This road cut in New York contains a wealth of information about Earth's past. Fossils in the strata tell us of ancient environments and the tilting of the beds tells us about ancient mountain-building events.

Chapter Objectives

By the end of this chapter, you should know . . .

- the meaning of geologic time, and the difference between relative and numerical ages.
- geologic principles (uniformitarianism, superposition, fossil succession) and their implications.
- how unconformities form and what they represent.
- the basis for correlating stratigraphic formations, and how correlation led to development of the geologic column.
- how geologists determine the numerical age of rocks by using isotopic dating.
- the basis for determining dates on the geologic time scale, and for determining the age of the Earth.

If the Eiffel Tower were now representing the world's age, the skin of paint on the pinnacle-knob at its summit would represent man's share of that age; and anybody would perceive that that skin was what the tower was built for. I reckon they would, I dunno.

—Mark Twain (1835–1910)

10.1 Introduction

In May of 1869, a one-armed Civil War veteran named John Wesley Powell set out with a team of nine geologists and scouts to explore the previously unmapped expanse of the Grand Canyon, the greatest gorge on Earth. Though Powell and his companions battled fearsome rapids and the pangs of starvation, most managed to emerge from the mouth of the canyon three months later. During their voyage, seemingly insurmountable walls of rock both imprisoned and amazed the explorers, and led them to pose important questions about the Earth and its history, questions that even casual tourists to the canyon ponder today: Did the Colorado River sculpt this marvel, and if so, how long did it take? When did the rocks making up the walls of the canyon form? Was there a time *before* the colorful layers accumulated? Such questions pertain to **geologic time**, the span of time since Earth's formation.

In this chapter, we first cover the geologic principles that allowed geologists to develop the concept of geologic time and develop a reference frame for describing the *relative* ages of rocks, fossils, structures, and landscapes. This information sets the stage for introducing the geologic column, the way that geologists divide time into intervals. Then we look at the tools geologists use to determine the *numerical age* of the Earth and its features in years; specifically, we introduce isotopic (radiometric) dating and the geologic time scale. With the concept of geologic time in hand, a hike down a trail into the Grand Canyon becomes a trip into what authors call *deep time*. The geological discovery that our planet's history extends billions of years into the past changed humanity's perception of time and the Universe as profoundly as did the astronomical discovery that the limit of space extends billions of light years beyond the edge of our Solar System.

10.2 The Concept of Geologic Time

Setting the Stage for Studying the Past

Until relatively recently, people in most cultures believed that geologic time began about the same time that human history began, and that our planet has been virtually unchanged since its birth. This view was challenged by James Hutton (1726–1797), a Scottish gentleman farmer and doctor. Hutton lived during the Age of Enlightenment, when, sparked by the discovery of physical laws by Sir Isaac Newton, many people sought natural, rather than supernatural, explanations for features of the world around them. While wandering in the highlands of Scotland, a region where rocks are well exposed, Hutton noted that many features (such as ripple marks and cross beds) found in sedimentary rocks resembled features that he could see forming today in modern depositional environments. These observations led Hutton to speculate that the formation of rocks and landscapes, in general, were a consequence of processes that he could see happening today.

Hutton's idea came to be known as the principle of **uniformitarianism**. According to this principle, physical processes that operate in the modern world also operated in the past, at roughly the same rates, and these processes were responsible for forming geologic features preserved in outcrops. More concisely, the principle can be stated as: *the present is the key to the past*. Hutton deduced that the development of individual geologic features took a long time, and that not all features formed at the same time, so the Earth must have a history that includes a succession of slow geologic events. Since no one in recorded history has seen the entire process of sediment first turning into rock and then later rising into mountains, Hutton also realized that there must have been a long time *before* human history began.

Hutton was not a particularly clear writer, and it took the efforts of subsequent geologists to clarify the implications of the principle of uniformitarianism and to publicize them. Onc this had been accomplished, geologists around the world bega to apply their growing understanding of geologic processes t define and interpret geologic events of the Earth's past.

Relative versus Numerical Age

Like historians, geologists strive to establish both the sequen of events that produced an array of geologic features (such rocks, structures, and landscapes) and, when possible, the da on which each event happened. We specify the age of one fe ture with respect to another in a sequence as its **relative ag** and the age of a feature given in years as its **numerical a** (or, in older literature, its "absolute age"). Geologists learn how to determine relative age long before they could det mine numerical age, so we look next at the principles leadi to relative-age determination.

Take-Home Message

The principle of uniformitarianism—the present is th key to the past—implies that the Earth must be very ol for geologic processes happen slowly. Geologists distir guish between relative age (older or younger?) and nu merical age (how many years ago?).

10.3 Geologic Principles for Defining Relative Age

Building from the work of Steno, Hutton, and others, the ish geologist Charles Lyell (1797–1875) laid out a set of fo usable geologic principles in the first modern textbook of ogy. These principles, defined below, continue to provid basic framework within which geologists read the reco Earth history and determine relative ages.

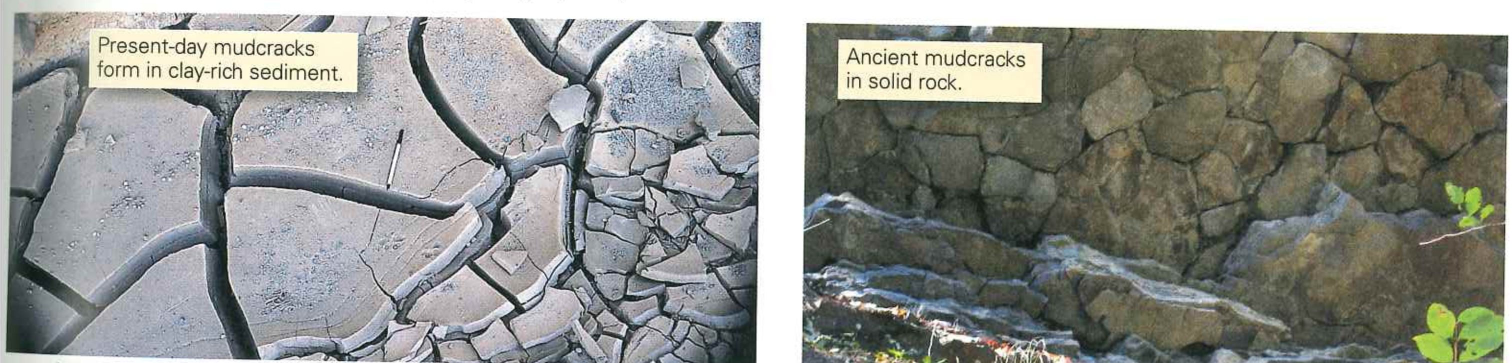
- *The principle of uniformitarianism* states that physical cesses we observe operating today also operated in the at roughly comparable rates, so the present is the key past (**Fig. 10.1a**).
- *The principle of* ***original horizontality*** states tha ers of sediment, when first deposited, are fairly hori (**Fig. 10.1b, c**), because sediments accumulate on surfa low relief (such as floodplains or the sea floor) in a tational field. If sediments were deposited on a steep they would likely slide downslope before they could be and lithified. With this principle in mind, geologist clude that examples of folds and tilted beds represe consequences of deformation after deposition.

- *The principle of* **superposition** states that in a sequence of sedimentary rock layers, each layer must be younger than the one below, for a layer of sediment cannot accumulate unless there is already a substrate on which it can collect. Thus, the layer at the bottom of a sequence is the oldest, and the layer at the top is the youngest (**Fig. 10.1d**).
- *The principle of lateral continuity* states that sediments generally accumulate in continuous sheets within a given region. If today you find a sedimentary layer cut by a canyon, then you can assume that the layer once spanned the area that was later eroded by the river that formed the canyon (**Fig. 10.1e**).
- *The principle of* **cross-cutting relations** states that if one geologic feature cuts across another, the feature that has been cut is older. For example, if an igneous dike cuts across a sequence of sedimentary beds, the beds must be older than the dike (**Fig. 10.1f**). If a fault cuts across and displaces layers of sedimentary rock, then the fault must be younger than the layers. But if a layer of sediment buries a fault, the sediment must be younger than the fault.
- *The principle of baked contacts* states that an igneous intrusion "bakes" (metamorphoses) surrounding rocks, so the rock that has been baked must be older than the intrusion (**Fig. 10.1g**).
- *The principle of inclusions* states that a rock containing an inclusion (fragment of another rock) must be younger than the inclusion. For example, a conglomerate containing pebbles of basalt is younger than the basalt, and a sill containing fragments of sandstone must be younger than the sandstone (**Fig. 10.1h**).

Geologists apply geologic principles to determine the relative ages of rocks, structures, and other geologic features at a given location. They then go further by interpreting the formation of each feature to be the consequence of a specific "geologic event." Examples of geologic events include: deposition of sedimentary beds; erosion of the land surface; intrusion or extrusion of igneous rocks; deformation (folding and/or faulting); and episodes of metamorphism. The succession of events in order of relative age that have produced the rock, structure, and landscape of a region is called the **geologic history** of the region.

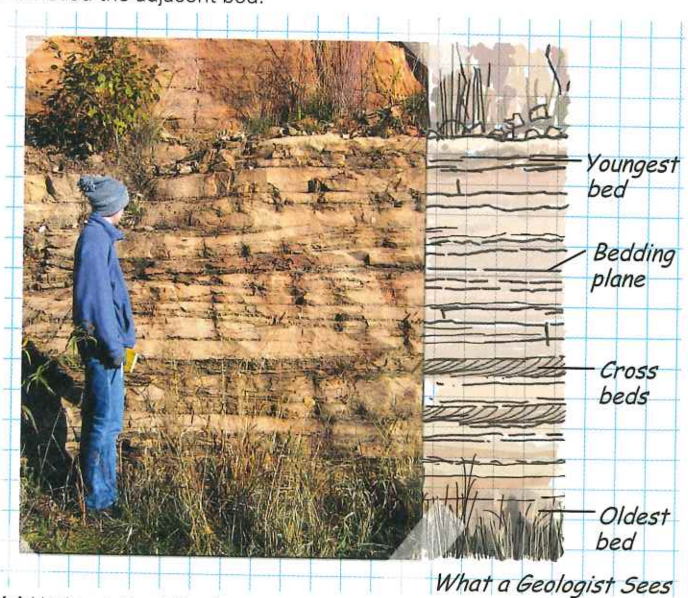
We can use these principles to determine relative ages of the features shown in **Figure 10.2a**. In so doing, we develop a geologic history of the region, defining the relative ages of events that took place there. For this example, we propose the following

FIGURE 10.1 Examples of the major geologic principles.



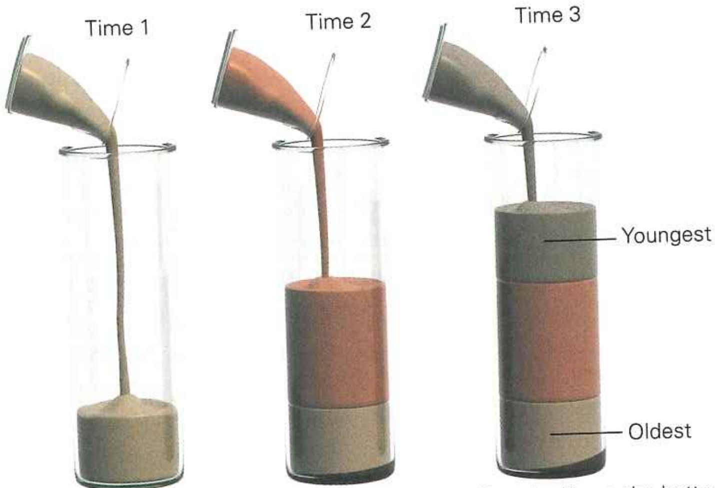
(a) Uniformitarianism: The processes that formed cracks in the dried-up mud puddle on the left also formed the mudcracks preserved in the ancient, solid rock on the right. We can see these ancient mudcracks because erosion removed the adjacent bed.

(b) Original horizontality: Gravity causes sediment to accumulate in fairly horizontal sheets on a flat plain.

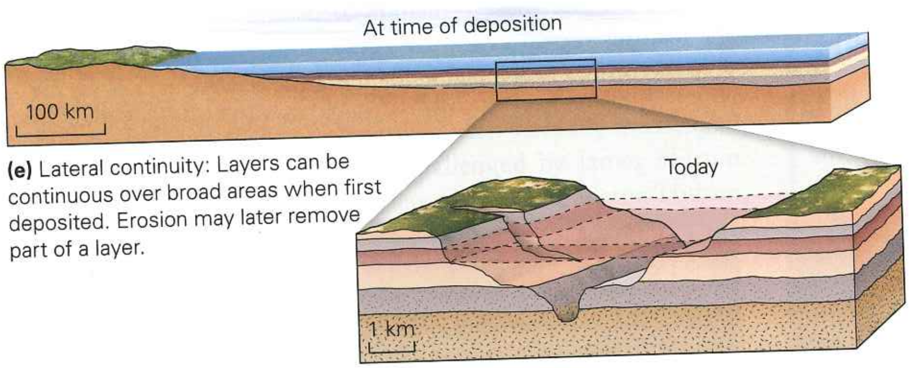


(c) Horizontal bedding in an outcrop of sandstone in Wisconsin.

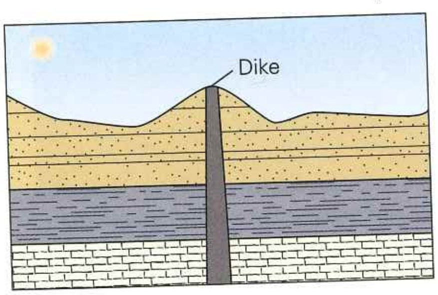
FIGURE 10.1 *(continued)*



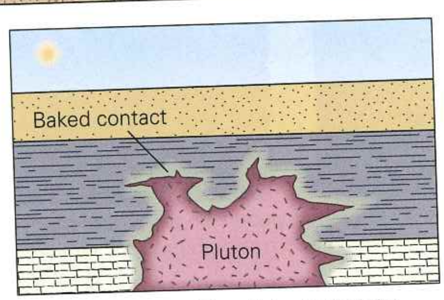
(d) Superposition: In a sequence of strata, the oldest bed is on the bottom, and the youngest on top. Pouring sand into a glass illustrates this point.



