Part V
Geologic Time and Sequences

Cross-cutting relations established by dikes intruding a granite, Coahuila, Mexico

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 (Fig. 13.1C), or sedimentary rocks were deposited on top of older, cooled igneous rocks (Fig. 13.1D). These geologic relationships record the forces and events that help shape the Earth.

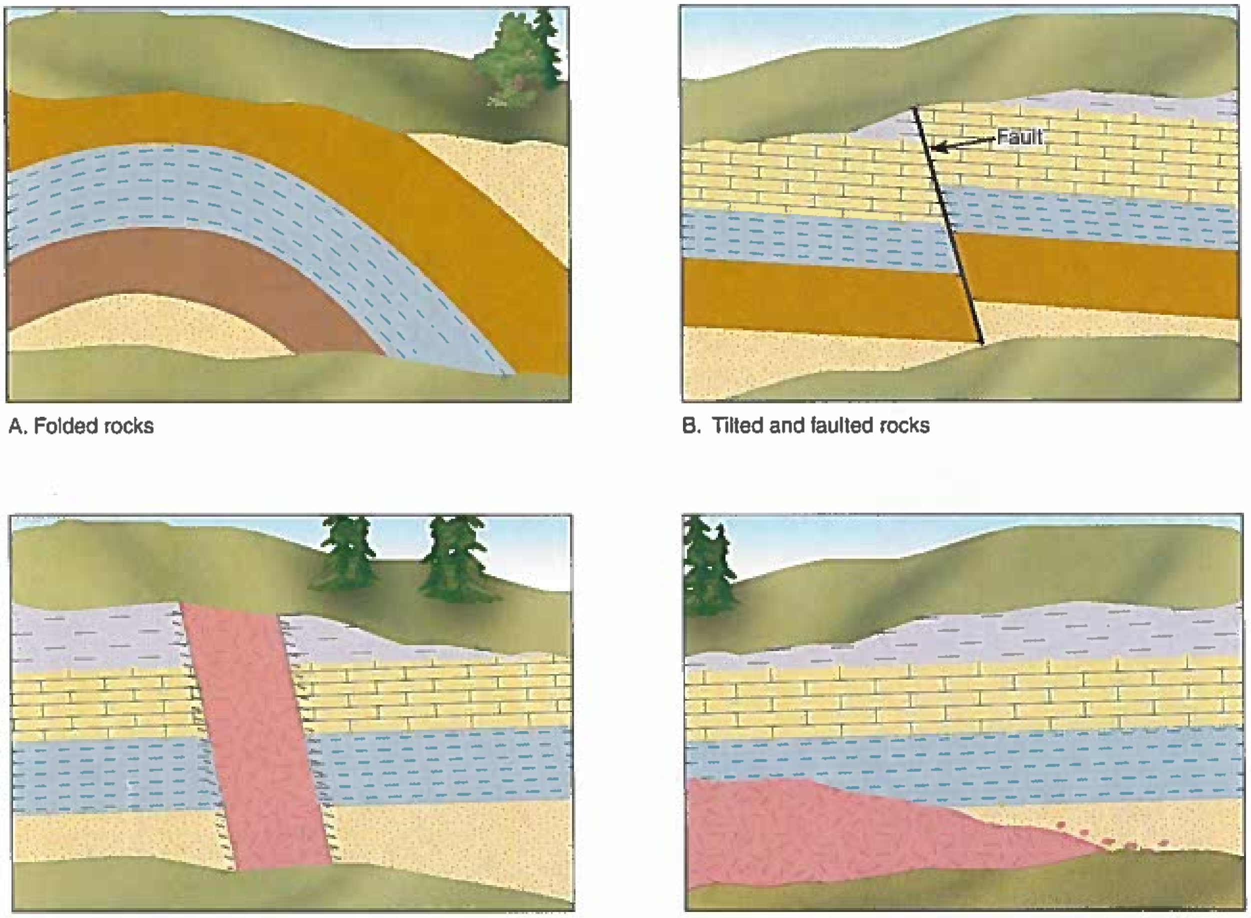
It was in the late 1700s that James Hutton, the father of modern geology, realized that the events recorded in the rock record must have taken a very long time to unfold. He and his contemporaries used careful field observations and scientific principles to recognize many different types of events, including 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



A. Folded rocks

B. Tilted and faulted rocks

C. Igneous dike that intruded older sediments

D. Igneous rock upon which sediments were deposited

FIGURE 13.1
Perspective sketches of some geologic structures that might be observed in roadcuts or cliff faces. 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.

