CHAPTER 13

# GEOLOGIC AGE

## MATERIALS NEEDED

- Pencil and eraser
- Metric ruler
- Calculator

## INTRODUCTION

Rocks exposed at the Earth's surface often have long and complex histories. To understand the formation of these rocks, and thus to unravel the history of the Earth, it is necessary for geologists to use rigorous techniques to figure out not only what, but also when things happened. For centuries, geologists have determined the *relative* ages of different events using simple observational techniques: this sandstone was deposited first, then came a limestone, and finally a granite intruded both. Only since World War II have geologists developed the sophisticated methods required to determine numerical ages. Thus, a sandstone was deposited 250 million years ago, a limestone 245 million years ago, and a granite intruded both 40 million years ago. The problems in this chapter illustrate the techniques used to determine both relative and numerical ages.

Geologists working in mountain ranges are regularly confronted with the complexity of the Earth's past. Instead of seeing merely horizontal layers of sedimentary rock, we often see sedimentary layers that are folded or steeply tilted (Fig. 13.1A, B). Other layers may be abruptly offset by fractures called faults (Fig. 13.1B). And sometimes igneous rocks have clearly intruded sedimentary rocks, or sedimentary rocks were deposited on top of older, cooled igneous rocks (Fig. 13.1C, D). These geologic relationships record the forces and events that help shape the Earth.

It was in the late 1700s that James Hutton, the father of modern geology, realized that the events recorded in the rock record must have taken a very long time to unfold. He and his contemporaries used careful observations and scientific principles to recognize many different types of events, including deposition and burial of sediment, igneous activity, rock deformation, and uplift and erosion of preexisting rocks. They also were able to arrange these events in a *relative* sequence from oldest to youngest. However, they were unable to assign exact dates to anything that occurred before the beginning of recorded history. It was like knowing only that you are younger than your mother, and that she is younger than your grandfather, but not knowing anyone's actual age.

Geologists now are able to determine quite precisely the dates, or **numerical geologic ages** (also known as *absolute geologic ages*), of many types of geologic events. Determining a numerical geologic age is complex and expensive, so numerical ages are not always readily available. However, many thousands of numerical ages have been determined so that if the *relative* geologic age is known, an estimate of the numerical age can be made. Both types of ages, relative and numerical, are important pieces of information for interpreting and understanding the geology of an area, unraveling the complexities of past tectonic-plate movements and interactions, and reconstructing the history of climate change and the long pageant of prehistoric life.

## RELATIVE GEOLOGIC TIME

### GENERAL CONCEPT

Although it is important to know the numerical age of a particular geologic event, it is equally important to be able to indicate whether that event occurred before or after another event. This is the basis for a **relative geologic age**—the age of one event relative to another.