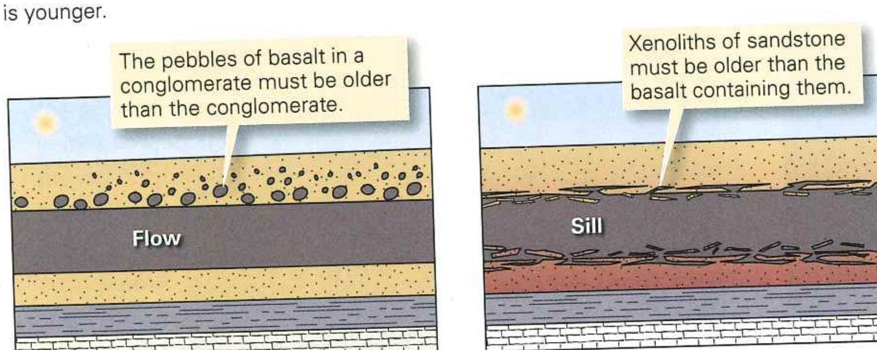
(e) Lateral continuity: Layers can be continuous over broad areas when first deposited. Erosion may later remove part of a layer.



(f) Cross-cutting relations: The dike cuts across the sedimentary beds, so the dike is younger.



(g) Baked contact: The pluton baked the adjacent rock, so the adjacent rock is older.



(h) Inclusions: Rock that occurs as an inclusion in another rock must be the older of the two.

geologic history for this region (**Fig. 10.2b**): deposition of the sedimentary sequence in order from beds 1 to 7; intrusion of the sill; folding of the sedimentary beds and the sill; intrusion of the granite pluton; faulting; intrusion of the dike; erosion to form the land surface.

Adding Fossils to the Story: Fossil Succession

As Britain entered the industrial revolution in the late 18th and early 19th centuries, new factories demanded coal to fire their steam engines and needed an inexpensive means to transport goods. Investors decided to construct a network of canals to transport coal and iron, and hired an engineer named William Smith (1769–1839) to survey some of the excavations. Canal digging provided fresh exposures of bedrock, which previously had been covered by vegetation. Smith learned to recognize distinctive layers of sedimentary rock and to identify the **fossil assemblage** (the group of fossil species) that they contained. He also realized that a particular assemblage can be found only in a limited interval of strata, and not above or below this interval. Thus, once a fossil species disappears at a horizon in a sequence of strata, it never reappears higher in the sequence or, put another way, extinction is forever. Smith's observation has been repeated at millions of locations around the world, and has been codified as the *principle of* **fossil succession**. It provides the geologic underpinning for the theory of evolution (see Interlude E).

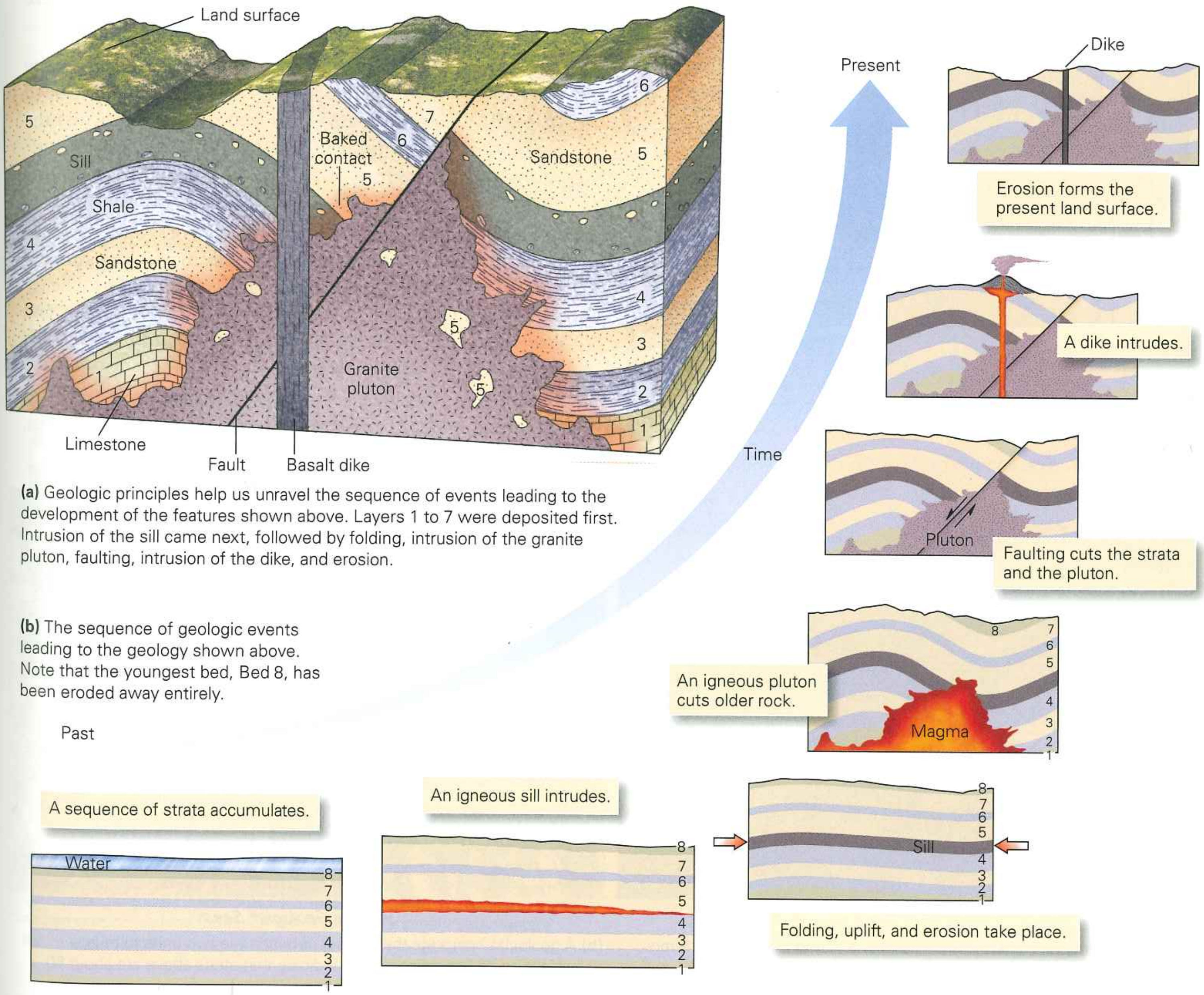
To see how this principle works, examine **Figure 10.3**, which depicts a sequence of strata. Bed 1 at the base contains fossil species A, Bed 2 contains fossil species A and B, Bed 3 contains B and C, Bed 4 contains C, and so on. From these data, we can define the *range* of specific fossils in the sequence, meaning the interval in the sequence in which the fossils occur. Note that the sequence contains a definable succession of fossils (A, B, C, D, E, F), that the range in which a particular species occurs may overlap with the range of other species, and that once a species vanishes, it does not reappear higher in the sequence. Once the relative ages of a number of fossils have been determined, the fossils can be used to determine the relative age of the beds containing them. For example, if a bed contains Fossil F (from the succession specified above), geologists can say the bed is older than a bed containing Fossil A, even if the two beds do not crop out in the same area. As we will see, painstaking work over many years eventually allowed geologists to assign numerical age ranges to fossil species. Of note, some fossil species are widespread, but survived only for a realtively short interval of geologic time. Such species are called **index fossils** (or guide fossils), because they can be used by geologists to associate the strata with the specific time interval.

> **Take-Home Message**
>
> **Relative-age determination is based on geologic principles, including uniformitarianism, superposition (younger strata overlie older strata), cross-cutting relations (younger features cut older ones), and fossil succession (fossil species occur in a predictable order).**

10.4 Unconformities: Gaps in the Record

To find good exposures of rock, James Hutton sometimes boated along the coast of Scotland, where waves of the stormy North Sea have stripped away soil and shrubbery. He was particularly puzzled by an outcrop at Siccar Point, where two distinct sequences of sedimentary rock lie in contact (**Fig. 10.4a, b**). In the lower portion of the outcrop, beds of gray sandstone and shale dip nearly vertically, whereas in the upper portion, beds of red sandstone and conglomerate display a dip of less than 20°. Further,

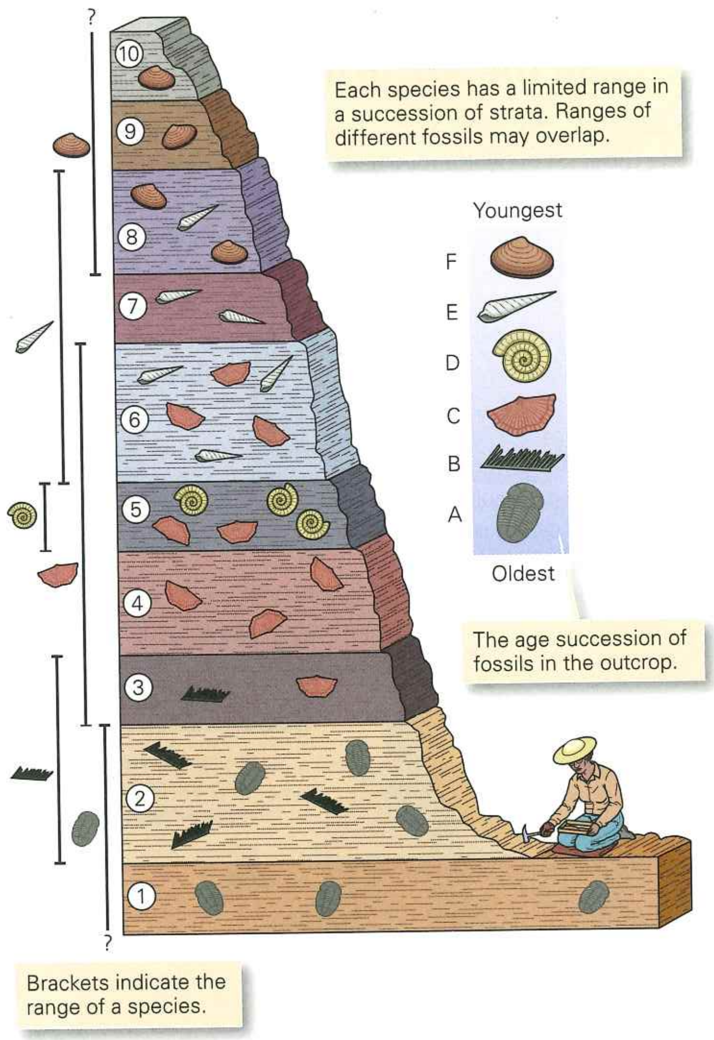
FIGURE 10.2 Interpreting the geologic history of a region, using geologic principles as a guide.



(a) Geologic principles help us unravel the sequence of events leading to the development of the features shown above. Layers 1 to 7 were deposited first. Intrusion of the sill came next, followed by folding, intrusion of the granite pluton, faulting, intrusion of the dike, and erosion.

(b) The sequence of geologic events leading to the geology shown above. Note that the youngest bed, Bed 8, has been eroded away entirely.

FIGURE 10.3 The principle of fossil succession.

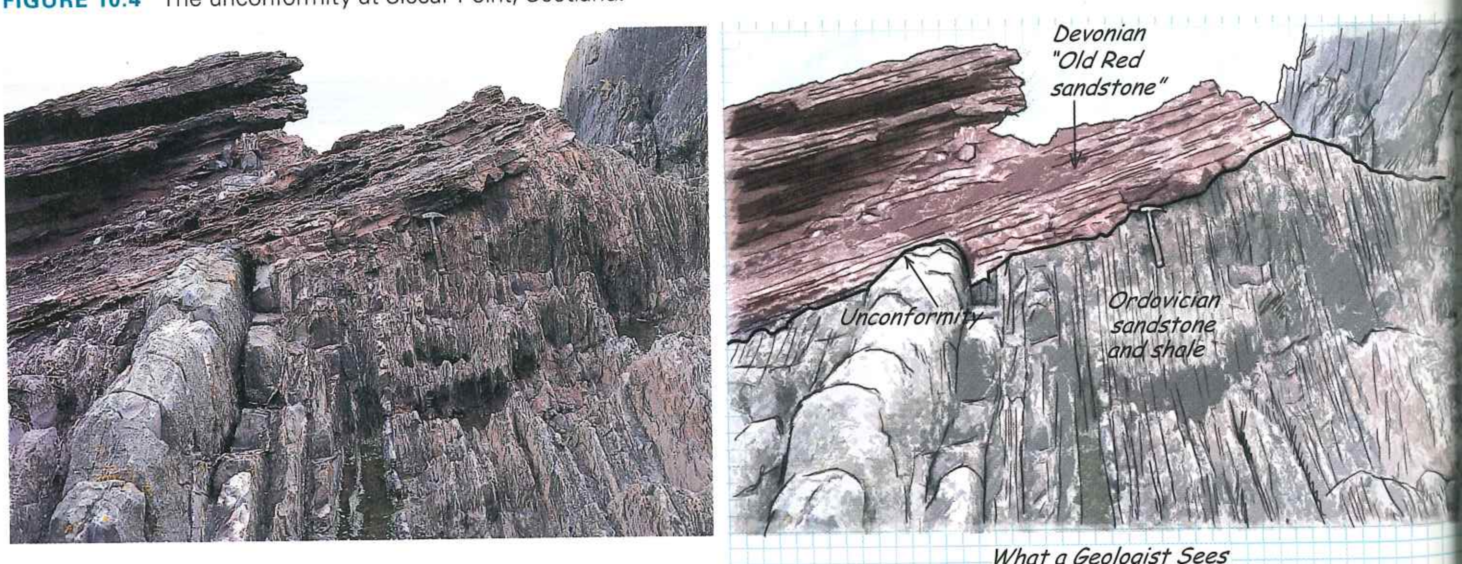


the gently dipping layers seem to lie across the truncated ends of the vertical layers, like a handkerchief lying across a row of books. We can imagine that as Hutton was examining this odd geometric relationship, the tide came in and deposited a new layer of sand on top of the rocky shore. With the principle of uniformitarianism in mind, Hutton suddenly realized the significance of what he saw. The gray sandstone–shale sequence had been deposited, turned into rock, tilted, and truncated by erosion *before* the red sandstone–conglomerate beds had been deposited.