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.

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 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.

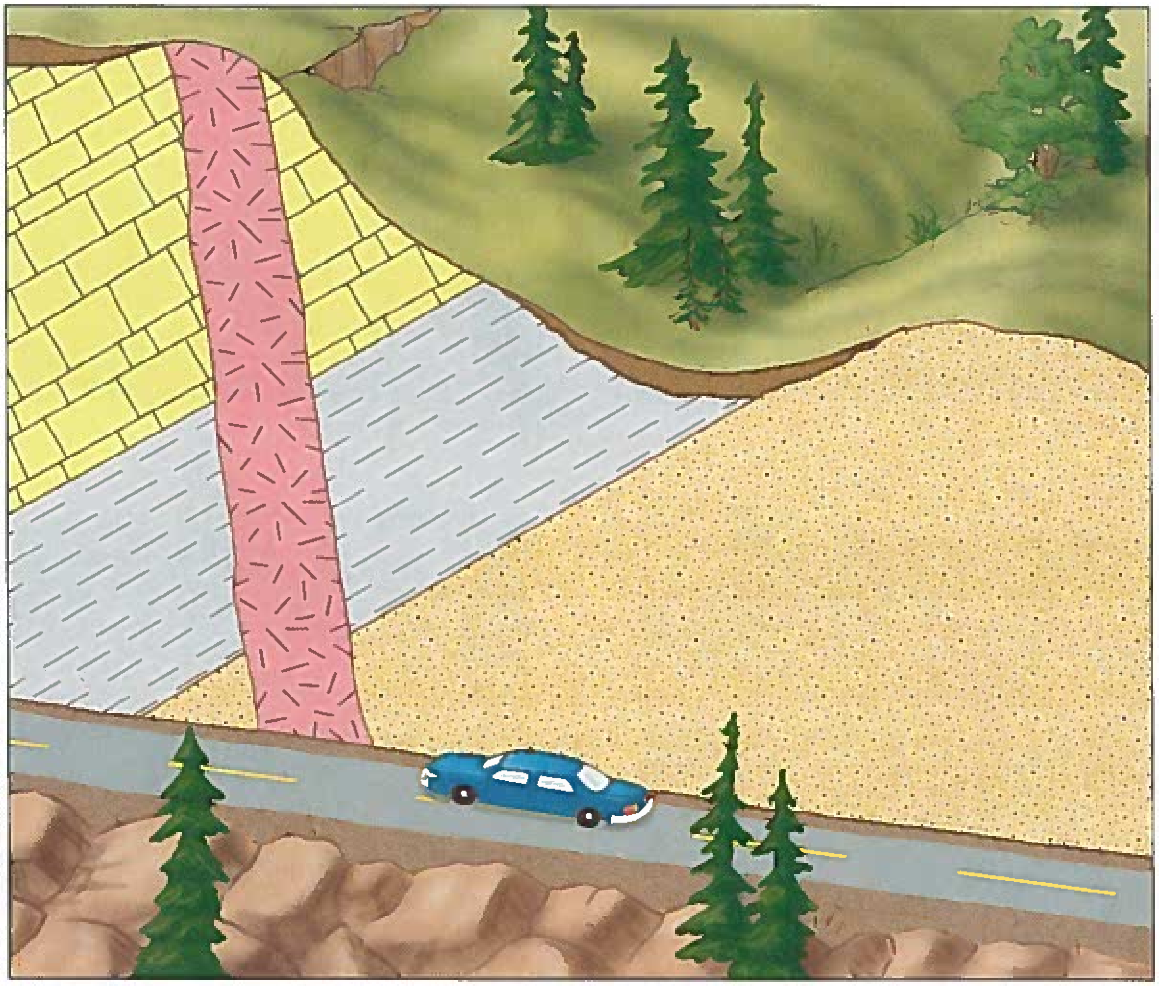


FIGURE 13.2
View of rocks exposed in a vertical roadcut in a mountainous area. Sedimentary rocks are limestone (brick pattern), shale (parallel dashes), and sandstone (dots); granite dike shown with random dashes. What sequence of events led to what we see?

