intrusion. Unfortunately, the span of time between 1 and 4 is commonly too long to permit the relative age of the intrusion to be useful in detailed geochronology. Radiometric dating of such rocks does establish the time of major igneous events, however.

## The Geologic Time Scale

The currently accepted **geologic time scale** is based on the standard geologic column, established by faunal succession and superposition, plus the numerical radiometric dates of rocks that can be placed precisely in the column. Each dating system provides a cross-check on the other because one is based on relative time and the other on numerical time. Agreement between the two systems is remarkable and discrepancies are few. In a sense, the radiometric dates act as the scale on a ruler, providing reference markers between which interpolation can be made. Enough dates have been established so that the time span of each geologic period can be estimated with considerable confidence. The age of a rock can be determined by finding its location in the geologic column and interpolating between the nearest radiometric time marks.

From this radiometric time scale, we can make several general conclusions about the history of Earth and geologic time:

1. Present evidence indicates that Earth formed about 4.5 to 4.6 billion years ago. The oldest rocks on Earth are a little more than 4 billion years old.
2. The Precambrian constitutes more than 80% of geologic time.
3. Phanerozoic time began about 540 million years ago. Rocks deposited since Precambrian time can be correlated worldwide by means of fossils, and the dates of many important events during their formation can be determined from radiometric dating.
4. Some major events in Earth's history are difficult to place in their relative positions on the geologic column but can be dated by radiometric methods.

## DECIPHERING GEOLOGIC HISTORY

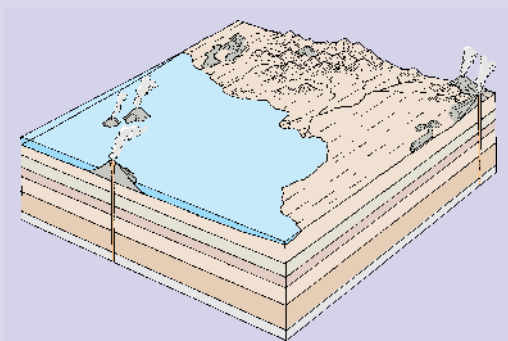
Using the principles of relative and numerical dating, geologists can deduce the details of the geologic history of a region.

One of the best areas in the world to visualize the sequence of events recorded in the geologic record is the Grand Canyon of the Colorado River in Arizona (GeoLogic essay on next page). Here, many rock formations are completely exposed, and the major events they record are exceptionally clear. Three major groups of rocks are shown in the photograph and are separated by major unconformities. They are (1) the Vishnu Schist and the granitic rocks that intrude it, which are exposed in the deep, rugged inner gorge; (2) the Grand Canyon series, a sequence of sedimentary rocks nearly 4000 m thick, all tilted about 15°; and (3) the Paleozoic sedimentary rocks, which are 1500 m thick and are essentially horizontal. They form a series of alternating steep cliffs and gentle slopes extending from the top of the Grand Canyon series up to the canyon rim. Above the Paleozoic rocks to the north is another thick sequence of Mesozoic strata (not visible in the photograph), which forms the Grand Staircase in southern Utah.

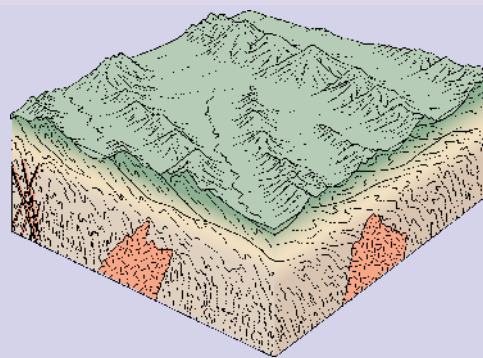
To interpret the events recorded by these rocks, we need only think a moment about how each major rock formation formed and what is implied by the relationship of one rock body to another. The major events are shown graphically in the series of block diagrams on the next page. The diagrams show several kinds of crosscutting relationships, as well as unconformities and superposition of major