Hutton deduced that the surface between the gray and red rock sequences represented a time interval during which new strata had not been deposited at Siccar Point and the older strata had been eroded away. We now call such a surface, representing a period of nondeposition and possibly erosion, an **unconformity**. The gap in the geologic record that an unconformity represents is called a hiatus. Geologists recognize three kinds of unconformities:

- *Angular unconformity*: Rocks below an angular unconformity were tilted or folded before the unconformity developed (**Fig. 10.5a**). Thus, an angular unconformity cuts across the underlying layers, and the orientation of layers below an unconformity differs from that of the layers above. (The outcrop at Siccar Point exposes an angular unconformity.)
- *Nonconformity*: A nonconformity is a type of unconformity at which sedimentary rocks overlie generally much older intrusive igneous rocks and/or metamorphic rocks (**Fig. 10.5b**). The igneous or metamorphic rocks underwent cooling, uplift, and erosion prior to becoming the substrate, or *basement*, on which new sediments accumulated.
- *Disconformity*: Imagine that a sequence of sedimentary beds has been deposited beneath a shallow sea. Then sea level drops,

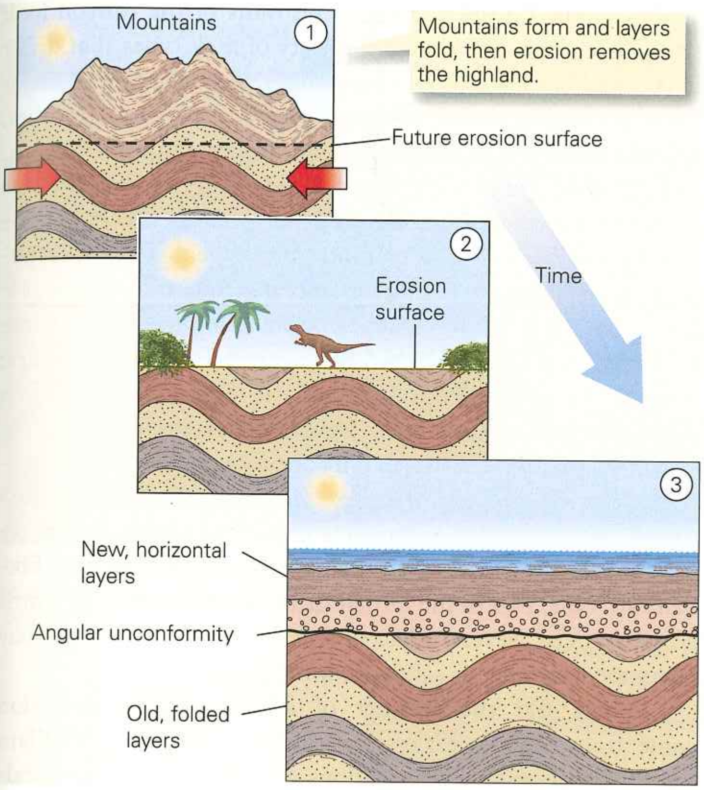
FIGURE 10.4 The unconformity at Siccar Point, Scotland.



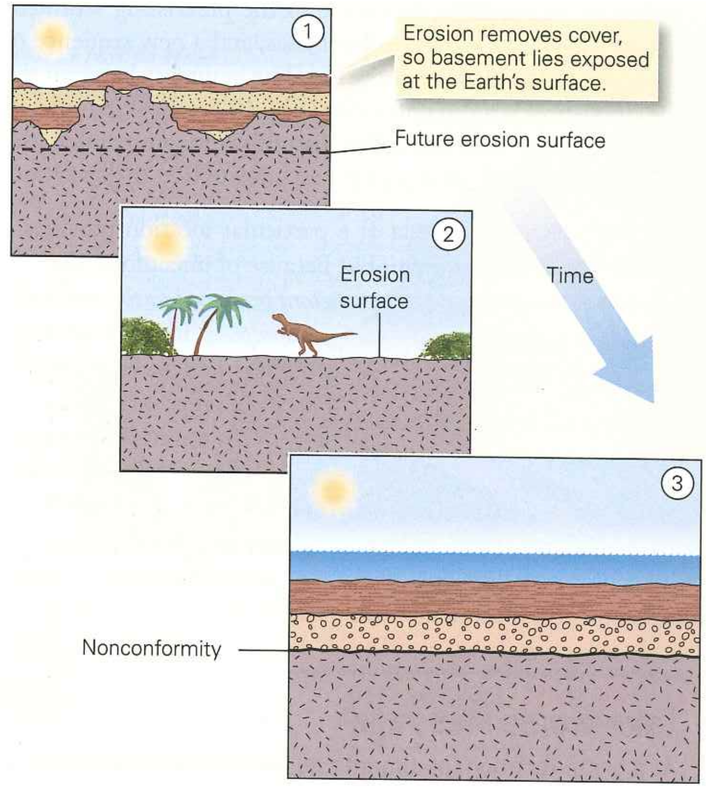
(a) James Hutton found this unconformity and deduced that the layers above were deposited long after the beds below had been tilted.

(b) A geologist interprets the contact between the two units to be an unconformity. Subsequent studies indicate that strata above are about 50 million years younger than strata below.

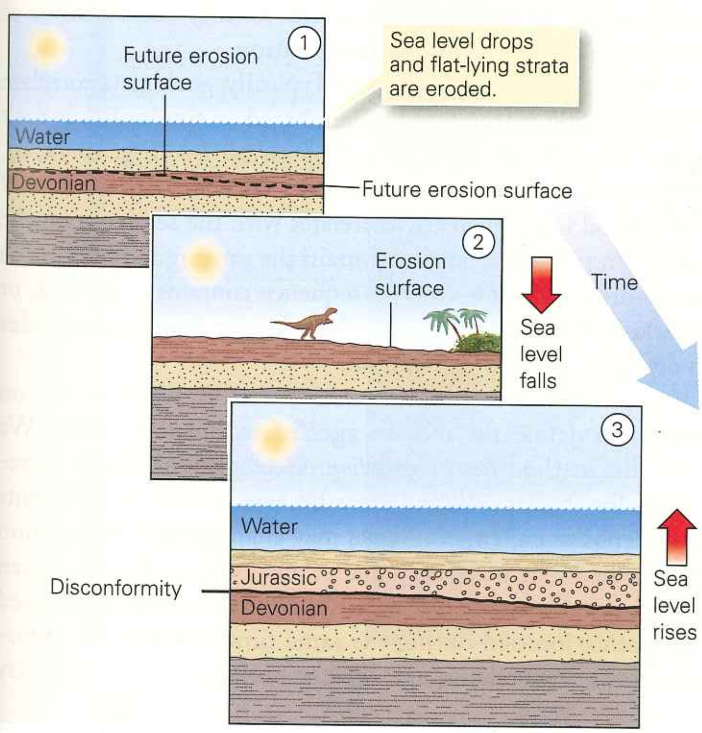
FIGURE 10.5 The three kinds of unconformities and their formation.



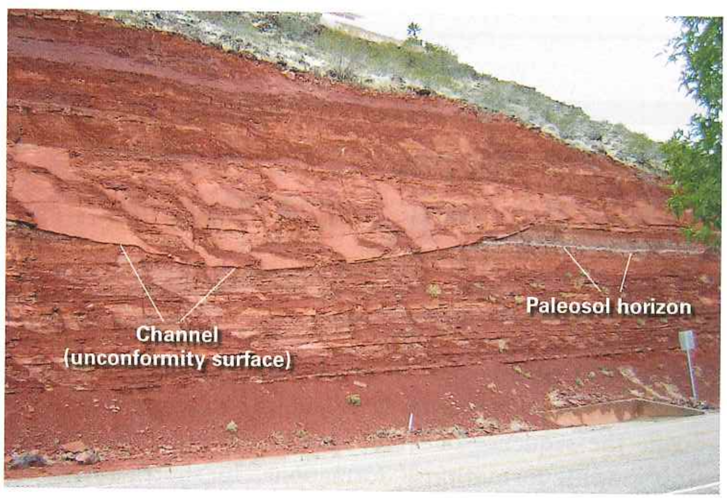
(a) An angular unconformity: (1) layers undergo folding; (2) erosion produces a flat surface; (3) sea level rises and new layers of sediment accumulate.



(b) A nonconformity: (1) a pluton intrudes; (2) erosion cuts down into the crystalline rock; (3) new sedimentary layers accumulate above the erosion surface.



(c) A disconformity: (1) layers of sediment accumulate; (2) sea level drops and an erosion surface forms; (3) sea level rises and new sedimentary layers accumulate.



(d) This roadcut in Utah shows a sand-filled channel cut down into floodplain mud. The mud was exposed between floods, and a soil formed on it. When later buried, all the sediment turned into rock; the channel floor is an unconformity, and the ancient soil is a "paleosol." Note that the channel cut across the paleosol. The paleosol also represents an unconformity, a time during which deposition did not occur.

exposing the beds for some time. During this time, no new sediment accumulates, and some of the preexisting sediment gets eroded away. Later, sea level rises, and a new sequence of sediment accumulates over the old. The boundary between the two sequences is a disconformity (**Fig. 10.5c, d**). Even though the beds above and below the disconformity are parallel, the contact between them represents an interruption in deposition.

The succession of strata at a particular location provides a record of Earth history there. But because of unconformities, *the record preserved in the rock layers is incomplete*. It's as if geologic history is being chronicled by a tape recorder that turns on only intermittently—when it's on (times of deposition), the rock record accumulates, but when it's off (times of nondeposition and possibly erosion), an unconformity develops. Because of unconformities, no single location on Earth contains a complete record of Earth history.

Did you ever wonder . . .
do Grand Canyon strata represent all Earth's history?

Take-Home Message

At a given location, sediments do not accumulate continuously, so unconformities, surfaces representing intervals of nondeposition and/or erosion, can form. Because of unconformities, the geologic record at any given location is incomplete.

10.5 Stratigraphic Formations and Their Correlation

We can summarize information about the sequence of sedimentary strata at a location by drawing a **stratigraphic column**. Typically, we draw columns to scale, so that the relative thicknesses of layers portrayed on the column reflect the thicknesses of layers in the outcrop. Then, we divide the sequence of strata represented on a column into **stratigraphic formations** ("formations," for short), a sequence of beds of a specific rock type or group of rock types that can be traced over a fairly broad region. The boundary surface between two formations is a type of geologic **contact**. (Fault surfaces and the boundary between an igneous intrusion and its wallrock are also types of contacts.) Typically, a formation has a specific geologic age.

Let's see how the concept of a stratigraphic formation applies to the Grand Canyon. The walls of the canyon look striped, because they expose a variety of rock types that differ in color and in resistance to erosion. Geologists identify major contrasts distinguishing one interval of strata from another, and use them as a basis for dividing the strata into formations, each of which may consist of many beds (**Fig. 10.6a–c**). Some formations include a single rock type, whereas others include interlayered beds of two or more rock types. Not all formations have the same thickness, and the thickness of a single formation can vary with location. Commonly, geologists name a formation after a locality where it was first identified or first studied. For example, the "Schoharie Formation" was first defined based on exposures in Schoharie Creek, in New York.

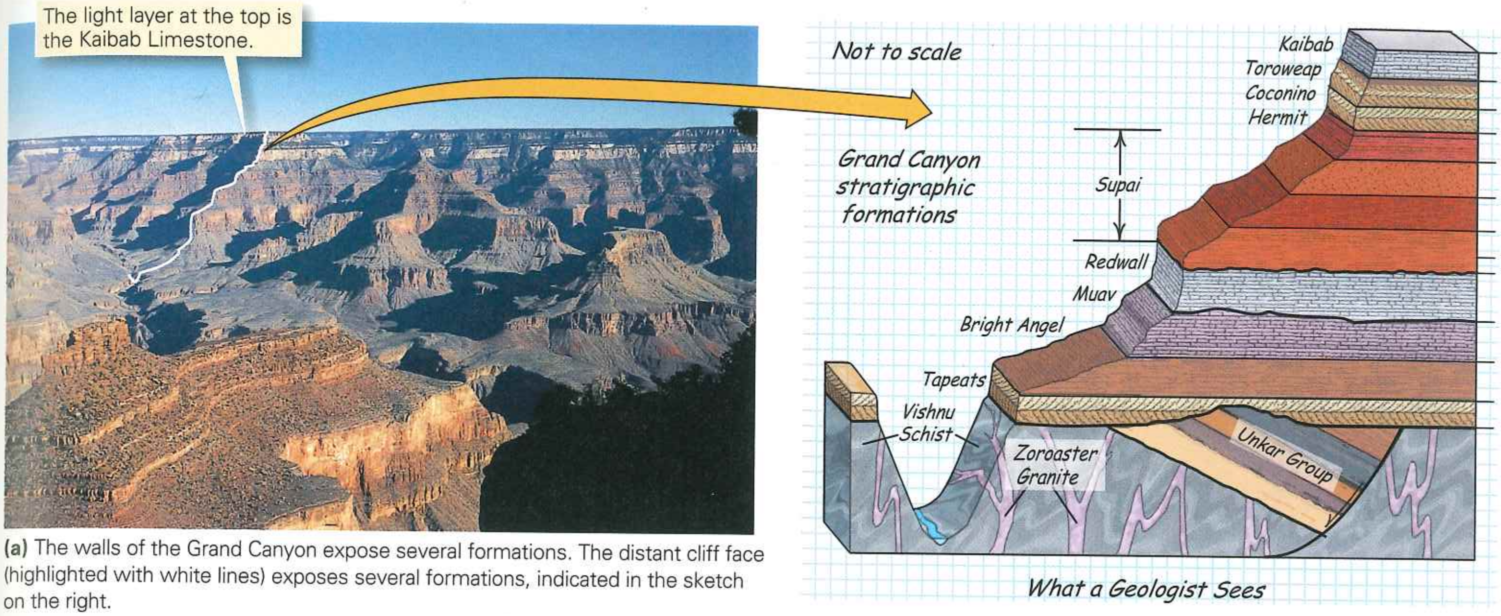
If a formation consists of only one rock type, we may incorporate that rock type in the name (for example, Kaibab Limestone), but if a formation contains more than one rock type, we use the word "formation" in the name (such as Toroweap Formation). Note that in the formal name of a formation, all words are capitalized. Several adjacent formations in a succession may be lumped together as a **stratigraphic group**.

Where did the concept of a stratigraphic formation come from? While excavating canals in England, William Smith discovered that formations cropping out at one locality resembled formations cropping out at another, in that their beds looked similar and contained similar fossil assemblages. In other words, Smith was able to define the stratigraphic relationship between the strata at one locality and the strata at another, a process now called **correlation**.