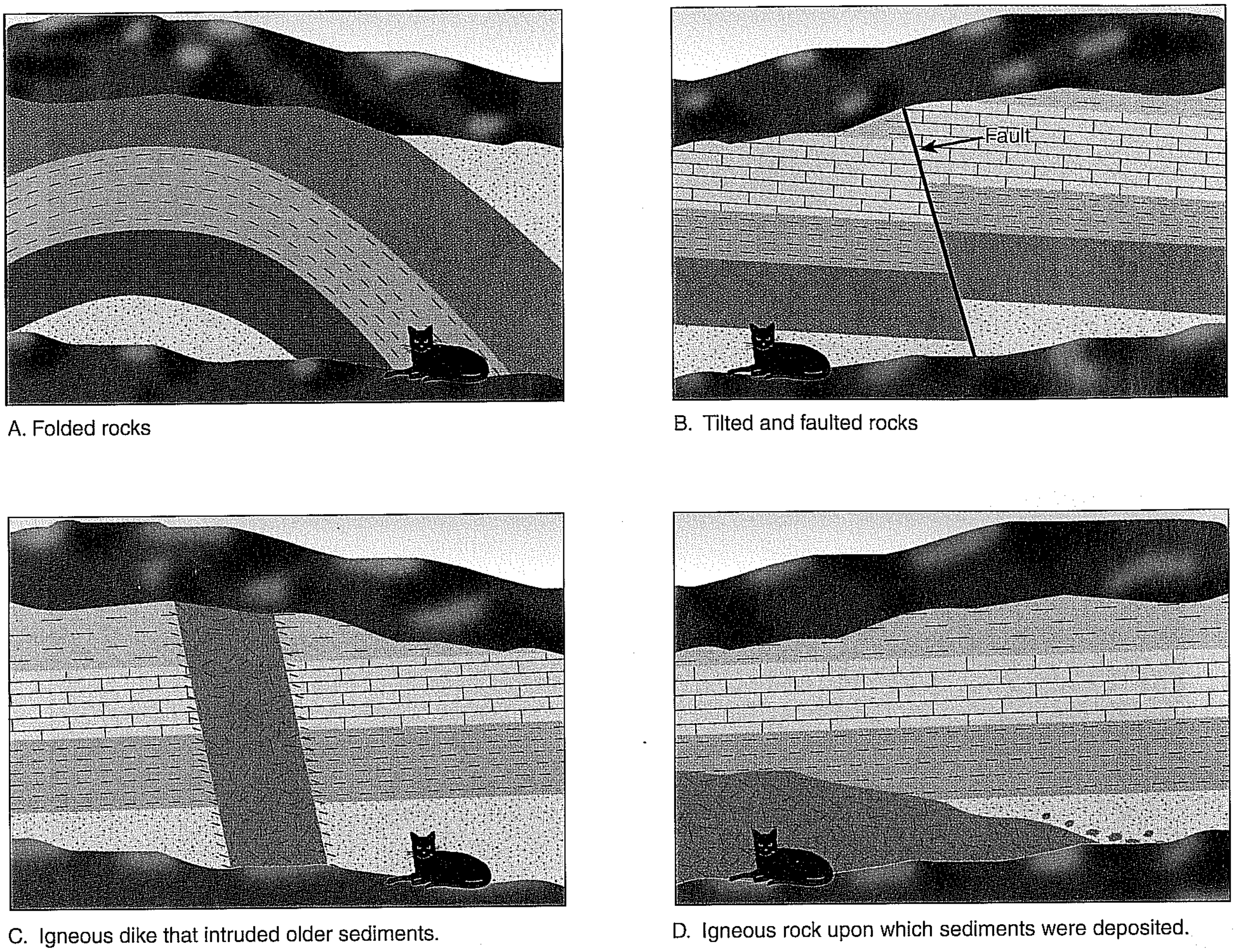


**FIGURE 13.1**
Examples of basic rock structures observed in the field. A. Folded rocks. B. Tilted rocks with a fault offsetting the sedimentary layers. C. Intrusive igneous rock, in this case a dike (a tabular body filling an opened fracture). The crosshatches along the igneous/sedimentary rock contact indicate a contact metamorphic rock called hornfels. D. Intrusive igneous rock, exposed to erosion and later buried by sediment. No contact metamorphism is apparent.

A description of the geology of an area includes a list of the geologic events that took place, in the sequence in which they occurred, from oldest to youngest. Geologic events that are commonly described include deposition of sedimentary units, extrusion or intrusion of igneous rocks, metamorphism, folding, faulting, uplift, and erosion.

To understand how a sequence of events is determined, consider Figure 13.2, a sketch of a roadcut in a mountainous area. The sketch shows three inclined layers of sedimentary rock—sandstone, shale, and limestone—intruded by a granite dike. What geologic events must have occurred to produce what is seen in the roadcut, and in what order did they occur?

Start with the simplest, the dike. Because it cuts (intrudes) all three sedimentary layers, it must be younger than all of them.

Next, what are the relative ages of the sedimentary layers? The one on the bottom must have been deposited first (assuming the layers are not upside down, a possibility that is considered later), and the one on top last.

So far we have the following sequence:

intrusion of granite dike **(youngest)**
deposition of limestone
deposition of shale
deposition of sandstone **(oldest)**

But there is more. Was the original sediment of the sedimentary rocks deposited as inclined layers? Not likely. The layers must have been tilted or folded after deposition.

And the dike—was it intruded before or after the beds were tilted? Can you tell? Not without more information, of a kind that is too detailed to discuss here. So we must be satisfied with two possibilities for now; the dike could be older or younger than the tilting event.