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. This means that if you find a layer that abruptly ends, something has cut this layer after it was deposited. Faults, dikes, and erosion can all truncate otherwise laterally continuous layers.

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,

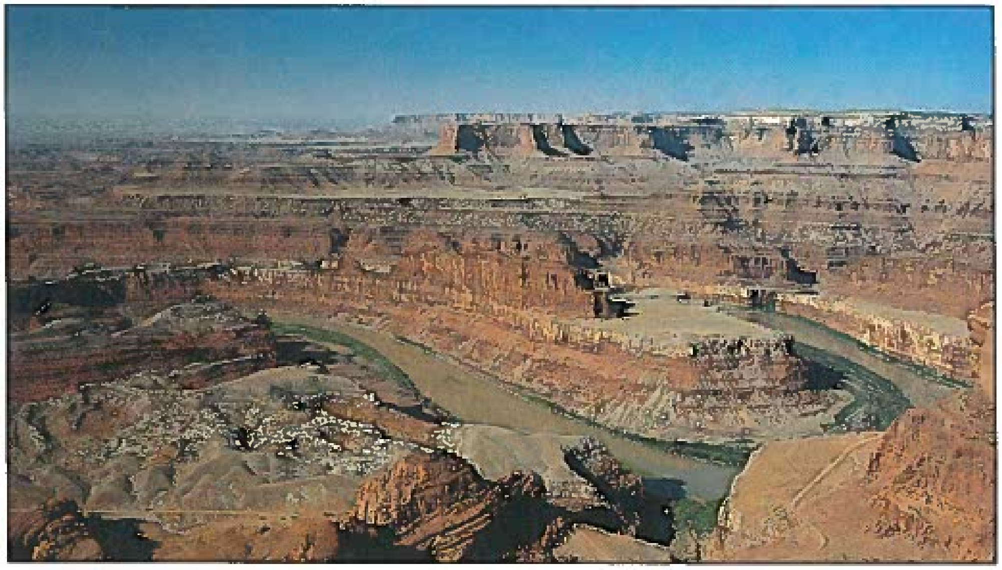


FIGURE 13.3
Sedimentary rocks viewed from Dead Horse Point State Park, Utah, illustrate the principles of Original Horizontality (sediment is deposited in horizontal layers), Superposition (younger beds are deposited on older beds), and Original Lateral Continuity (sedimentary layers do not abruptly end unless they hit the edge of a basin or are cut by younger features).

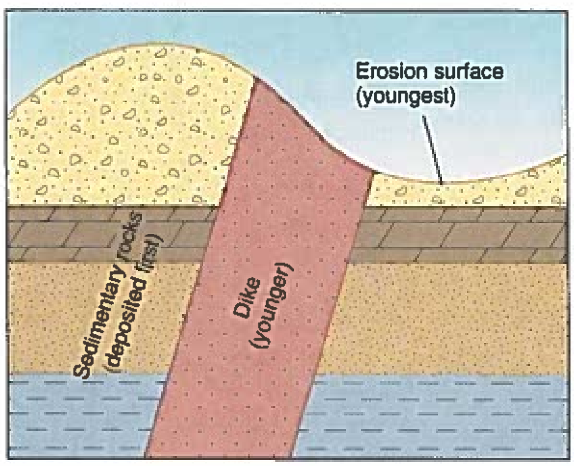


FIGURE 13.4
Principle of Cross-Cutting Relations. This cross section shows a dike cutting preexisting layers of sedimentary rock; the dike is younger than the rocks it cuts. The erosion surface cuts both the sedimentary rocks and the dike, so it is the youngest.