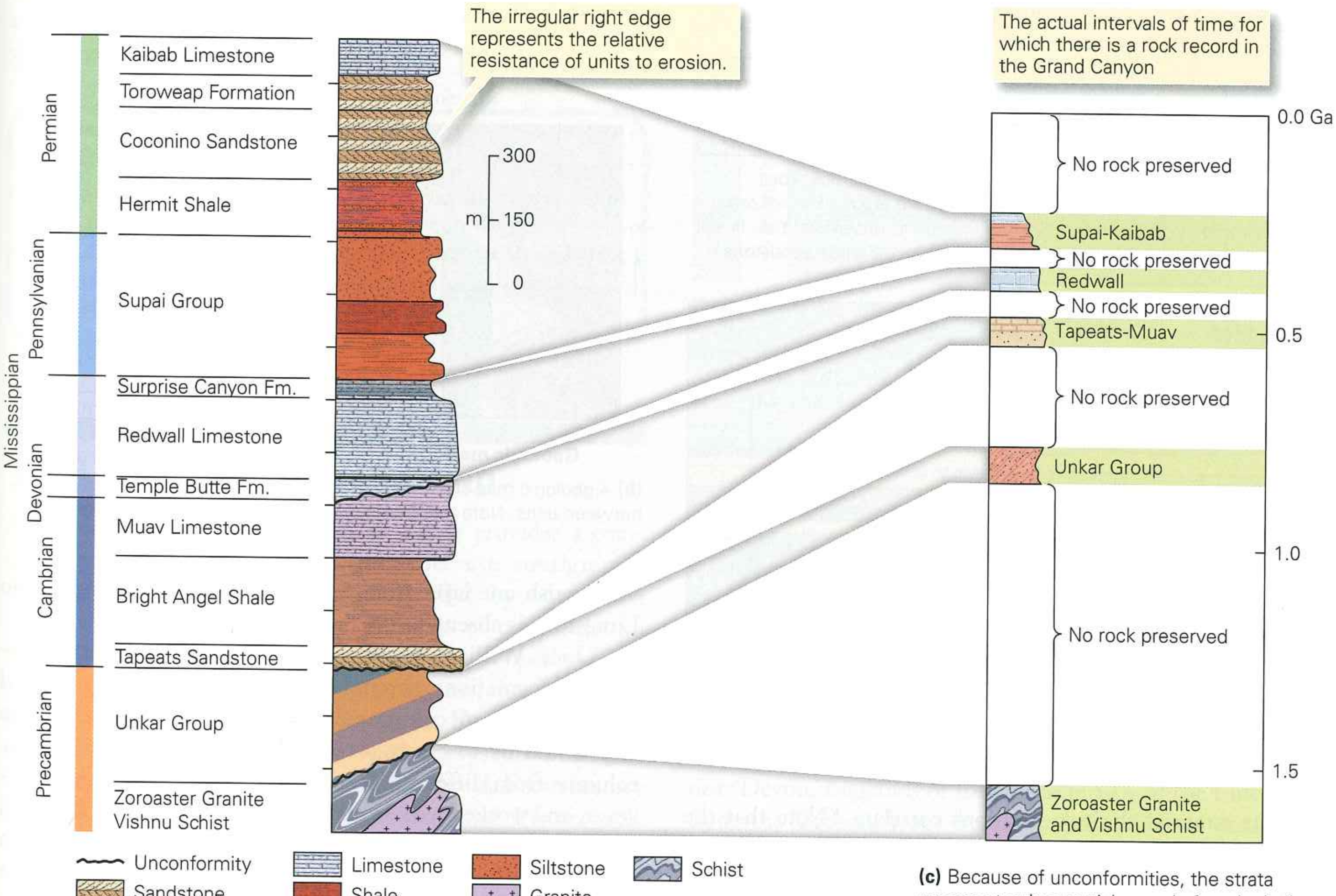
How does correlation work? Typically, geologists correlate formations between *nearby* regions based on similarities in rock type. We call this method *lithologic correlation* (**Fig. 10.7a, b**). For example, the sequence of strata on the southern rim of the Grand Canyon clearly correlates with the sequence on the northern rim, because they contain the same rock types in the same order. In some cases, a sequence contains a key bed, or **marker bed**, which is a particularly unique layer that provides a definitive basis for correlation.

To correlate rock units over *broad* areas, we must rely on fossils to define the relative ages of sedimentary units. We call this method *fossil correlation*. Geologists use fossil correlation for studies of broad areas because sources of sediments and depositional environments may change from one location to another. The beds deposited at one location during a given time interval may look quite different from the beds deposited at another location during the same time interval. But if fossils of the same relative age occur at both locations, we can sa

FIGURE 10.6 The stratigraphic formations and stratigraphic column for the Grand Canyon in Arizona.



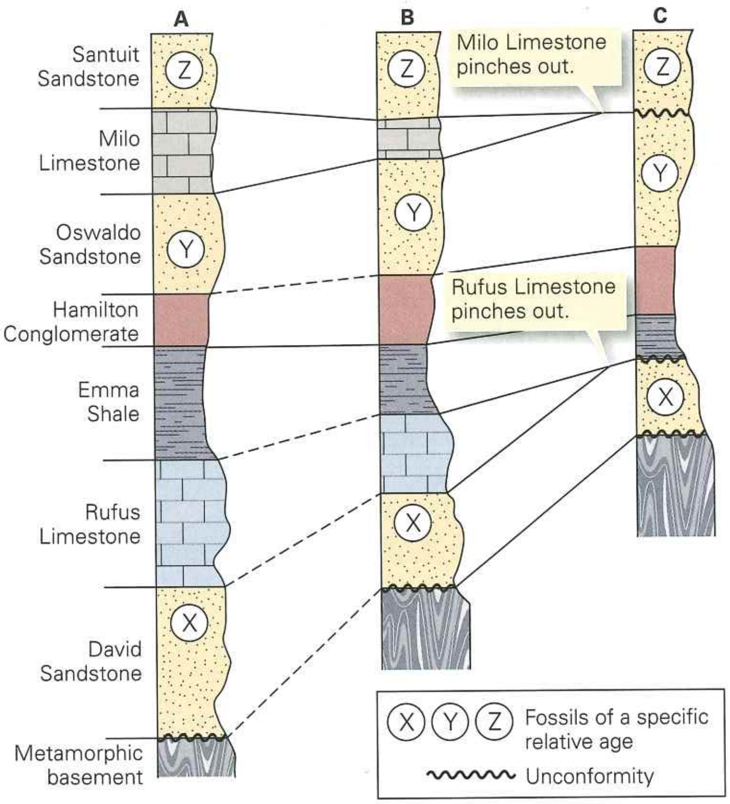
(a) The walls of the Grand Canyon expose several formations. The distant cliff face (highlighted with white lines) exposes several formations, indicated in the sketch on the right.



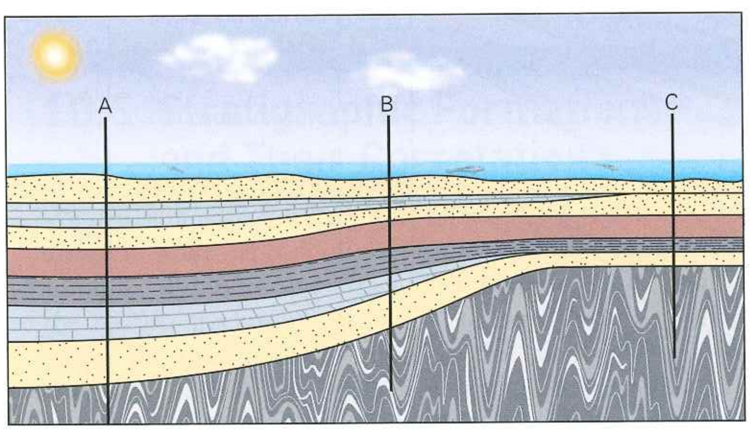
(b) A formalized stratigraphic column for strata of the Grand Canyon. The vertical scale indicates unit thickness. Patterns represent different rock types. The Unkar Group is one of three units that together comprise the Grand Canyon Supergroup.

(c) Because of unconformities, the strata represent only a partial record of geologic time. This chart, with a time scale on the vertical axis, shows large gaps in the record.

FIGURE 10.7 The principles of correlation.



(a) Stratigraphic columns can be correlated by matching rock types (lithologic correlation). The Hamilton Conglomerate is a marker horizon. Because some strata pinch out, Column C contains unconformities. Fossil correlation indicates that the youngest beds in C are Santuit Sandstone.

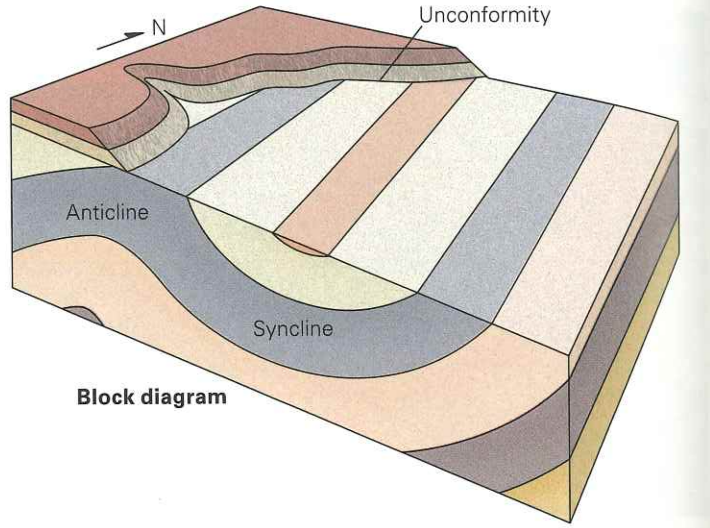


(b) At the time of deposition, locations A, B, and C were in different parts of a basin. The basin floor was subsiding fastest at A.

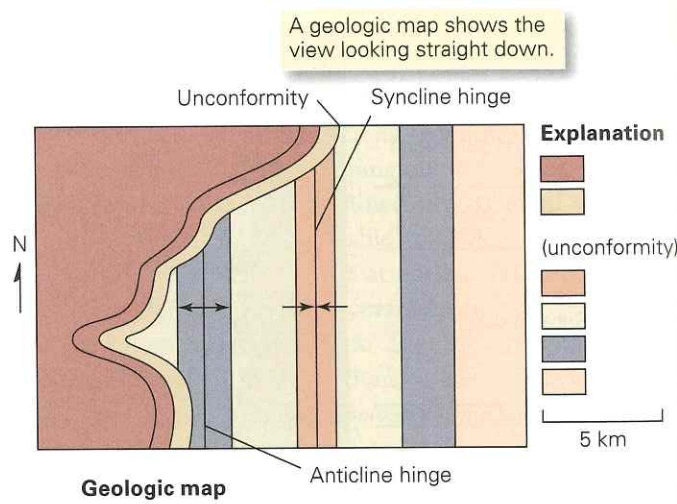
that the strata at the two locations correlate. (Note that the fossils are not necessarily of the same species—they won't be if the depositional environments are different—but they are of the same age.) Fossil correlation may also come in handy when rock types are not distinctive enough to allow correlation. For example, imagine that the Santuit Sandstone and Oswaldo Sandstone of Figure 10.7a look the same. Only fossils may distinguish one layer from the other, if the intervening Milo Limestone is absent.

Once William Smith succeeded in correlating stratigraphic formations throughout central England, he faced the challenge of communicating his ideas to others. One way would be to create a table that compared stratigraphic columns from different locations. But since Smith was a surveyor, and worked with maps, it occurred to him that he could outline and color in areas on a map to represent areas in which strata of a given relative age occurred. He did this using the data he had collected, and in 1815, produced the first modern geologic map. In general, a **geologic map** portrays the spatial distribution of rock units at the Earth's surface. Significantly, the pattern displayed on a geologic map provides insight into

FIGURE 10.8 A geologic map depicts the distribution of rock units and structures.

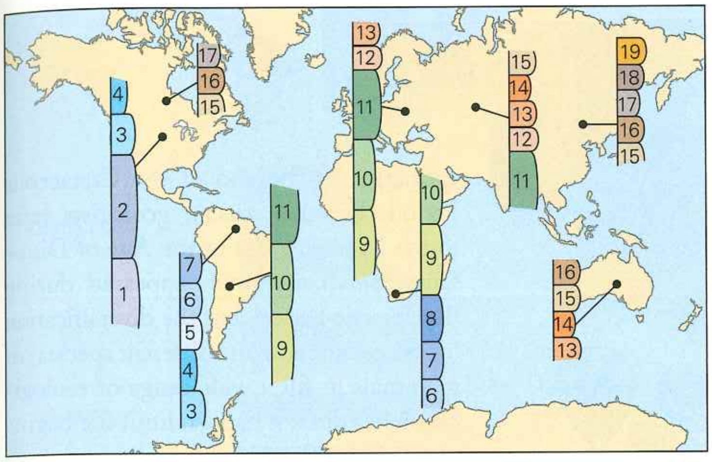


(a) A block diagram provides a three-dimensional representation. Here, we see an angular unconformity over folded strata.

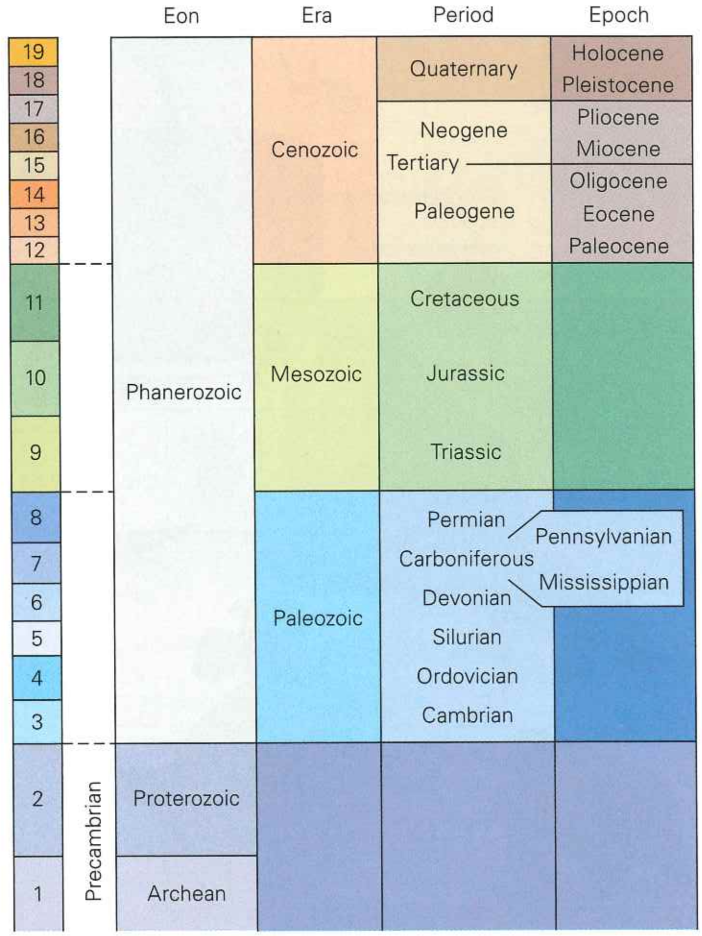


(b) A geologic map shows the distribution of units. Contacts occur between units. Note that the map also shows geologic structures.