What about the present-day surface, at the top of the roadcut? It is still forming, by erosion. Because the original sediments must have accumulated in a low place, and because they must have been buried under younger sediment in order to become lithified, the erosion must have been accompanied by uplift of the whole area.

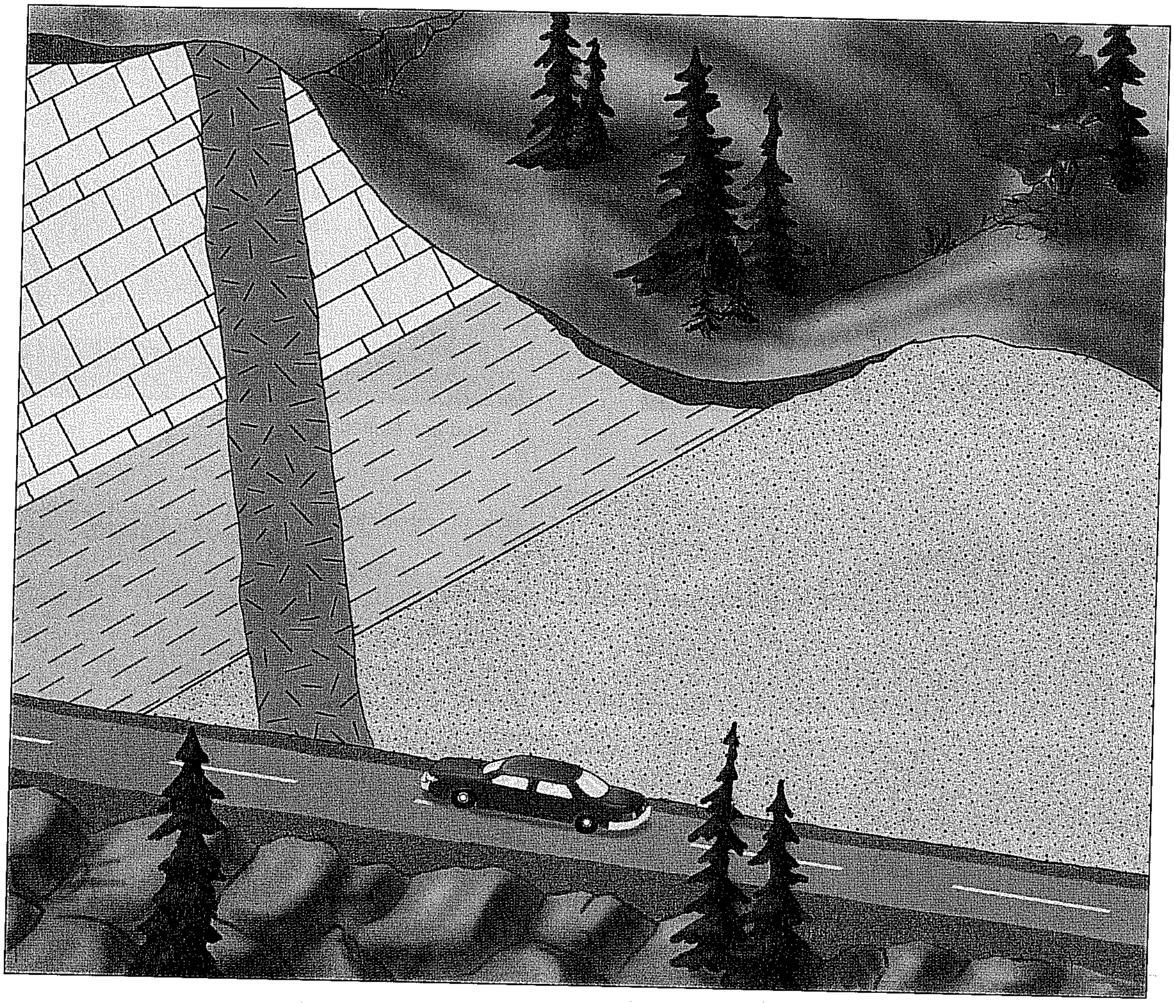

FIGURE 13.2
View of rocks exposed in a vertical roadcut in a mountainous area. Sedimentary rocks are limestone (brick pattern), shale (parallel dashes), and sandstone (dots); granite dike shown with random dashes. What sequence of events led to what we see?