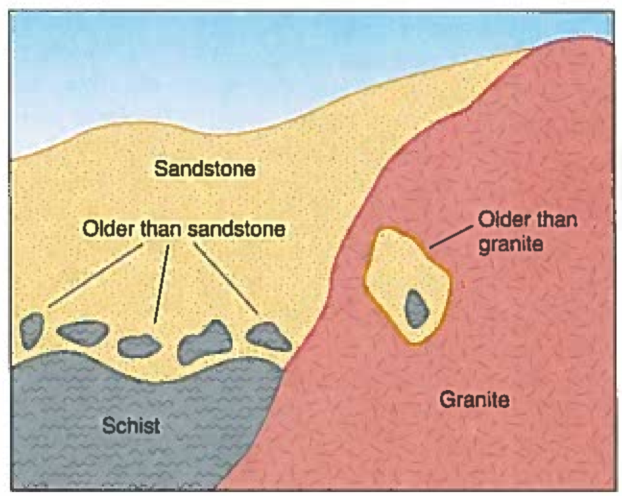


FIGURE 13.5
Principle of Inclusions. This cross section shows boulders of schist at the base of a sandstone; the boulders must be older than the sandstone containing them. Similarly, the xenolith of sandstone in the granite must be older than the granite.

examined the nicely layered sedimentary rocks and their fossils across England. (**Fossils** are the preserved remains, traces, or imprints 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 can 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. 4.5)—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. 4.4B)—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 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. This implies that the underlying rocks were folded or tilted *and* eroded before the overlying layers were deposited. 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 non-deposition 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.**

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 enables us to calculate 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 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

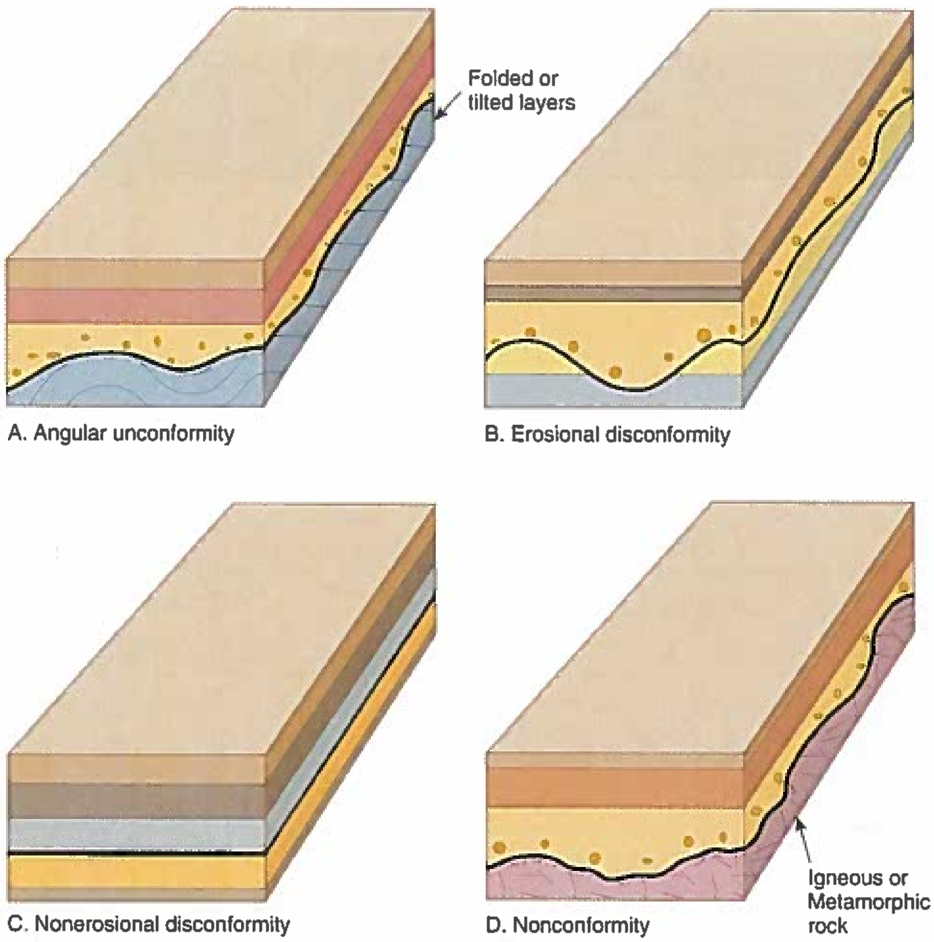


FIGURE 13.6
Three-dimensional diagrams of: A. angular unconformity; B. erosional disconformity; C. nonerosional disconformity; D. nonconformity. The unconformity is an ancient erosion surface in A, B, and D, but in C it is a surface on which no erosion or deposition occurred for a long period of time.

away in a year. The age can be determined graphically or mathematically, as illustrated by the problems at the end of the chapter.