FIGURE 10.9 Global correlation of strata led to the development of the geologic column (not to scale).



(a) Each of these small columns represents the stratigraphy at a given location. By correlating these columns, geologists determined their relative ages, filled in the gaps in the record, and produced the geologic column.



(b) By correlation, the strata from localities around the world were stacked in a chart representing geologic time to create the Geologic Column. Geologists assigned names to time intervals, but since the column was built without knowledge of numerical ages, it does not depict the duration of these intervals. Subdivisions of eons in the Precambrian are not shown. The Hadean is not shown because rocks do not preserve a record of it.

the presence and orientation of geologic structures in the map area (**Fig. 10.8a, b**). The inside of this book's back cover provides a geologic map of North America.

Take-Home Message

A stratigraphic formation is a recognizable sequence of beds that can be mapped across a broad region. Geologists correlate formations regionally on the basis of rock type and fossil content, and portray the configuration of formations in a region on a geologic map.

10.6 The Geologic Column

As stated earlier, no one locality on Earth provides a complete record of our planet's history, because stratigraphic columns can contain unconformities. But by correlating rocks from locality to locality at millions of places around the world, geologists have pieced together a *composite* stratigraphic column, called the **geologic column**, that represents the entirety of Earth history (**Fig. 10.9a, b**). The column is divided into segments, each of which represents a specific interval of time. The largest subdivisions break Earth history into the Hadean, Archean, Proterozoic, and Phanerozoic **Eons**. (The first three together constitute the **Precambrian**.) The suffix *–zoic* means life, so Phanerozoic means visible life, and Proterozoic means first life. (It wasn't until after the eons had been named that geologists determined that the earliest life, cells of Bacteria and Archaea, appeared in the Archean Eon.) The Phanerozoic Eon is subdivided into **eras**. In order from oldest to youngest, they are the Paleozoic (ancient life), Mesozoic (middle life), and Cenozoic (recent life) Eras. We further divide each era into **periods** and each period into **epochs**.

Where do the names of the periods come from? They refer either to localities where a fairly complete stratigraphic column representing that time interval was first identified (for example, rocks representing the Devonian Period crop out near Devon, England) or to a characteristic of the time (rocks from the Carboniferous Period contain a lot of coal). The terminology was not set up in a planned fashion that would make it easy to learn. Instead, it grew haphazardly in the years between 1760 and 1845, as geologists began to refine their understanding of geologic history and fossil succession. Also, because the divisions were defined before numerical ages could be determined, they are all of different durations.

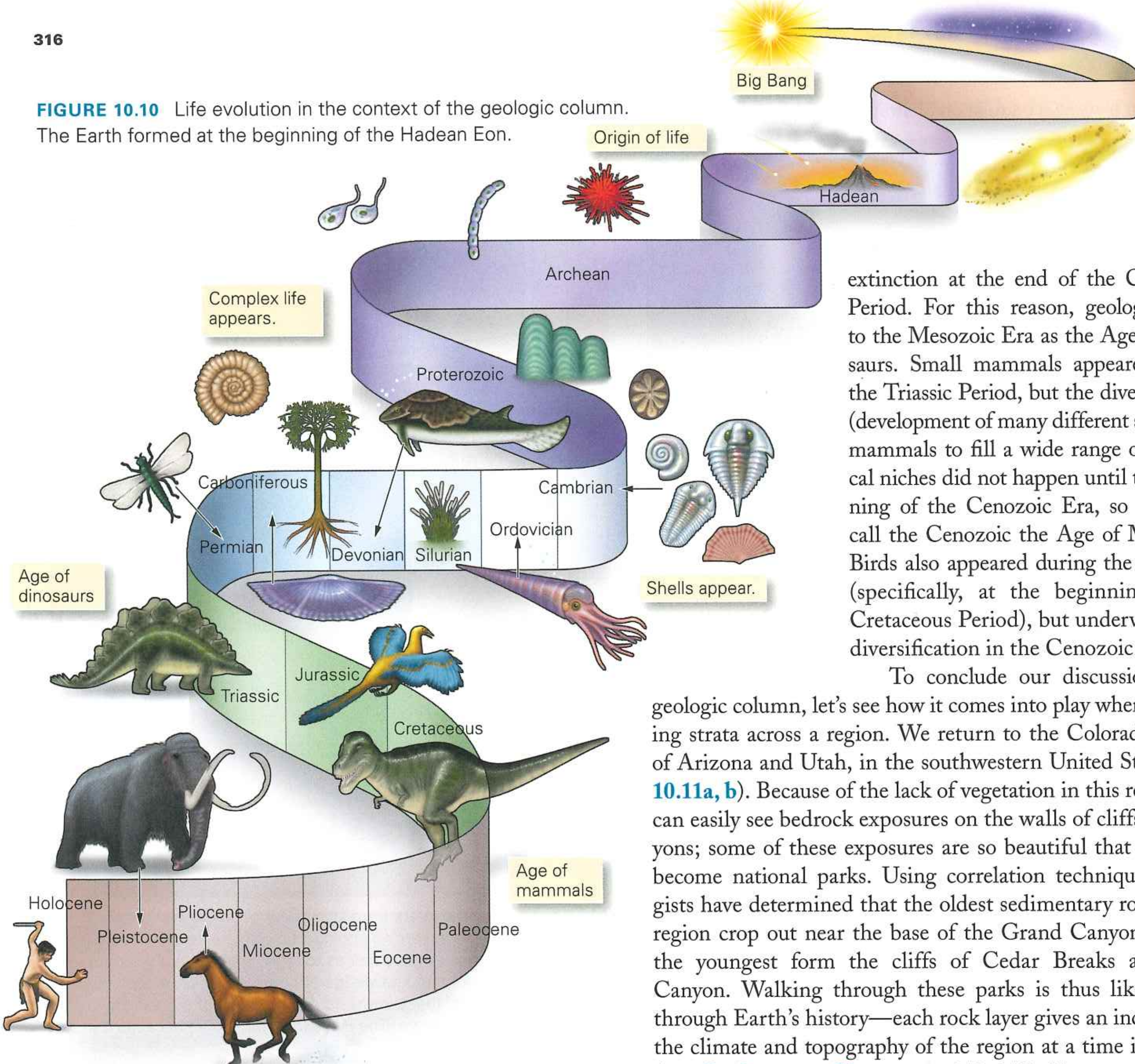


FIGURE 10.10 Life evolution in the context of the geologic column. The Earth formed at the beginning of the Hadean Eon.

The succession of fossils preserved in strata of the geologic column defines the course of life's evolution throughout Earth history (**Fig. 10.10**). Simple bacteria and archaea appeared during the Archean Eon, but complex shell-less invertebrates did not evolve until the late Proterozoic. The appearance of invertebrates with shells defines the Precambrian-Cambrian boundary. At this time, there was a sudden diversification in life, with many new types of organisms appearing over a relatively short interval—this event is called the **Cambrian explosion**.

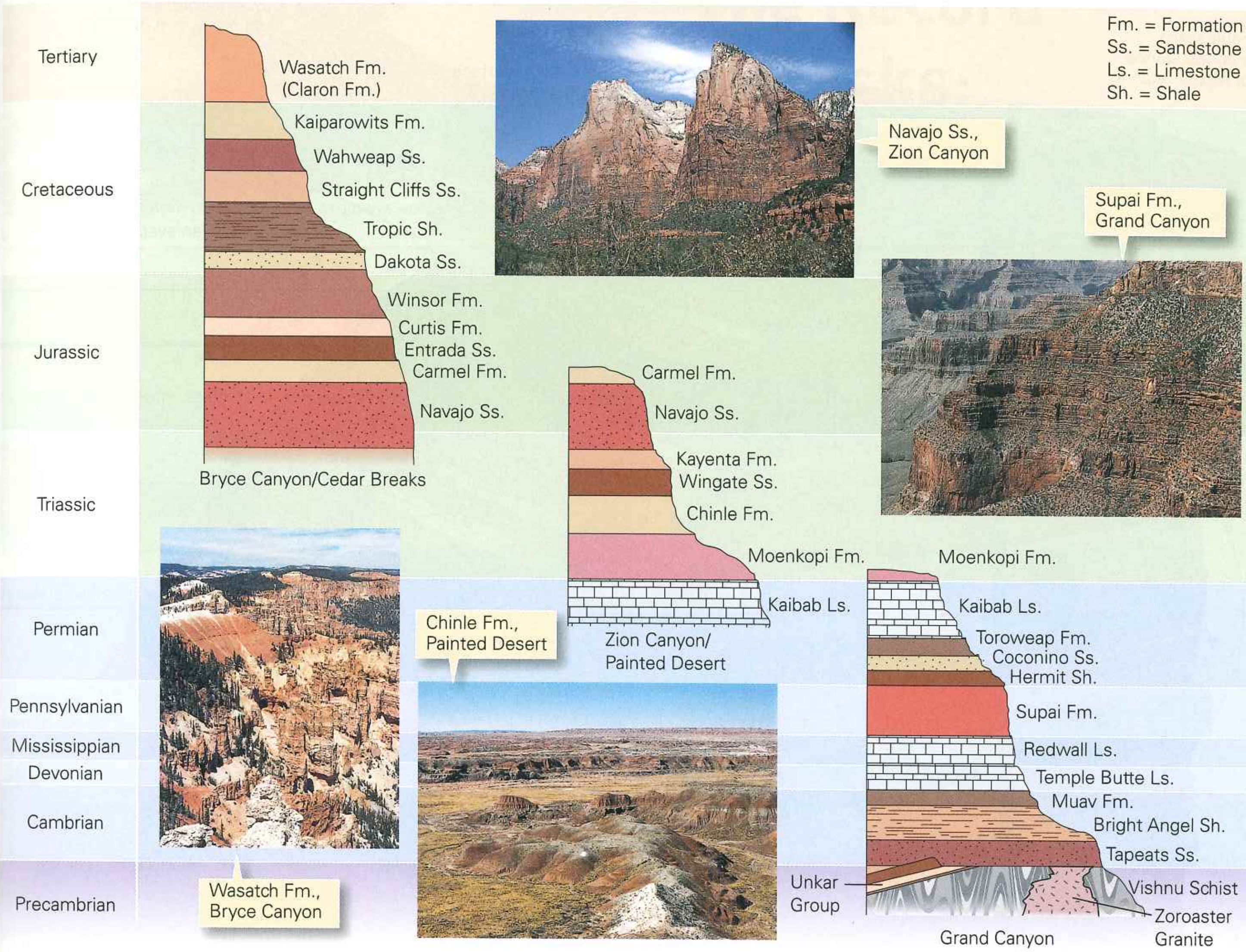
Progressively more complex organisms populated the Earth during the Paleozoic. For example, the first fish appeared in Ordovician seas, land plants started to spread over the continents during the Silurian (prior to the Silurian, the land surface was unvegetated), and amphibians appeared during the Devonian. Though reptiles appeared during the Pennsylvanian Period, the first dinosaurs did not stomp across the land until the Triassic. Dinosaurs continued to inhabit the Earth until their sudden extinction at the end of the Cretaceous Period. For this reason, geologists refer to the Mesozoic Era as the Age of Dinosaurs. Small mammals appeared during the Triassic Period, but the diversification (development of many different species) of mammals to fill a wide range of ecological niches did not happen until the beginning of the Cenozoic Era, so geologists call the Cenozoic the Age of Mammals. Birds also appeared during the Mesozoic (specifically, at the beginning of the Cretaceous Period), but underwent great diversification in the Cenozoic Era.

To conclude our discussion of the geologic column, let's see how it comes into play when correlating strata across a region. We return to the Colorado Plateau of Arizona and Utah, in the southwestern United States (**Fig. 10.11a, b**). Because of the lack of vegetation in this region, you can easily see bedrock exposures on the walls of cliffs and canyons; some of these exposures are so beautiful that they have become national parks. Using correlation techniques, geologists have determined that the oldest sedimentary rocks of the region crop out near the base of the Grand Canyon, whereas the youngest form the cliffs of Cedar Breaks and Bryce Canyon. Walking through these parks is thus like walking through Earth's history—each rock layer gives an indication of the climate and topography of the region at a time in the past (see **Geology at a Glance**, pp. 318–319). For example, when the Precambrian metamorphic and igneous rocks exposed in the inner gorge of the Grand Canyon first formed, the region was a high mountain range, perhaps as dramatic as the Himalayas today. When the fossiliferous beds of the Kaibab Limestone at the rim of the canyon first developed, the region was a Bahama-like carbonate reef and platform, bathed in a warm, shallow sea. And when the rocks making up the towering red cliffs of sandstone in Zion Canyon were deposited, the region was a Sahara-like desert, blanketed with huge sand dunes.

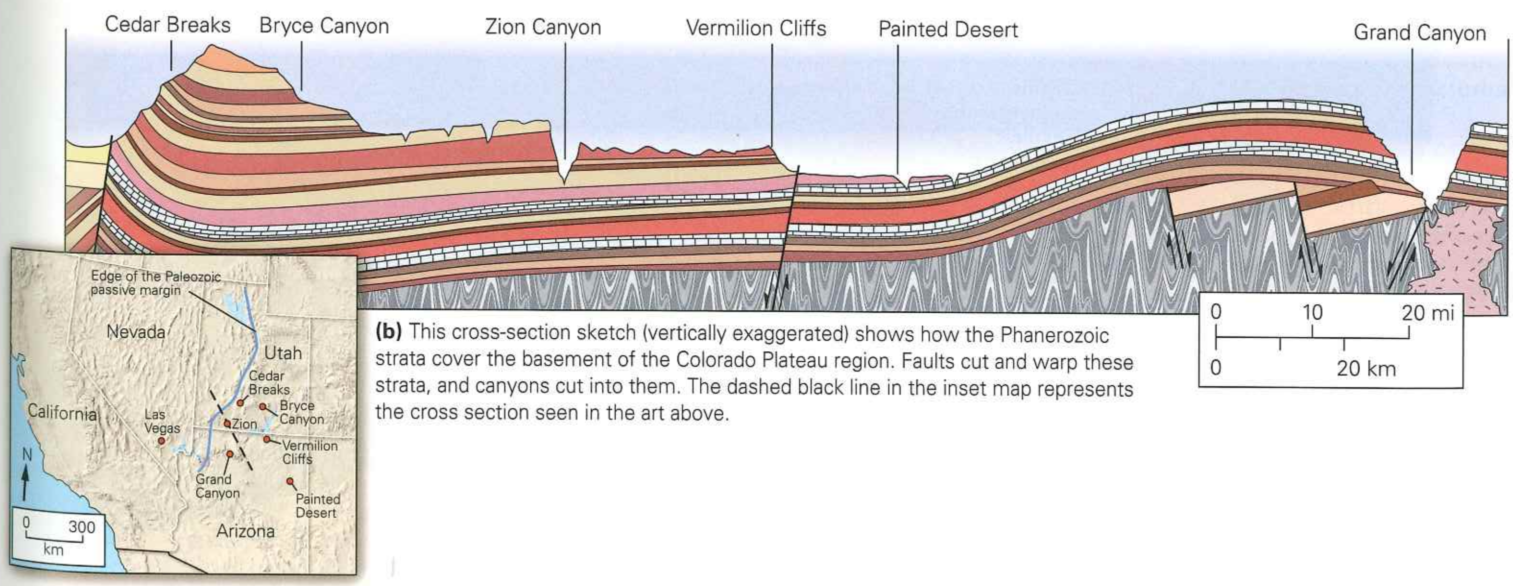
Take-Home Message

Correlation of stratigraphic sequences from around the world led to the production of a chart, the geologic column, that represents the entirety of Earth history. The column, developed using only relative-age relations, is subdivided into eons, eras, periods, and epochs.