Now we can list the entire sequence in order of relative age:

- uplift and erosion **(youngest)**
- intrusion of granite dike (or tilting)
- tilting of beds (or granite dike)
- deposition of limestone
- deposition of shale
- deposition of sandstone **(oldest)**

As you can see, there is nothing magical or mystical about the way in which this sequence was determined. Logic and a few basic principles are all that's needed.

## Basic Principles

From the preceding example, you can see that several fundamental principles exist to help interpret the relative time relations among rocks. Among the more useful are the following, the first three of which were formulated by Nicholas Steno in the late 17th century.

*Steno's Principle of Original Horizontality* (Fig. 13.3): Sediments are deposited in horizontal or near-horizontal layers. Therefore, non-horizontal layers have generally been folded or tilted from their original positions.

*Steno's Principle of Superposition* (Fig. 13.3): In any succession of sedimentary rock layers lying in their original horizontal position, the rocks at the bottom of the sequence are older than those lying above.

*Steno's Principle of Original Lateral Continuity* (Fig. 13.3): Sediments are deposited in layers that continue laterally in all directions until they thin out as a result of nondeposition, or until they reach the edge of the basin in which they are deposited. A layer that ends abruptly at some point other than the edge of the original basin was offset by a fault or intruded by an igneous rock, or has been partially removed by erosion.

*Principle of Cross-Cutting Relations* (Fig. 13.4): Any geologic feature (intrusive igneous rock, fault, fracture, erosion surface, rock layer) is younger than any feature that it cuts.

*Principle of Inclusions* (Fig. 13.5): An inclusion in a rock is older than the rock containing it. Examples of inclusions are pebbles, cobbles, or boulders in a conglomerate, or *xenoliths* (pieces of other rocks) in igneous rocks.

## Relative Ages Based on Fossils

These basic principles establish age relations among rocks that occur together in a local area. William Smith, working in the 1790s, examined the nicely lay-

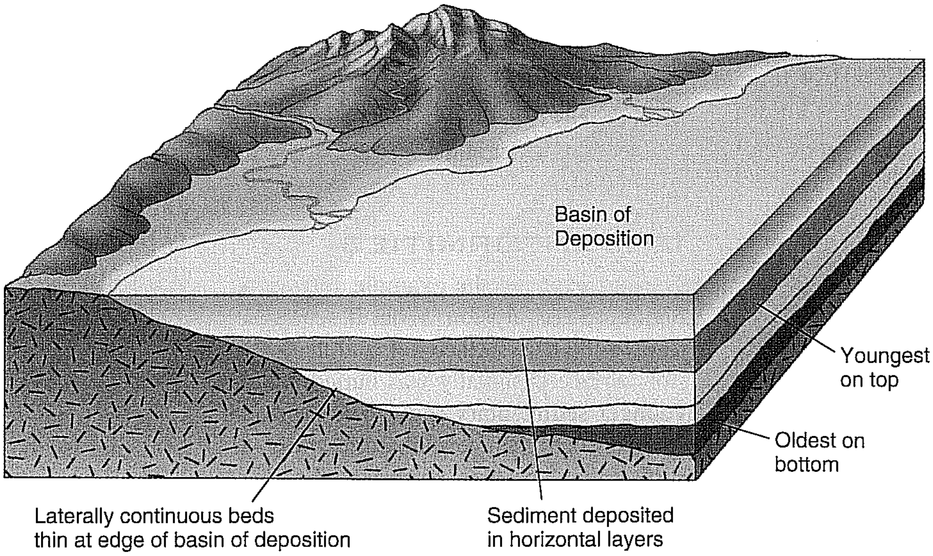


FIGURE 13.3
This three-dimensional view illustrates the principles of *Original Horizontality* (sediment is deposited in horizontal layers), *Superposition* (younger beds are deposited on older beds), and *Original Continuity* (sedimentary layers continue to the edge of the basin of deposition).