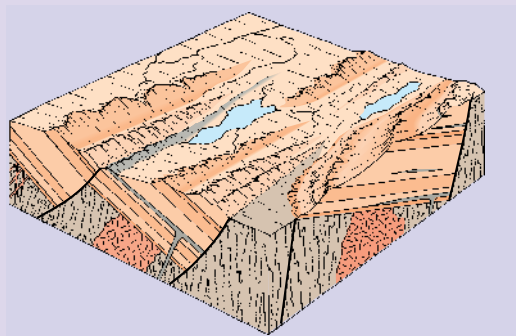
**The Grand Canyon of Arizona** exposes rocks that are as much as 1.7 billion years old. Relative and radiometric dating have been used to reconstruct its geologic history. The major events that formed the rocks and landscapes of the Grand Canyon are shown in the block



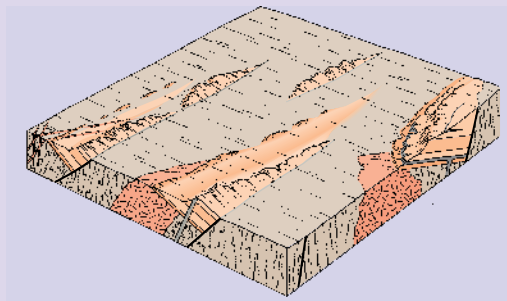
(A) Deposition of Vishnu sediment and associated arc volcanic rocks (1.75 billion years ago)



(B) Mountain building and metamorphism form Vishnu Schist, followed by several episodes of granite intrusion (1.7 to 1.4 billion years ago)



(E) Normal faulting (800 to 740 million years ago)



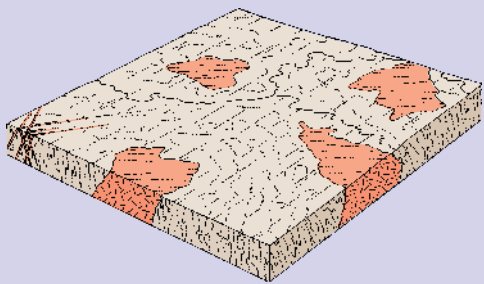
(F) Erosion and formation of Great Unconformity (740 to 550 million years ago)



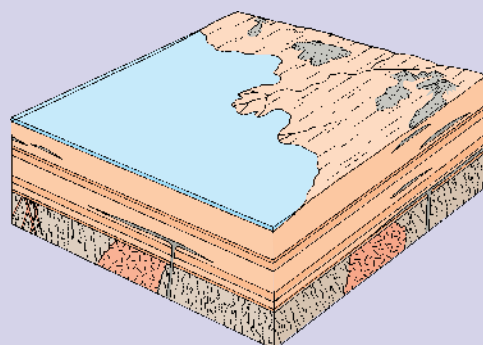
## *Revealed in Stone*



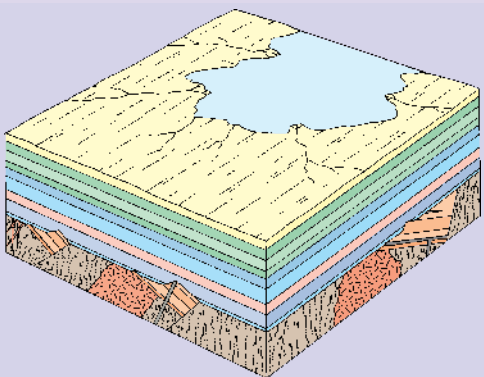
diagrams below. This sequence of geologic events was deciphered using superposition and crosscutting relations. The absolute ages of many of the events have been established by radiometric dating. The major rock units are labeled on the photograph.