The age is calculated mathematically using the following equation:

$$t = ln(N_D/N_P + 1)/\lambda \quad \text{Eq. 13.1}$$

where t is time in years, N_D and N_P represent the number of atoms of daughter and parent, respectively, and λ is the decay constant in units of 1/year. The natural logarithm function, *ln*, is available on most scientific calculators.

As an example, if N_D = 4000 atoms, N_P = 5000 atoms, and the decay constant for the parent isotope is $\lambda = 1.40 \times 10^{-8}$/year, then:

$$t = ln(4000atoms/5000atoms + 1)/(1.40 \times 10^{-8}/year)$$

$$t = ln(0.8000 + 1)/(1.40 \times 10^{-8}/year)$$

$$t = ln(1.8000)/(1.40 \times 10^{-8}/year)$$

$$t = 0.5878/(1.40 \times 10^{-8}/year)$$

$$t = 4.20 \times 10^{7} \text{ years or } 42{,}000{,}000 \text{ years}$$

Note that in practice two complications arise. First, daughter isotopes are commonly present in minerals when they first form. Second, surface weathering or metamorphism can cause parent or daughter elements to be gained or lost from minerals within a rock. Both types of complications are easily handled by modern methods, but we will not discuss them here.

Geologic Time Scale

The **geologic time scale** (Fig. 13.7) subdivides Earth's history into unequal intervals based on distinctive fossil assemblages and globally important geologic features, such as widespread unconformities. The scale was developed first as a *relative time scale,* using the principles discussed previously, but numerical ages are now known for all parts of the time scale. The largest subdivisions of geologic time are **eons;** eons are divided into **eras,** eras into **periods,** and periods into **epochs.** The Phanerozoic Eon has many subdivisions because well-preserved shelly fossils are present throughout and are found worldwide. That is not true for the time preceding the Phanerozoic, when organisms were simple life forms without easily preserved shells. Instead, subdivisions of that time, called the **Precambrian** (Fig. 13.7), are based on major geologic features or events and on numerical ages.

Geologic Time Scale

Eon	Era	Period		Epoch	Age (millions of years ago)	Event (Problem 4)
Phanerozoic	Cenozoic (Cz)	Quaternary (Q)		Recent or Holocene	0.01	
Phanerozoic	Cenozoic (Cz)	Quaternary (Q)		Pleistocene	1.8	
Phanerozoic	Cenozoic (Cz)	Tertiary (T)	Neogene (N)	Pliocene	5.3	
Phanerozoic	Cenozoic (Cz)	Tertiary (T)	Neogene (N)	Miocene	23	
Phanerozoic	Cenozoic (Cz)	Tertiary (T)	Paleogene (Pε)	Oligocene	34	
Phanerozoic	Cenozoic (Cz)	Tertiary (T)	Paleogene (Pε)	Eocene	56	
Phanerozoic	Cenozoic (Cz)	Tertiary (T)	Paleogene (Pε)	Paleocene	65	
Phanerozoic	Mesozoic (Mz)	Cretaceous (K)			146	
Phanerozoic	Mesozoic (Mz)	Jurassic (J)			200	
Phanerozoic	Mesozoic (Mz)	Triassic (TR)			251	
Phanerozoic	Paleozoic (Pz)	Permian (P)			299	
Phanerozoic	Paleozoic (Pz)	Carboniferous (C)	Pennsylvanian (IP)		318	
Phanerozoic	Paleozoic (Pz)	Carboniferous (C)	Mississippian (M)		359	
Phanerozoic	Paleozoic (Pz)	Devonian (D)			416	
Phanerozoic	Paleozoic (Pz)	Silurian (S)			444	
Phanerozoic	Paleozoic (Pz)	Ordovician (O)			488	
Phanerozoic	Paleozoic (Pz)	Cambrian (Є)			542	
Precambrian: Proterozoic					2500	
Precambrian: Archean					4000	
Precambrian: Hadean					4500	

FIGURE 13.7
The geologic time scale, with symbol abbreviations in parentheses.
Based on U.S.G.S. Fact Sheet 2007–3015, March 2007.