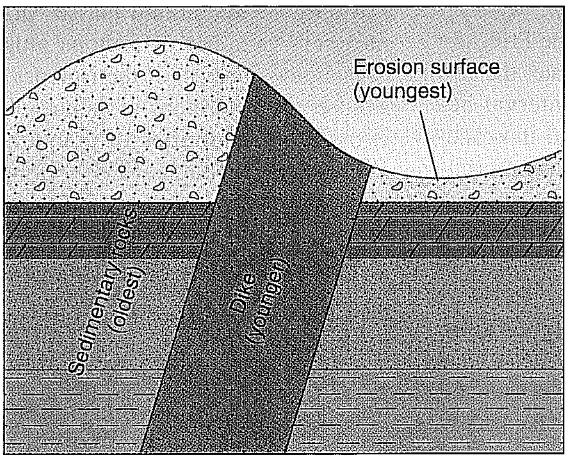


FIGURE 13.4
*Principle of Cross-Cutting Relations.* This cross section shows a dike cutting preexisting layers of sedimentary rock; the dike is younger than the rocks it cuts. The erosion surface cuts both the sedimentary rocks and the dike, so it is the youngest.

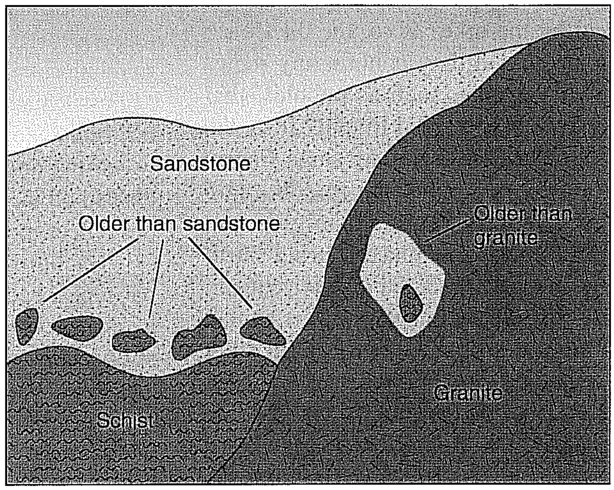


FIGURE 13.5
*Principle of Inclusions.* This cross section shows boulders of schist at the base of a sandstone; the boulders must be older than the sandstone containing them. Similarly, the xenolith of sandstone in the granite must be older than the granite.

ered sedimentary rocks and their fossils across England. (**Fossils** are the preserved remains of ancient plants and animals). Employing the Principle of Superposition, he collected fossils from successive layers and discovered that he could use the fossils to determine the age-equivalence of widely separated sedimentary units, much as archaeologists recognize different historical periods in their excavations based on distinctive coins or pottery. Smith's work helped establish two important principles:

*Principle of Fossil Succession:* Fossil organisms succeed one another in time in a definite and recognizable order. Each distinct organism existed for a specific interval of time and not at older or younger times. The fossils in a sedimentary unit therefore define a specific, unique interval of geological time.

*Principle of Fossil Assemblages:* Characteristic groups of fossil organisms also define unique geologic ages.

Fossils are an exceptionally useful means of determining relative time because they establish age relationships among widely separated rocks and because the sequence of fossil organisms is known over a very long interval of geologic time. The dinosaur *Tyrannosaurus rex,* for example, lived for a relatively short period of time. Any rocks found on any continent that contain its bones must date to this same short interval of time. Because the position of *T. rex* is known relative to the rest of the long fossil record, these rocks are securely located within all of geologic time.

## Testing Hypotheses

In the example in which the sequence of events illustrated in Figure 13.2 was hypothesized, some assumptions were made that should not have been made without further observations.

The first assumption, a very reasonable one, was that the dike cut the layers of sedimentary rock. There is a *very* remote possibility that the dike was there first, standing as an inclined rock wall, while sediments were deposited on both sides of it. How would you tell? One way is to carefully examine the sedimentary rocks adjacent to the contact with the dike. For example, were they metamorphosed by the dike? If so, the dike must be younger. Do they contain any inclusions of the dike, such as pebbles, that might have been eroded from it? If so, the dike is older. Are there any small fingers of granite extending from the dike into the sedimentary rock that might have squeezed into weak places during intrusion of magma? If so, the dike is younger. Notice that the sedimentary layers cannot be projected straight across the dike but appear to be offset. Why? Because when the magma was intruded, it forced the rocks apart at 90° to the dike margins.