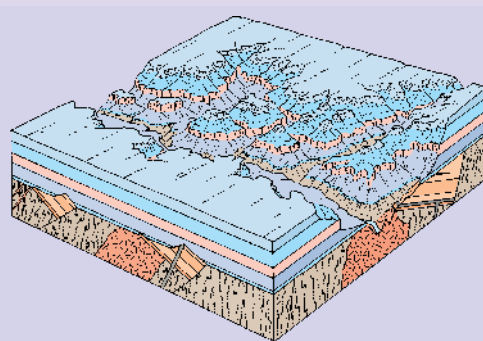
(C) Up lift and erosion (1.4 to 1.2 billion years ago)



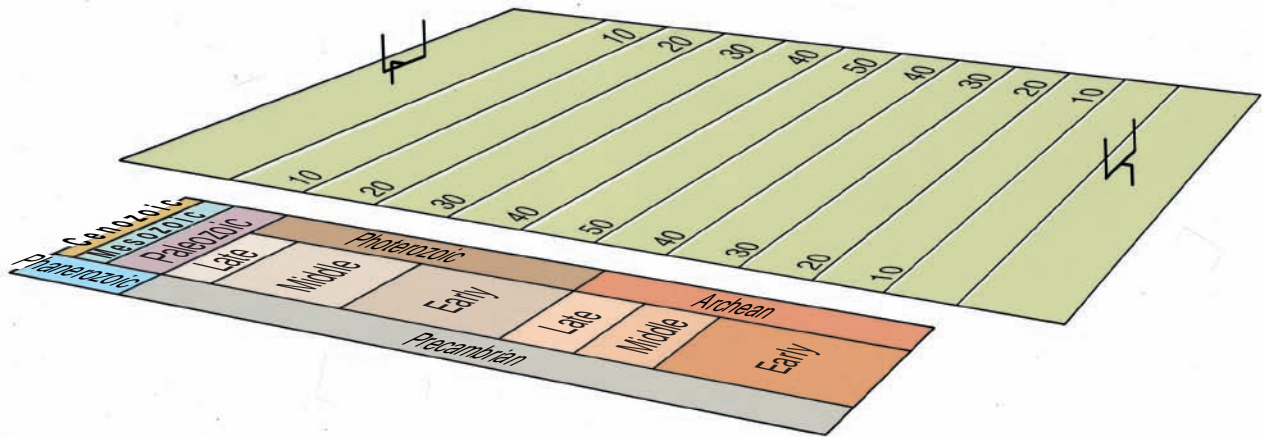
(D) Deposition of Grand Canyon Supergroup (1.2 to 1.0 billion years ago)



(G) Deposition of Paleozoic (blue), Mesozoic (green) and Cenozoic (yellow) rocks (550 to 20 million years ago)



(H) Erosion of Grand Canyon by Colorado River (20 million years to present)



**FIGURE 8.16** If the length of geologic time is compared to a football field, Precambrian time represents the first 87 yd, and all events since the beginning of the Paleozoic are compressed into the last 13 yd. Dinosaurs first appeared 5 yd from the goal line. The glacial epoch occurred in the last inch, and historic time is so short that it cannot be represented on this figure.

rock bodies. Study each figure carefully. Refer to the photograph of the canyon. Do you recognize each rock body? Do you understand the reasons for each event illustrated in the cross sections? If not, try again, and your reward will be a new awareness of time.

## MAGNITUDE OF GEOLOGIC TIME

The magnitude of geologic time is easier to comprehend when compared to some tangible linear time line.

Geologists speak of millions of years as casually as politicians speak of billions of dollars. A billion dollars is difficult to comprehend; indeed, it does not seem like real money. Great time spans are also difficult for most people to comprehend and do not seem to be real time. Today, we accept that our planet is 4.6 billion years old, but it is not easy to deal with this astonishing number. Yet, we should not accept it without trying to understand what it means. Without an expanded conception of time, extremely slow geologic processes, considered only in terms of human experience, have little meaning.