Hands-On Applications

Rocks are the pages in the Earth's history book. Unfortunately, there is no single place on Earth where the whole book is intact. Pages, or even whole chapters, have been locally removed by erosion or bent or torn apart by deformation. The geologist's job is to read the book the way it is, and that requires sorting out the time relations using sound scientific methods. In this lab, you first will learn how basic principles are used to establish the order in which rocks formed or geologic events occurred. Additional problems illustrate how numerical geologic ages are determined.

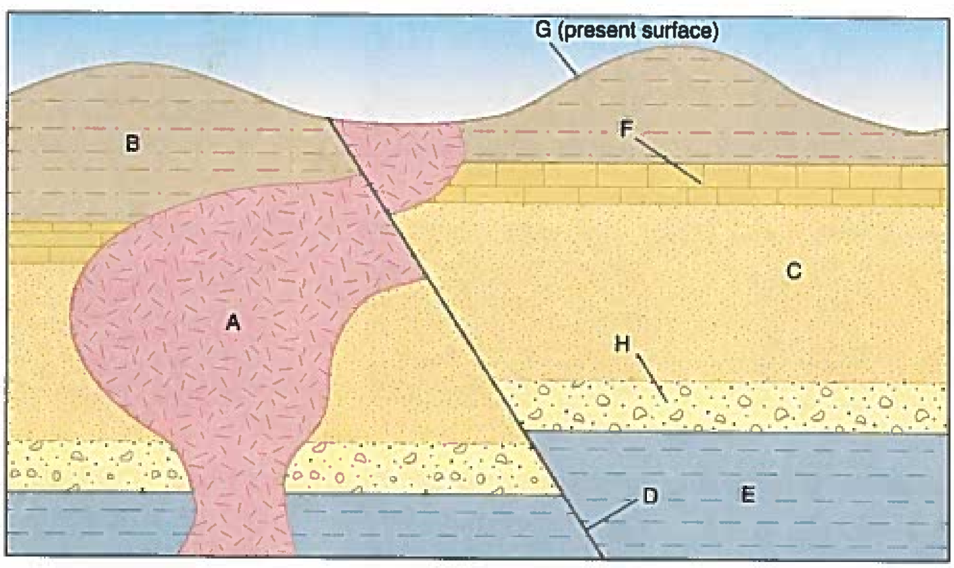
Objectives

If you are assigned all the problems, you should be able to:

1. Determine relative ages and the sequence of geologic events as illustrated in a geologic cross section.
2. Use daughter-parent ratios, half-life, and the decay constant to determine the numerical age of a rock or mineral graphically and mathematically.

Problems

1. Figures 13.8 and 13.9 are geologic cross sections. Determine the sequence of events that led to the present situation, and list them in order, from oldest to youngest, in the blanks provided. Use the letters on the illustrations to specify rock units or events. Identify the rock types represented by each letter from the symbols given in Figure 13.10; identify other events by name (for example, "folding" or "uplift and erosion"). The number of blanks equals the number of events required.