A second assumption was that the layers, though not horizontal, have not been completely overturned. If they have, then the limestone is the oldest, and the sandstone the youngest. How can you tell? One way is to look for sedimentary structures that allow you to tell top from bottom, up from down. Some useful sedimentary structures, shown in Chapter 4, are:

**Cross-stratification** (see Fig. 4.4)—cross beds are commonly cut off on the top of the bed and become parallel to adjacent layers on the bottom.

**Oscillation ripple marks** (see Fig. 4.5B)—symmetrical, wave-like features whose crests point to the top of the bed.

**Graded beds** (see Fig. 4.6)—grain size commonly becomes progressively finer upward.

**Mud cracks** (see Fig. 4.7)—in cross-section, wider at the top than at the bottom.

## Unconformities

The last event in the example shown in Figure 13.2 is erosion. What if sea level rose, or the land surface fell, and that erosion surface eventually was buried under younger sedimentary rock? The erosion surface would then be an **unconformity,** a surface that represents a substantial gap in the geologic record. It may be an ancient erosion surface, or it may be a surface on which neither erosion nor deposition occurred for a long period of time. If it is an erosion surface, it is recognizable because it cross-cuts older rocks, and its relative age can be determined by the Principle of Cross-Cutting Relations. If neither erosion nor deposition occurred, the unconformity may be difficult to recognize without studying fossils and applying the Principle of Fossil Succession. At any rate, there is no rock record of the time interval between the underlying rocks and those deposited on the unconformity. Unconformities reflect significant geologic events.

Unconformities are of three principal types, each of which reflects distinct geologic events (Fig. 13.6). Figure 13.6A shows an **angular unconformity,** an erosion surface separating rocks whose layers are not parallel. Layers above and below meet at an angle. A **disconformity** is either an erosion surface or a surface of nondeposition separating rocks whose layers are parallel. An erosion surface is uneven and cuts layers of underlying rocks (Fig. 13.6B); a surface of nondeposition parallels underlying rock layers (Fig. 13.6C). A **nonconformity** (Fig. 13.6D) is an erosion surface separating sedimentary rocks from older plutonic or massive metamorphic rocks (that is, crystalline rocks that are not layered).

# Numerical Geologic Time

Numerical ages or dates can be determined in several ways. For example, you can tell how old a tree is by counting the number of growth rings. Or you can determine how long some glacial meltwater lakes existed by counting the number of varves—annually deposited sets of layers—present in the lake sediment. For obvious reasons, these and similar methods have limited applicability. Radioactivity, however, provides a much more widely applicable method for determining numerical dates.

## Radioactivity

Some isotopes of elements are **radioactive;** that is, their nuclei spontaneously break down or decay. In these reactions, a radioactive isotope, or **parent,** decays to form a different isotope, the **daughter.** The decay process is described in the box titled "Radioactive Decay."

**Isotopes** are varieties of an element containing different numbers of neutrons in their nuclei. For example, the element uranium has two common radioactive isotopes, $^{235}$U and $^{238}$U. The superscripts 235 and 238 are the atomic masses or **mass numbers** (number of protons plus neutrons in the nucleus) of the isotopes. Each isotope has 92 protons in its nucleus—92 is the **atomic number** of uranium—but $^{235}$U has 143 neutrons ($235 - 92 = 143$), whereas $^{238}$U has 146 neutrons.

## Ages from Isotopes

Laboratory measurements show that each radioactive isotope decays at a constant rate that is not affected by geologic age or surrounding temperature, pressure, or chemical conditions. The constant decay rate of each isotope forms the heart of calculating the numerical age of geologic samples. The decay rate is often described in terms of a **half-life,** which is the time required for half the atoms of any starting mass of a radioactive isotope to decay away. After one half-life, half of the parent atoms are gone, having produced an equal number of daughter atoms. After two half-lives, only half of one-half, or one quarter, of the original parent remains; three-quarters of the parent has converted to daughter, so there are three times more atoms of daughter than parent.