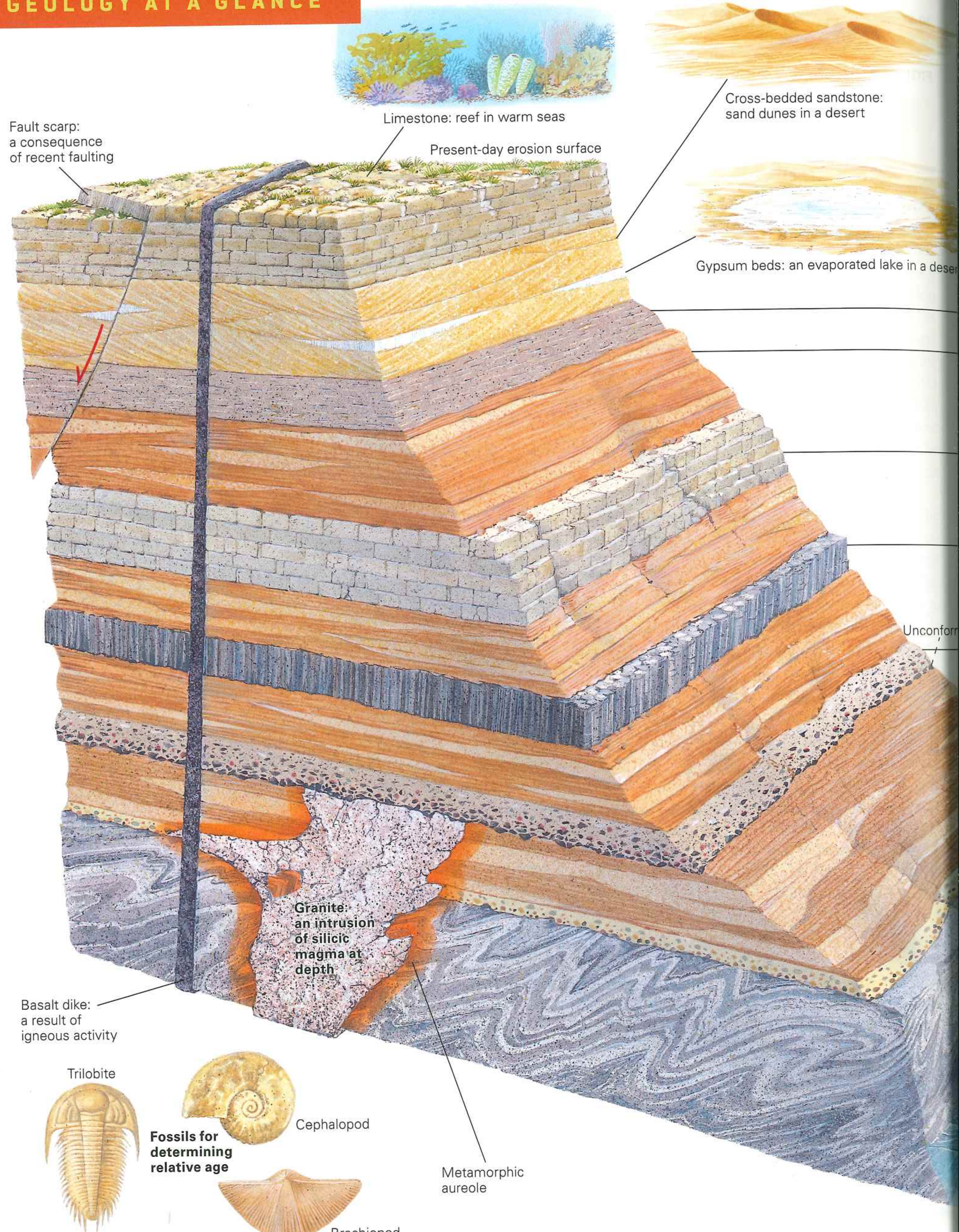
FIGURE 10.11 Correlation of strata among the national parks of Arizona and Utah.



(a) Different intervals of geologic time are represented by the strata of different parks.

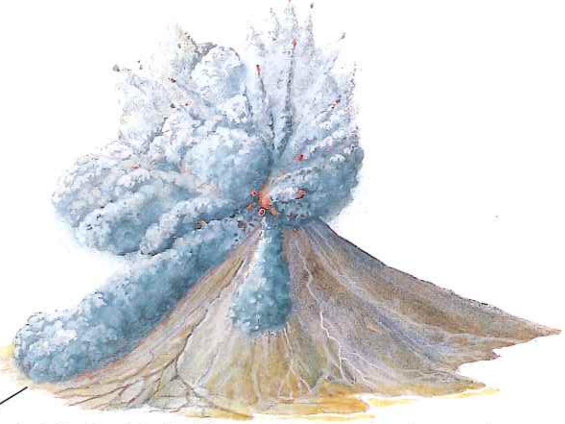


(b) This cross-section sketch (vertically exaggerated) shows how the Phanerozoic strata cover the basement of the Colorado Plateau region. Faults cut and warp these strata, and canyons cut into them. The dashed black line in the inset map represents the cross section seen in the art above.



Limestone: reef in warm seas
Cross-bedded sandstone: sand dunes in a desert
Fault scarp: a consequence of recent faulting
Present-day erosion surface
Gypsum beds: an evaporated lake in a deser
Unconforr
Granite: an intrusion of silicic magma at depth
Basalt dike: a result of igneous activity
Trilobite
Cephalopod
Fossils for determining relative age
Brachiopod
Metamorphic aureole

The Record in Rocks: Reconstructing Geologic History

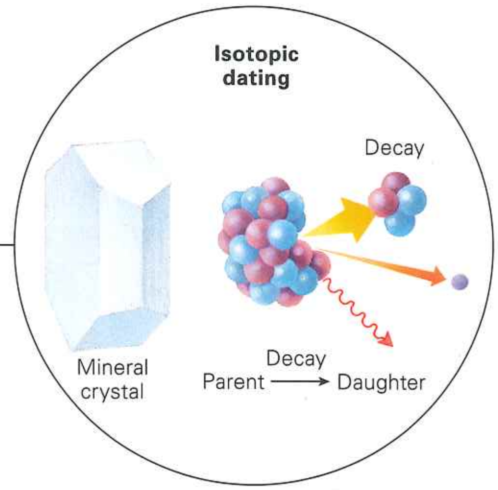


Ignimbrite (welded tuff): an explosive volcanic eruption

Redbeds: sand and mud deposited in a river channel and bordering floodplain

Limestone: reef in warm seas

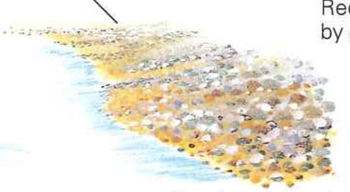
Basalt lava: flows from a volcano



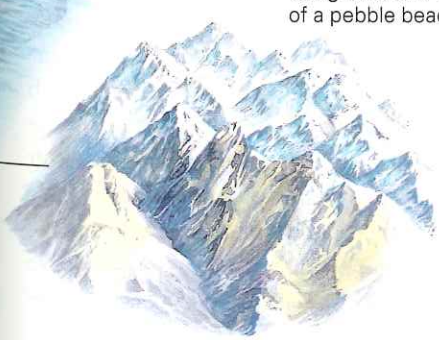
Conglomerate: debris eroded from a cliff

Redbeds: sand and mud deposited by distributaries of a delta plain

Unconformity



Conglomerate: deposits of a pebble beach



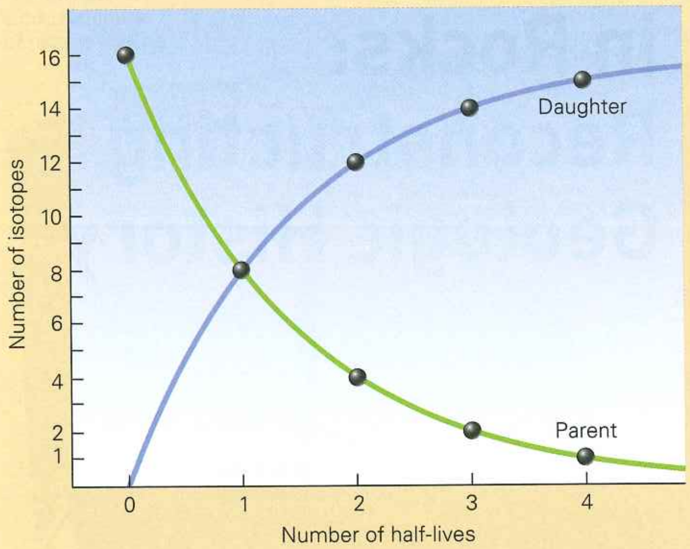
Gneiss: metamorphism at depth beneath a mountain belt

When geologists examine a sequence of rocks exposed on a cliff, they see a record of Earth history that can be interpreted by applying the basic principles of geology, by searching for fossils, and by using isotopic dating. On this cliff, we see evidence for many geologic events. The layers of sediment (and the sedimentary structures they contain), the igneous intrusions, and the geologic structures tell us about past climates and past tectonic activity.

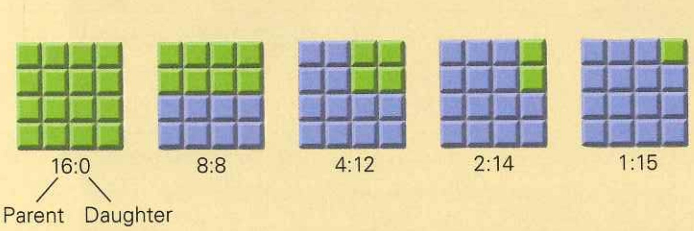
The insets show the way the region looked in the past, based on the record in the rocks. For example, the presence of gneiss at the base of the canyon indicates that at one time the region was a mountain belt, for the protoliths of the gneiss were buried deeply. Unconformities indicate that the region underwent uplift and erosion. Sedimentary successions record transgressions and regressions of the sea, igneous rocks are evidence of volcanic and intrusive activity, and faults indicate deformation.

Clearly, the land surface portrayed in this painting was sometimes a river floodplain or a delta (indicated by redbeds), sometimes a shallow sea (limestone), and sometimes a desert dune field (cross-bedded sandstone). And at several times in the past, volcanic activity occurred in the region. We can gain insight into the age of the sedimentary rocks by studying the fossils they contain, and into the age of the igneous and metamorphic rocks by using isotopic dating methods.

FIGURE 10.12 The concept of a half-life, in the context of radioactive decay.



(a) This graph shows how the number of parent isotopes decreases and the number of daughter isotopes increases, as time passes. The rate of change decreases with time.



(b) The ratio of parent-to-daughter isotopes changes with the passage of each successive half-life.

(c) In a cluster of isotopes undergoing decay, there is no way to predict which parent will decay next.

10.7 How Do We Determine Numerical Age?

Geologists since the days of Hutton could determine the relative ages of geologic events, but they had no way to specify numerical ages (called "absolute ages" in older literature). Thus, they could not define a timeline for Earth history or determine the duration of events. This situation changed with the discovery of radioactivity. Simply put, radioactive elements decay at a constant rate that can be measured in the lab and can be specified in years. In the 1950s, geologists developed techniques for using measurements of radioactive elements to calculate the numerical ages of rocks. Geologists originally referred to these techniques as radiometric dating; more recently, this has come to be known as **isotopic dating**. The overall study of numerical ages is **geochronology**. Since the 1950s, isotopic dating techniques have steadily improved, and geologists have learned how to make very accurate measurements from very small samples. But the basis of the techniques remains the same, and to explain them, we must first review radioactive decay.

Did you ever wonder . . .
how geologists can specify the age of some rocks in years?

Radioactive Decay

All atoms of a given element have the same number of protons in their nucleus—we call this number the atomic number (see Chapter 1). However, not all atoms have the same number of neutrons in their nucleus. Therefore, not all atoms of a given element have the same atomic weight (roughly, the number of protons plus neutrons). Different versions of an element, called **isotopes** of the element, have the same atomic number but a different atomic weight (see Box 1.1). For example, all uranium atoms have 92 protons, but the uranium-238 isotope (abbreviated ^{238}U) has an atomic weight of 238 and thus has 146 neutrons, whereas the ^{235}U isotope has an atomic weight of 235 and thus has 143 neutrons.

Some isotopes of some elements are stable, meaning that they last essentially forever. Radioactive isotopes are unstable in that eventually, they undergo a change called **radioactive decay**, which converts them to a different element. Radioactive decay can take place by a variety of reactions that change the atomic number of the nucleus and thus form a different element. In these reactions, the isotope that undergoes decay is the **parent isotope**, while the decay product is the **daughter isotope**. For example, rubidium-87 (^{87}Rb) decays to strontium-87 (^{87}Sr), potassium-40 (^{40}K) decays to argon-40 (^{40}Ar), and uranium-238 (^{238}U) decays to lead-206 (^{206}Pb). In some cases, decay takes many steps before yielding a stable daughter.