Youngest ________________

____

____

____

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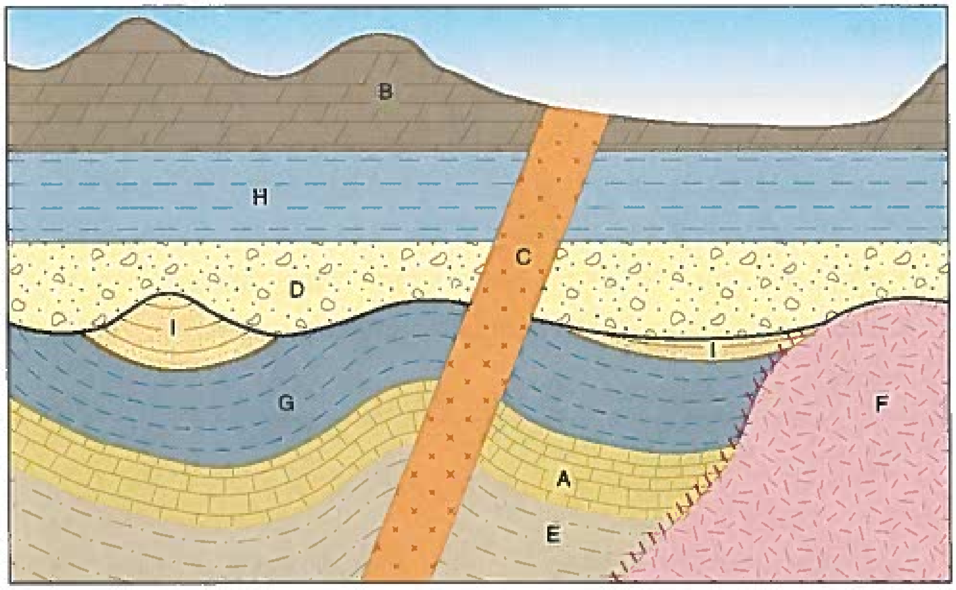
____

____

Oldest ________________

FIGURE 13.8
For Problem 1, determine the relative ages of the lettered geologic features illustrated in this cross section, and list them chronologically in the spaces provided. D (dark line) is a fault, and G is the present surface.



Youngest ____________________

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Oldest ____________________

FIGURE 13.9
For Problem 1, determine the relative ages of the geologic features illustrated in this cross section, and list them chronologically in the spaces provided. Letters indicate rock units; *other events are not labeled.* Also see Problem 6.