The age of a mineral is determined from the relative amounts of parent and daughter isotopes it contains. The relative

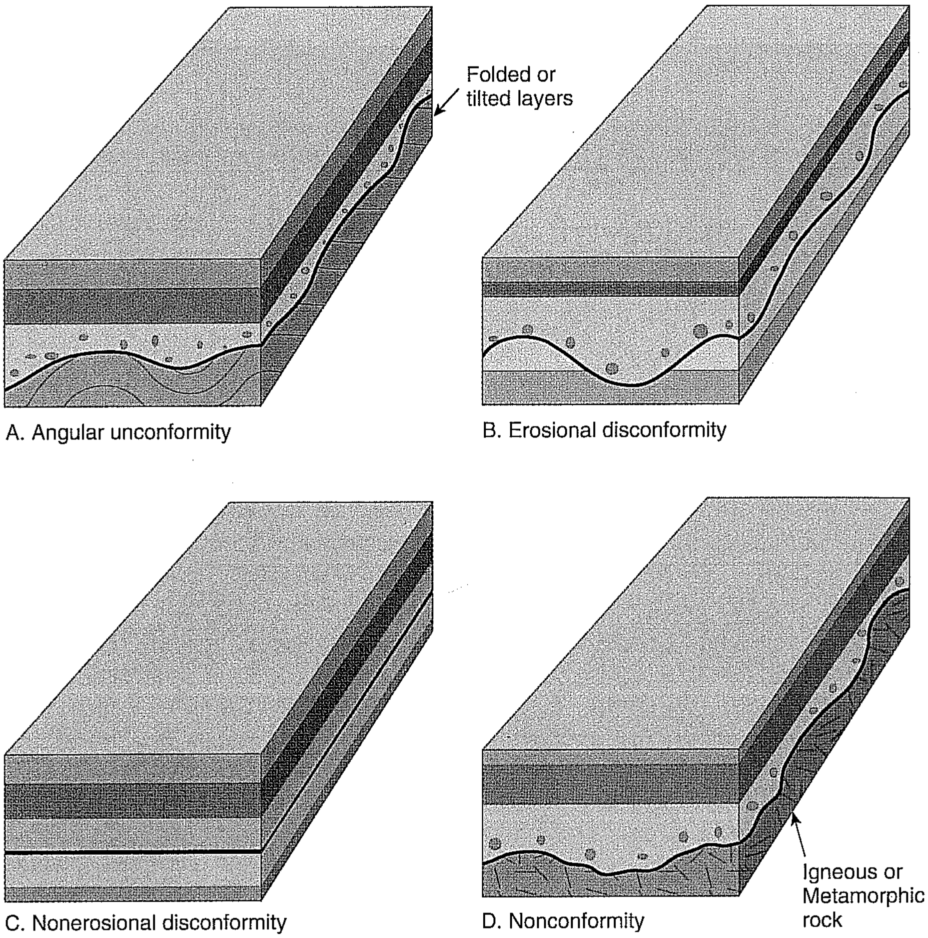


**FIGURE 13.6**
Three-dimensional diagrams of: A. angular unconformity; B. erosional disconformity; C. nonerosional disconformity; D. nonconformity. The unconformity is an ancient erosion surface in A, B, and D, but in C, it is a surface on which no erosion or deposition occurred for a long period of time.

amounts of parent and daughter atoms are measured with an instrument called a mass spectrometer. If one knows the relative number of atoms of daughter and parent isotopes that are present, the ratio of these two combined with the **decay constant** can be used to determine the age. The decay constant, which is directly related to the half-life, describes the proportion of a starting mass of a given isotope that will decay away in a year. The age can be determined graphically or mathematically, as illustrated by the problems at the end of the chapter.

For isotopes with small decay constants (long half-lives), and for the problems in this chapter, the following equation can be used:

$$t \approx (N_D/N_P)/\lambda$$

in which $t$ is time in years, $N_D$ and $N_P$ represent the number of atoms of daughter and parent, respectively, and $\lambda$ is the decay constant, with units of 1/year.