To appreciate the magnitude of geologic time, we will abandon numbers for the moment and refer instead to something tangible and familiar. In Figure 8.16, the length of a football field represents the lapse of time from the beginning of Earth's history to the present. A numeric time scale and the standard geologic periods are shown on the left. Precambrian time constitutes the greatest portion of Earth's history (87 yd). The Paleozoic and later periods are equivalent to only the last 13 yd. To show events with which most people are familiar, the upper end of the scale must be enlarged. The first abundant fossils occur at the 13-yd line. The great coal swamps are at about the 6-yd line. The dinosaurs became extinct about a yard from the goal line, and the last ice age occurred an inch from the goal line. Recorded history corresponds to less than the width of a blade of grass.

It has not been easy for man to face time. Some, in recoiling from the fearsome prospects of time's abyss, have toppled backward into the abyss of ignorance. (Albritton, *The Abyss of Time*, 1980.)

**What are some ways to envision the magnitude of geologic time?**



## KEY TERMS

angular unconformity (p. 192)	disconformity (p. 194)	nonconformity (p. 193)	radiometric dating (p. 203)
carbon-14 (p. 205)	faunal succession (p. 195)	numerical age (p. 201)	relative age (p. 195)
catastrophism (p. 191)	geologic column (p. 198)	Paleozoic (p. 200)	superposition (p. 195)
Cenozoic (p. 200)	geologic time scale (p. 211)	parent isotope (p. 202)	tree-ring dating (p. 208)
correlation (p. 198)	half-life (p. 202)	Phanerozoic (p. 200)	uniformitarianism (p. 190)
crosscutting relations (p. 196)	inclusion (p. 196)	Precambrian (p. 200)	varve (p. 208)
daughter isotope (p. 202)	Mesozoic (p. 200)	radioactivity (p. 201)	

## REVIEW QUESTIONS

1. Explain the modern concept of uniformitarianism.
2. Explain the concept of relative dating.
3. Explain how the following principles are used in determining the relative age of rock bodies: (a) superposition, (b) faunal succession, (c) crosscutting relations, and (d) inclusions.
4. Discuss the sequence of events illustrated in Figure 8.2.
5. What is the standard geologic column? How did it originate?
6. Explain the meaning of half-life in radioactive decay.
7. Examine Figure 8.10 and give the simple nuclear change for each type of decay shown.
8. How is the numerical age of a rock determined?
9. Give examples of the important limitations on radiometric dating. In what situation could a rock be too old to obtain an accurate age? Too young? In what situations might there be insufficient radioactive elements?
10. What kinds of rocks—igneous, sedimentary, or metamorphic—are best for radiometric dating? Why?
11. Can you think of a simple test of the accuracy of radiometric dating using several minerals found in one volcanic rock?
12. Why are most rocks dated with respect to their position in the standard geologic column rather than assigned a definite numerical age, even though accurate methods of radiometric dating are well established?
13. How old are the oldest rocks on Earth? How old is Earth thought to be?

## ADDITIONAL READINGS

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- Gould, S. J. 1987. *Time's Arrow, Time's Cycle: Myth and Metaphor in the Discovery of Geologic Time*. Cambridge, Mass.: Harvard University Press.
- Hallam, A. 1982. *Great Geologic Controversies*. New York: Oxford University Press.
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## MULTIMEDIA TOOLS



### Earth's Dynamic Systems Website

The Companion Website at [www.prenhall.com/hamblin](http://www.prenhall.com/hamblin) provides you with an on-line study guide and additional resources for each chapter, including:

- On-line Quizzes (Chapter Review, Visualizing Geology, Quick Review, Vocabulary Flash Cards) with instant feedback
- Quantitative Problems
- Critical Thinking Exercises
- Web Resources



### Earth's Dynamic Systems CD

Examine the CD that came with your text. It is designed to help you visualize and thus understand the concepts in this chapter. It includes:

- Animations showing how relative ages are established
- An interactive tutorial on numerical dating
- Slide show and animation illustrating the nature and development of unconformities
- A direct link to the Companion Website