Physicists cannot specify how long an individual radioactive isotope will survive before it decays, but they can measure how long it takes for half of a group of parent isotopes to decay. This time is called the **half-life** of the isotope. Figure 10.12a–c can help you visualize the concept of a half-life. Imagine a crystal containing 16 radioactive parent isotopes. (In real crystals, the number of atoms would be much larger.) After one half-life, 8 isotopes have decayed, so the crystal now contains 8 parent and 8 daughter isotopes. After a second half-life, 4 of the remaining parent isotopes have decayed, so the crystal contains 4 parent and 12 daughter isotopes. And after a third half-life, 2 more parent isotopes have decayed, so the crystal contains 2 parent and 14 daughter isotopes. For a given decay reaction, the half-life is a constant.

Isotopic Dating Techniques

Since radioactive decay proceeds at a known rate, like the tick-tock of a clock, it provides a basis for telling time. In other

TABLE 10.1 Isotopes Used in the Isotopic Dating of Rock

Parent → Daughter	Half-Life (years)	Minerals Containing the Isotopes
$^{147}Sm \rightarrow {}^{143}Nd$	106.0 billion	Garnets, micas
$^{87}Rb \rightarrow {}^{87}Sr$	48.8 billion	Potassium-bearing minerals (mica, feldspar, hornblende)
$^{238}U \rightarrow {}^{206}Pb$	4.5 billion	Uranium-bearing minerals (zircon, uraninite)
$^{40}K \rightarrow {}^{40}Ar$	1.3 billion	Potassium-bearing minerals (mica, feldspar, hornblende)
$^{235}U \rightarrow {}^{207}Pb$	713.0 million	Uranium-bearing minerals (zircon, uraninite)

Sm = samarium, Nd = neodymium, Rb = rubidium, Sr = strontium, U = uranium, Pb = lead, K = potassium, Ar = argon

words, because an element's half-life is a constant, we can calculate the age of a mineral by measuring the ratio of parent to daughter isotopes in the mineral.

In practice, how can we obtain an isotopic date? First, we must find the right kind of elements to work with. Although there are many different pairs of parent and daughter isotopes among the known radioactive elements, only a few have long enough half-lives, and occur in sufficient abundance in minerals, to be useful for isotopic dating. **Table 10.1** lists particularly useful elements. Each radioactive element has its own half-life. (Note that carbon dating is *not* used for dating rocks because appropriate carbon isotopes occur only in organisms and radioactive carbon has a very short half-life).

Second, we must identify the right kind of minerals to work with. Not all minerals contain radioactive elements, but fortunately some fairly common minerals do. Once we have found the right kind of minerals, we can set to work using the following steps.

- *Collecting the rocks*: We need to find unweathered rocks for dating, for the chemical reactions that happen during weathering may lead to the loss of some isotopes.
- *Separating the minerals*: The rocks are crushed, and the appropriate minerals are separated from the debris.
- *Extracting parent and daughter isotopes*: To separate out the parent and daughter isotopes from minerals, we can use several techniques, including dissolving the minerals in acid or evaporating portions of them with a laser.
- *Analyzing the parent-daughter ratio*: Once we have a sample of appropriate atoms, we pass them through a mass spectrometer, an instrument that uses a strong magnet to separate isotopes from one another according to their respective weights (**Fig. 10.13**). The instrument can count the number of atoms of specific isotopes separately.

At the end of the laboratory process, we can define the ratio of parent to daughter isotopes in a mineral, and from this ratio calculate the age of the mineral. Needless to say, the description of the procedure here has been simplified—in reality, obtaining an isotopic date is time-consuming and expensive and requires complex calculations.

What Does an Isotopic Date Mean?

At high temperatures, atoms in a crystal lattice vibrate so rapidly that chemical bonds can break and reattach relatively easily. As a consequence, isotopes can escape from or move into crystals, so parent-daughter ratios are meaningless. Because isotopic dating is based on the parent-daughter ratio, the "isotopic clock" starts only when crystals become cool enough for isotopes to be locked into the lattice. The temperature below which isotopes are no longer free to move is called the **closure temperature** of a mineral. When we specify an isotopic date for a mineral, we are defining the time at which the mineral cooled below its closure temperature.

With the concept of closure temperature in mind, we can interpret the meaning of isotopic dates. In the case of igneous rocks, isotopic dating tells you when a magma or lava cooled to form a solid, cool igneous rock. In the case of metamorphic rocks, an isotopic date tells you when a rock cooled from a metamorphic temperature above the closure temperature to a temperature below. Not all minerals have the same closure temperature, so different minerals in a rock that cools very slowly will yield different dates.

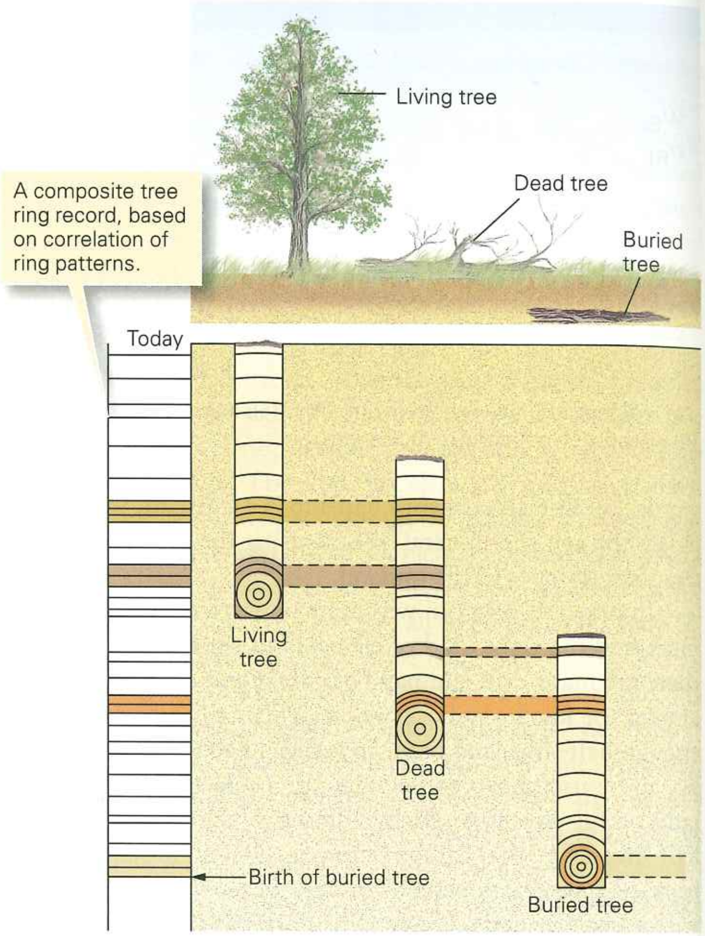
Can we isotopically date a clastic sedimentary rock directly? No. If we date minerals in a sedimentary rock, we determine only when these minerals first crystallized as part of an igneous or metamorphic rock, not the time when the minerals were deposited as sediment nor the time when the sediment lithified to form a sedimentary rock. For example, if we date the feldspar grains contained within a granite pebble in a conglomerate, we're dating the time the granite cooled below feldspar's closure temperature, not the time the pebble was deposited by a stream.

FIGURE 10.13 In an isotopic dating laboratory, samples are analyzed using a mass spectrometer. This instrument measures the ratio of parent to daughter isotopes.

FIGURE 10.14 Using tree rings as a basis for dating.

(a) Dust settling during the summer highlights boundaries between snow layers, now turned to ice in this Oregon glacier.

(b) Patterns of rings are like bar codes. Each ring in this slice of wood represents the growth of one year.



(c) Dendrochronology is based on the correlation of tree rings. Each of the columns in the diagram represents a core drilled out of a tree. By correlation, researchers extend the climate record back in time before the oldest living tree started to grow.

Other Methods of Determining Numerical Age

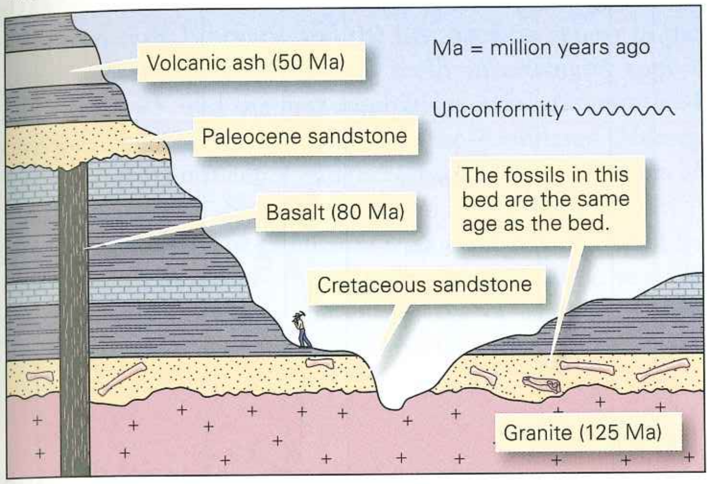
The rate of tree growth depends on the season. During the spring, trees grow rapidly and produce lighter, less-dense wood, but during the winter trees grow slowly or not at all, and produce darker, denser wood. Thus, wood contains recognizable annual growth rings. Such tree rings provide a basis for determining age. If you've ever wondered how old a tree that's just been cut down might be, just look at the stump and count the rings. Notably, by correlating clusters of distinctive rings in the older parts of living trees with comparable clusters of rings in dead logs, scientists can extend the tree-ring record back for many thousands of years, allowing geologists to track climate changes back into prehistory.

Seasonal changes also affect rates of such phenomena as shell growth, snow accumulation, clastic sediment deposition, chemical sediment precipitation, and production of organic material. Geologists have learned to use growth rings in shells, as well as rhythmic layering in sediments and in glacial ice (**Fig. 10.14 a–c**), to date events numerically back through recent Earth history.

Take-Home Message

Isotopic dating specifies numerical ages in years. To obtain an isotopic date, we measure the ratio of parent radioactive isotopes to stable daughter products in a mineral. A date for a mineral gives the time at which the mineral cooled below a closure temperature.

FIGURE 10.15 The Cretaceous sandstone bed was deposited on the granite, so it must be younger than 125 Ma. The dike cuts the bed, so the bed must be older than 80 Ma. Thus, the Cretaceous sandstone bed was deposited between 125 and 80 Ma. The Paleocene sandstone was unconformably deposited over the dike and lies beneath a 50-million-year-old layer of ash. Therefore, it must have been deposited between 80 and 50 Ma.



10.8 Numerical Age and Geologic Time

Dating Sedimentary Rocks?

The mind grows giddy gazing so far back into the abyss of time.

—John Playfair (1747–1819),
British geologist who popularized the works of Hutton

We have seen that isotopic dating can be used to date the time when igneous rocks formed and when metamorphic rocks metamorphosed, but not when sedimentary rocks were deposited. So how do we determine the numerical age of a sedimentary rock? We must answer this question if we want to add numerical ages to the geologic column.

Geologists obtain dates for sedimentary rocks by studying cross-cutting relationships between sedimentary rocks and datable igneous or metamorphic rocks. For example, if we find a sequence of sedimentary strata deposited unconformably on a datable granite, the strata must be younger than the granite (**Fig. 10.15**). If a datable basalt dike cuts the strata, the strata must be older than the dike. And if a datable volcanic ash buried the strata, then the strata must be older than the ash.

The Geologic Time Scale

Geologists have searched the world for localities where they can recognize cross-cutting relations between datable igneous rocks and sedimentary rocks or for layers of datable volcanic rocks interbedded with sedimentary rocks. By isotopically dating the igneous rocks, they have been able to provide numerical ages for the boundaries between all geologic periods. For example, work from around the world shows that the Cretaceous Period began about 145 million years ago and ended 65 million years ago. So the Cretaceous sandstone bed in Figure 10.15 was deposited during the middle part of the Cretaceous, not at the beginning or end.

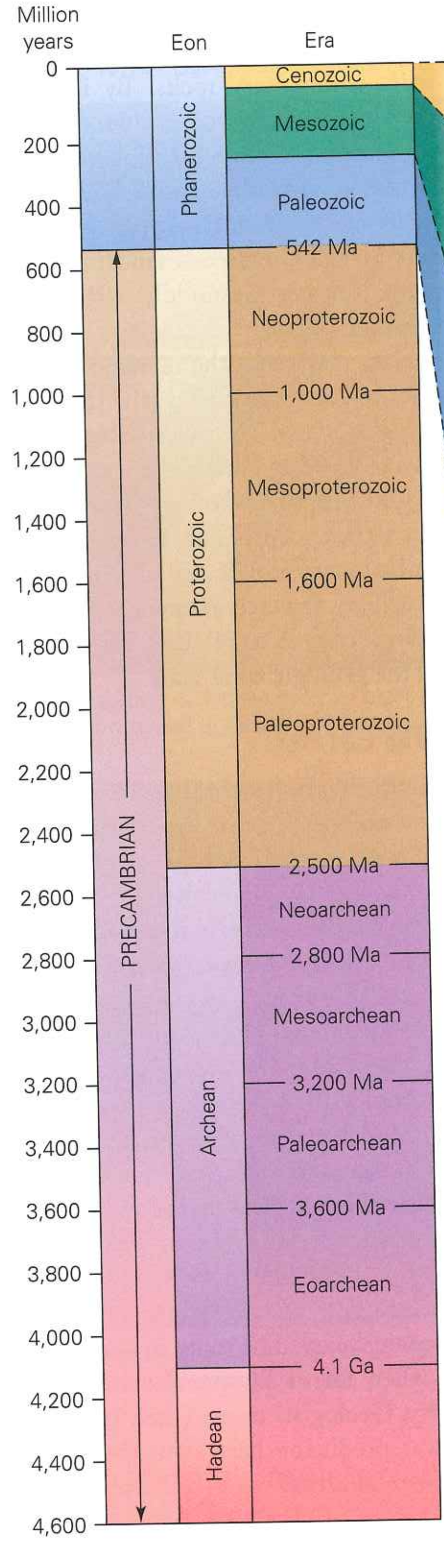
The discovery of new data may cause the numbers defining the boundaries of periods to change, which is why the term *numerical age* is preferred to *absolute age*. In fact, around 1995, new dates on rhyolite ash layers above and below the Cambrian-Precambrian boundary showed that this boundary occurred at 542 million years ago, in contrast to previous, less definitive studies that had placed the boundary at 570 million years ago. **Figure 10.16** shows the currently favored numerical ages of periods and eras in the geologic column as of 2009. This dated column is commonly called the **geologic time scale**.

What Is the Age of the Earth?