## Geologic Time Scale

The **geologic time scale** (Fig. 13.7) subdivides Earth's history into unequal intervals of time based on distinctive fossil assemblages and globally important geologic events. The scale is based on relative geologic time, but numerical ages are now known for all parts of the timescale. The largest subdivisions of geologic time are **eons;** eons are divided into **eras,** eras into **periods,** and periods into **epochs.** Subdivisions of the Phanerozoic eon are generally agreed upon worldwide, but this is not true with the time preceding the Phanerozoic. The subdivisions shown in Figure 13.7 for that time are more or less accepted in the United States. Because there has been so much disagreement about how to subdivide this time period, however, it is commonly just called the **Precambrian.**

For a better image of this figure go to http://www.nd.edu/~cneal/PhysicalGeo/Lab6/Fig13.7LM.jpg

| Eon | Era | Period | | Epoch | Age (millions of years ago) | Event (Problem 4) |
|---|---|---|---|---|---|---|
| Phanerozoic | Cenozoic (Cz) | Quaternary (Q) | | Recent or Holocene | 0.01 | |
| | | | | Pleistocene | 1.8 | |
| | | Tertiary (T) | Neogene (N) | Pliocene | 5 | |
| | | | | Miocene | 23 | |
| | | | Paleogene (Pε) | Oligocene | 38 | |
| | | | | Eocene | 54 | |
| | | | | Paleocene | 65 | |
| | Mesozoic (Mz) | Cretaceous (K) | | | 146 | |
| | | Jurassic (J) | | | 208 | |
| | | Triassic (TR) | | | 245 | |
| | Paleozoic (Pz) | Permian (P) | | | 286 | |
| | | Carboniferous (C) | Pennsylvanian (IP) | | 325 | |
| | | | Mississippian (M) | | 360 | |
| | | Devonian (D) | | | 410 | |
| | | Silurian (S) | | | 440 | |
| | | Ordovician (O) | | | 505 | |
| | | Cambrian (Є) | | | 544 | |
| Precambrian | Proterozoic | | | | 2500 | |
| | Archean | | | | 3800 | |
| | Hadean | | | | 4600 | |

**FIGURE 13.7**
The geologic time scale, with symbol abbreviations in parentheses.
Adapted from Web page of the Museum of Paleontology of the University of California at Berkeley.

## RADIOACTIVE DECAY

There are three common ways by which a radioactive parent isotope of one element decays to a daughter isotope of another element: alpha decay, beta decay, and electron capture.

(1) In *alpha decay,* an *alpha particle,* which consists of two protons and two neutrons, is released spontaneously from the nucleus. The result is a daughter with two fewer protons and two fewer neutrons in its nucleus. For example, the first step in the decay of the $^{238}U$ isotope is

$$^{238}_{92}U \rightarrow {}^{234}_{90}Th + \text{alpha}$$
$$({}_{92}U = \text{uranium};\ {}_{90}Th = \text{thorium}).$$

Note that the loss of two protons and two neutrons reduces the atomic number of the daughter by two, and the mass number by four; when the atomic number (shown as a subscript) changes, a new element is formed.

(2) *Beta decay* requires the release of an electron or *beta particle* from the nucleus. This is accomplished by the breakdown of a neutron into a proton and an electron; the electron escapes the nucleus, but the proton remains. The result is a daughter with one more proton and one less neutron in its nucleus. For example, the decay of $^{87}Rb$ is

$$^{87}_{37}Rb \rightarrow {}^{87}_{38}Sr + \text{beta}$$
$$({}_{37}Rb = \text{rubidium};\ {}_{38}Sr = \text{strontium}).$$

Note that gaining one proton increases the atomic number of the daughter by one, but the simultaneous loss of one neutron causes the mass number to remain the same.

(3) In *electron capture,* an electron is captured by a proton in the nucleus. In the process, the proton is converted to a neutron. The result is a daughter with one less proton in the nucleus. For example, the decay of $^{40}K$ is

$$\text{electron} + {}^{40}_{19}K \rightarrow {}^{40}_{18}Ar$$
$$({}_{19}K = \text{potassium};\ {}_{18}Ar = \text{argon}).$$

Note that the loss of a proton in the nucleus reduces the atomic number by one in the daughter, but since the proton is converted to a neutron, the mass number does not change.

*Questions:* What kinds of decay take place in the following useful reactions?

1. $^{14}_{6}C \rightarrow {}^{14}_{7}N$
2. $^{147}_{62}Sm \rightarrow {}^{143}_{60}Nd$