During the 18th and 19th centuries, before the discovery of isotopic dating, scientists came up with a great variety of clever solutions to the question, "How old is the Earth?"—all of which have since been proven wrong. Lord William Kelvin, a 19th-century physicist renowned for his discoveries in thermodynamics, made the most influential scientific estimate of the Earth's age of his time. Kelvin calculated how long it would take for the Earth to cool down from a temperature as hot as the Sun's, and concluded that this planet is about 20 million years old.

Kelvin's estimate contrasted with those being promoted by followers of Hutton, Lyell, and Darwin, who argued that if the concepts of uniformitarianism and evolution were correct, the Earth must be much older. They argued that physical processes that shape the Earth and form its rocks, as well as the process of natural selection that yields the diversity of species, all take a very long time. Geologists and physicists continued to debate the age issue for many years. The route to a solution didn't appear until 1896, when Henri Becquerel announced the discovery of radioactivity. Geologists immediately realized that the Earth's interior was producing heat from the decay of radioactive material. This realization uncovered one of the flaws in Kelvin's argument: Kelvin had assumed that no new heat was produced after the Earth first formed. Because radioactivity constantly generates new heat in the Earth, the planet has cooled down much more slowly than Kelvin had calculated and could be much older. The discovery of radioactivity not only invalidated Kelvin's estimate of the Earth's age, it also led to the development of isotopic dating.

Since the 1950s, geologists have scoured the planet to identify its oldest rocks. Rocks younger than 3.85 Ga are fairly common. Rock samples from several localities (Wyoming,



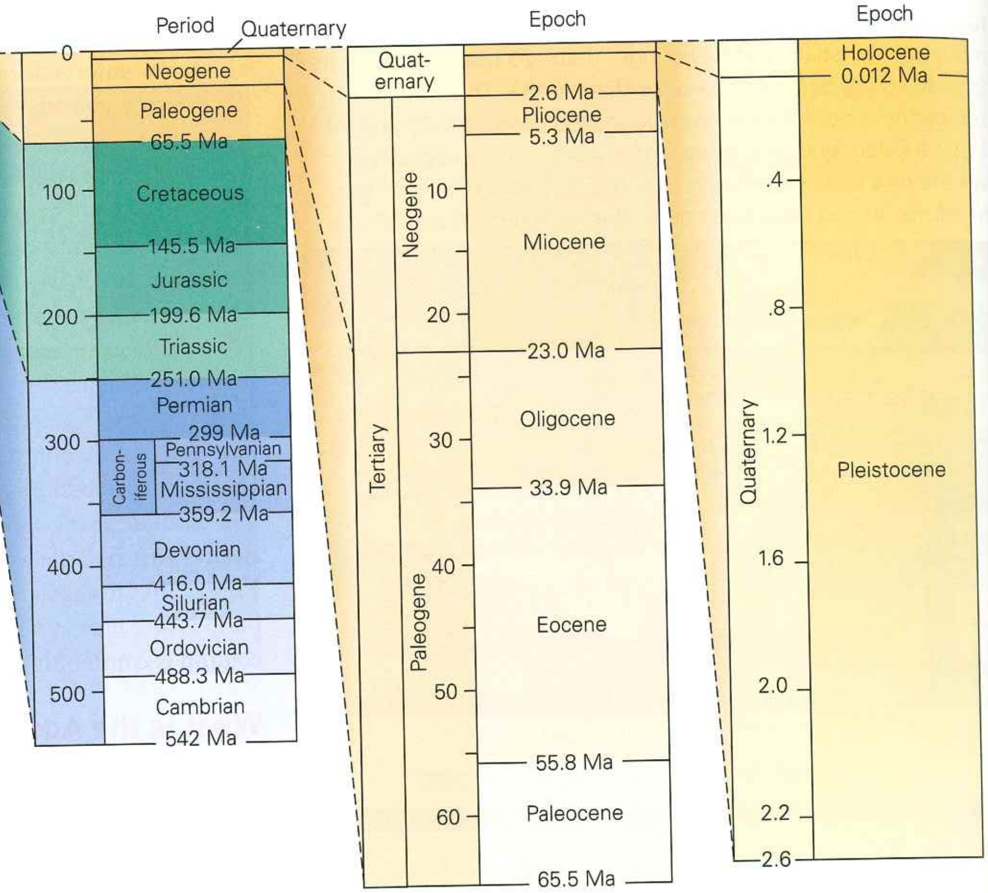


FIGURE 10.16 The geologic time scale assigns numerical ages to the intervals on the geologic column. Note that we have to change to a larger scale to portray the ages of intervals higher in the column, because these are shorter subdivisions. The time interval between 65.5 and 2.6 Ma is the Tertiary Period in older literature and the Neogene and Paleogene periods in more recent literature.

Canada, Greenland, and China) have yielded dates as old as 4.03 Ga. (Recall that "Ga" means "billion years ago.") Individual clastic grains of the mineral zircon have yielded dates of up to 4.4 Ga, indicating that rock as old as 4.4 Ga did once exist. Isotopic dating of Moon rocks yields dates of up to 4.50 Ga, and dates on meteorites have yielded ages as old as 4.57 Ga. Geologists consider 4.57-Ga meteorites to be fragments of planetesimals like those from which the Earth first formed. Thus, these dates are close to the age of the Earth's birth, for models of the Earth's formation assume that all objects in the Solar System developed at roughly the same time from the same nebula.

Did you ever wonder . . .
how old is the Earth's oldest rock?

Why don't we find rocks with ages between 4.03 and 4.57 Ga in the Earth's crust? Geologists have come up with several ideas to explain the lack of extremely old rocks. One idea comes from calculations defining how the temperature of our planet has changed over time. These calculations indicate that during the first half-billion years of its existence, the Earth might have been so hot that rocks in the crust remained above the closure temperature for minerals, and isotopic clocks could not start "ticking." Another idea comes from studies of cratering events on other moons and planets. These studies indicate that the inner planets were bombarded so intensely by meteorites at about 4.0 Ga that almost all crust formed earlier than 4.0 Ga was completely destroyed.

Picturing Geologic Time

The number 4.57 billion is so staggeringly large that we can't begin to comprehend it. If you lined up this many pennies in a row, they would make an 87,400-km-long line that would wrap around the Earth's equator more than twice. Notably, at the scale of our penny chain, human history is only about 100 city blocks long.

Another way to grasp the immensity of geologic time is to equate the entire 4.57 billion years to a single calendar year. On this scale, the oldest rocks preserved on Earth date from early February, and the first bacteria appear in the ocean on February 21. The first shelly invertebrates appear on October 25, and the first amphibians crawl out onto land on November 20. On December 7, the continents coalesce into the supercontinent of Pangaea. Birds and the ancestors of mammals appear about December 15, along with the dinosaurs, and the Age of Dinosaurs ends on December 25. The last week of December represents the last 65 million years of Earth history, including the entire Age of Mammals. The first human-like ancestor appears on December 31 at 3 P.M., and our species, *Homo sapiens*, shows up an hour before midnight. The last ice age ends a minute before midnight, and all of recorded human history takes place in the last 30 seconds. To put it another way, human history occupies the last 0.000001% of Earth history. The Earth is so old that there has been more than enough time for the rocks and life forms of Earth to have formed and evolved.

Take-Home Message

Numerical dates for sedimentary rocks come from isotopic dating of cross-cutting datable rocks. Such work led to the geologic time scale, assigning ages to periods. The oldest rock of Earth's crust is about 4.0 Ga. Dating of meteorites indicates the Earth is 4.57 Ga.

ANOTHER VIEW The pages of Earth history stand on end in Namibia, southwestern Africa. Here, in a false-color image, the Ugab River cuts across layer upon layer of strata that were tilted to near-vertical by a Precambrian mountain-building event. Subsequent erosion exposed the strata, and the desert climate keeps it clear of vegetation. The field of view is 45 km.

CHAPTER 10 REVIEW

Chapter Summary

- Geologic time refers to the time span since the Earth's formation.
- Relative age specifies whether one geologic feature is older than or younger than another; numerical age provides the age of a geologic rock or feature in years.
- Using such principles as uniformitarianism, original horizontality, superposition, and cross-cutting relations, we can construct the geologic history of a region.
- The principle of fossil succession states that the assemblage of fossils in strata changes from base to top of a sequence. Once a species becomes extinct, it never reappears.
- Strata are not necessarily deposited continuously at a location. An interval of nondeposition and/or erosion is called an unconformity. Geologists recognize three kinds: angular unconformity, nonconformity, and disconformity.
- A stratigraphic column shows the succession of strata in a region. A given succession of strata that can be traced over a fairly broad region is called a stratigraphic formation. The process of determining the relationship between strata at one location and strata at another is called correlation. A geologic map shows the distribution of formations and geologic structures.
- A composite chart that represents the entirety of geologic time is called the geologic column. The column's largest subdivisions, each of which represent a specific interval of time, are eons. Eons are subdivided into eras, eras into periods, and periods into epochs.
- The numerical age of rocks can be determined by isotopic (radiometric) dating. This is because radioactive elements decay at a rate characterized by a known half-life.
- The isotopic age of a mineral specifies the time at which the mineral cooled below a closure temperature. We can use isotopic dating to determine when an igneous rock solidified and when a metamorphic rock cooled. To date sedimentary strata, we must examine cross-cutting relations with dated igneous or metamorphic rock.
- Other methods for dating materials include counting growth rings in trees and seasonal layers in glaciers.
- Isotopic dating indicates that the Earth is 4.57 billion years old.

Key Terms

Cambrian explosion (p. 316)
closure temperature (p. 321)
contact (p. 310)
correlation (p. 312)
cross-cutting relations (p. 307)
daughter isotope (p. 320)
eon (p. 315)
epoch (p. 315)
era (p. 315)
fossil assemblage (p. 308)
fossil succession (p. 308)
geochronology (p. 320)
geologic column (p. 315)
geologic history (p. 307)
geologic map (p. 314)
geologic time (p. 305)
geologic time scale (p. 323)
half-life (p. 320)
index fossil (p. 309)
isotope (p. 320)
isotopic dating (p. 320)
marker bed (p. 312)
numerical age (p. 306)
original horizontality (p. 306)
parent isotope (p. 320)
period (p. 315)
Precambrian (p. 315)
radioactive decay (p. 320)
relative age (p. 306)
stratigraphic column (p. 312)
stratigraphic formation (p. 312)
stratigraphic group (p. 312)
superposition (p. 307)
unconformity (p. 310)
uniformitarianism (p. 306)

Review Questions

1. Explain the concept of uniformitarianism.
2. Compare numerical age and relative age.
3. Describe the principles that allow us to determine the relative ages of geologic events.
4. How does the principle of fossil succession allow us to determine the relative ages of strata?
5. How does an unconformity develop? Describe the differences among the three kinds of unconformities.
6. Describe two different methods of correlating rock units. How was correlation used to develop the geologic column? What is a stratigraphic formation?
7. Is there one place on Earth where we can see the complete geologic column?
8. What does the process of radioactive decay entail?
9. How do geologists obtain an isotopic date? What are some of the pitfalls in obtaining a reliable one?
10. Why can't we date sedimentary rocks directly? Why don't all periods on the geologic column last for the same amount of time?
11. What is the age of the oldest rocks on Earth? What is the age of the oldest rocks known? Why is there a difference?

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Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- Interactive exercise on biostratigraphy.
- What a Geologist Sees Exercises on strata and unconformities.
- An animation exercise on geologic history.

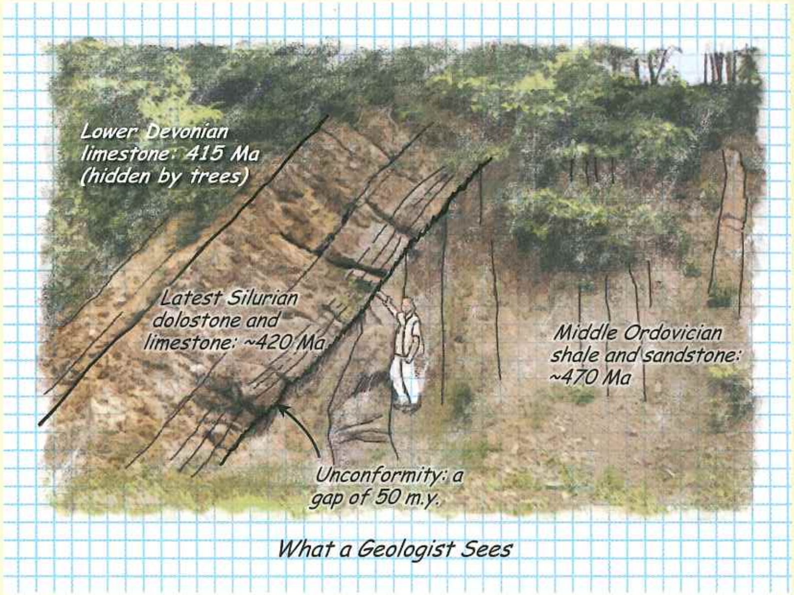
On Further Thought

12. Imagine an outcrop exposing a succession of alternating sandstone and conglomerate beds. A geologist studying the outcrop notes the following:

    - The sandstone beds contain land plants, but the fragments are too small to permit identification.
    - A layer of volcanic ash overlies the sandstone bed. Isotopic dating indicates that this ash is 300 Ma.
    - A paleosol occurs at the base of the ash layer.
    - A basalt dike, dated at 100 Ma, cuts both the ash and the sandstone-conglomerate sequence.
    - Pebbles of granite in the conglomerate yield radiometric dates of 400 Ma.

    On the basis of these observations, how old is the sandstone and conglomerate? (Specify both the numerical age range and the period or periods of the geologic column during which it formed.)

13. The figure below shows a geologist's interpretation of the chapter-opening photo. Describe the geologic history that led to the features visible in this outcrop.



What a Geologist Sees

SEE FOR YOURSELF J . . . Geologic Time

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet J of our **Geotours Workbook**.

Grand Canyon, Arizona
Latitude 36°5′53.99″N,
Longitude 112°10′58.58″W

Looking obliquely downstream from an elevation of 1.5 km, we see strata representing an immense amount of geologic time. The dark metamorphic rocks of the inner gorge are ~1.75 Ga. An unconformity separates them from overlying Paleozoic strata. The youngest unit is the ~270 Ma Kaibab Limestone.

Vermilion Cliffs, Arizona
Latitude 36°49′4.81″N,
Longitude 111°37′56.59″W

This locality shows Marble Canyon, the entry to the Grand Canyon. Outcrops in the distance comprise the Vermilion Cliffs, exposing reddish brown sandstone and shale of the Moenkopi Formation. The walls of Marble Canyon consist of the underlying Kaibab Limestone.