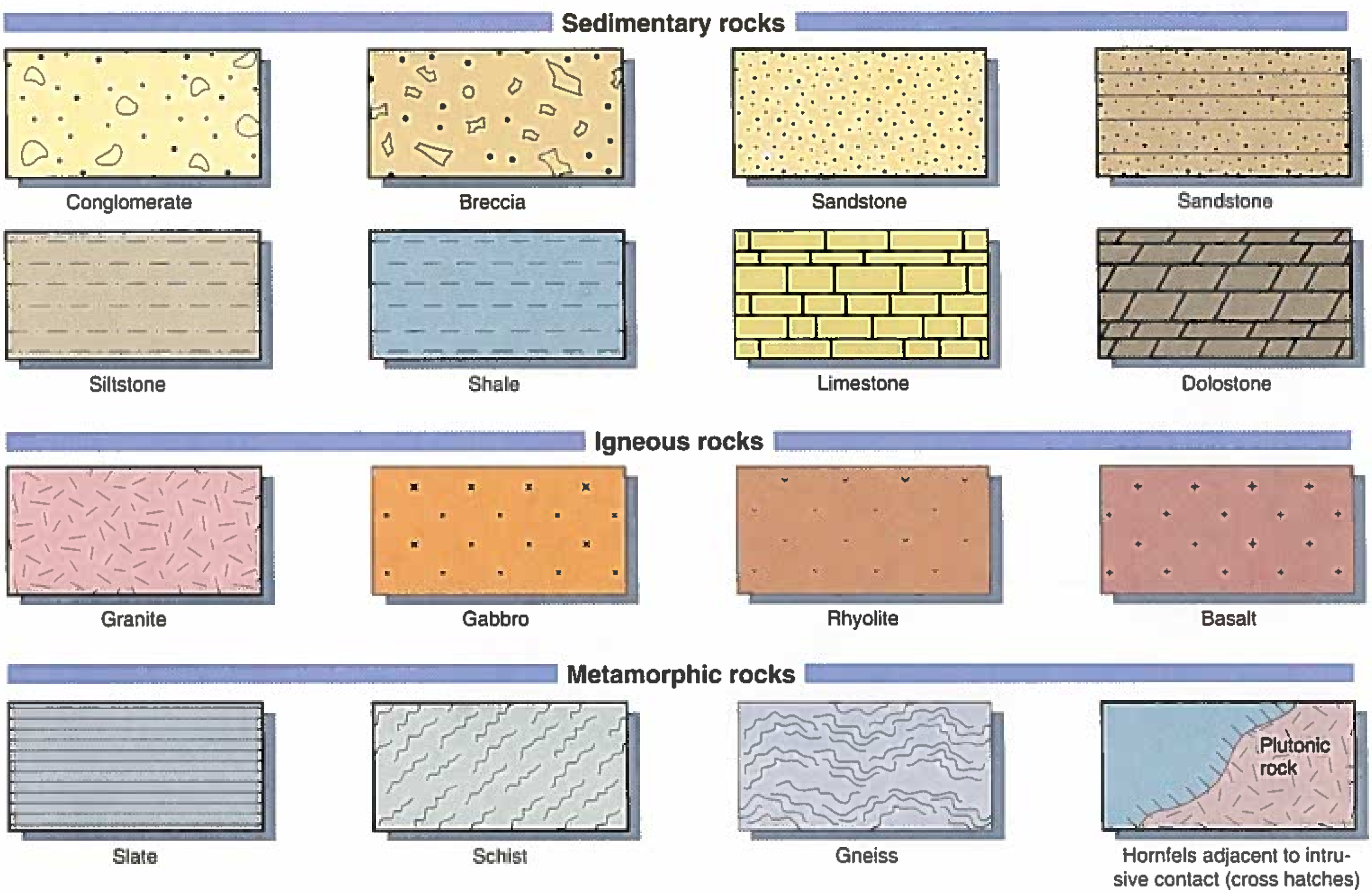

FIGURE 13.10
Symbols commonly (but not universally) used to show different kinds of rocks.

2. The purpose of this problem is to illustrate how numerical ages based on radioactivity can be determined graphically.

   a. Complete columns A and B in the table that follows. For example, after one half-life, the parent fraction is 0.5 and the daughter fraction is 0.5; after two half-lives, the parent fraction is 0.25 and the daughter fraction is 0.75. Remember, the sum of the two fractions must equal 1.0.

   b. Next, complete column C in the table by dividing values in Column B by corresponding values in Column A. For example, for one half-life elapsed, (Col. B)/(Col. A) = 0.5/0.5 = 1.

Half-Lives Elapsed	*A. Parent Fraction*	*B. Daughter Fraction*	*C. Daughter/ Parent Ratio*
0			
1	0.5	0.5	1
2	0.25	0.75	
3			
4			
5			

   c. Using Figure 13.11 and the data in the preceding table, construct a graph in which the veritcal axis is "Daughter-Parent Ratio" and the horizontal axis is "Half-Lives Elapsed." The point representing one half-life is already plotted. Plot the rest, and draw a *smooth* curve connecting the data points; that is, do not connect the points with straight-line segments, but estimate the curvature between points as best as you can so that the entire curve bends smoothly.

   d. For samples 1–3 in the following table, first calculate and record the daughter-parent ratio, N_D/N_P. Then, using your graph in Figure 13.11, determine the number of half-lives that have elapsed for each sample and write your answer in the "Half-Lives Elapsed" column.

Sample Number	*Atoms of Parent N_P*	*Atoms of Daughter N_D*	*N_D/N_P*	*Half-Lives Elapsed*	*Age in Years*
1	2135	3203			
2	4326	10,815			
3	731	14,620			

   e. If the half-life is 8200 years, calculate the age in years of the samples in the preceding table and write your answer in the "Age in Years" column. Show your work.

3. The purpose of this problem is to illustrate how numerical ages based on radioactivity can be determined mathematically. Show all your calculations.

   a. If the decay constant for radioactive decay of ^{40}K is $\lambda = 5.543 \times 10^{-10}$/year, use Equation 13.1 on p. 251 to calculate the ages of the samples in the following table, and write them in the "Age in Years" column.

Sample Number	*Atoms of Parent N_P*	*Atoms of Daughter N_D*	*N_D/N_P*	*Half-Lives Elapsed*	*Age in Years*
1	6439	2303			
2	4395	1303			
3	8763	1893			

Problem 3 is continued on next page.

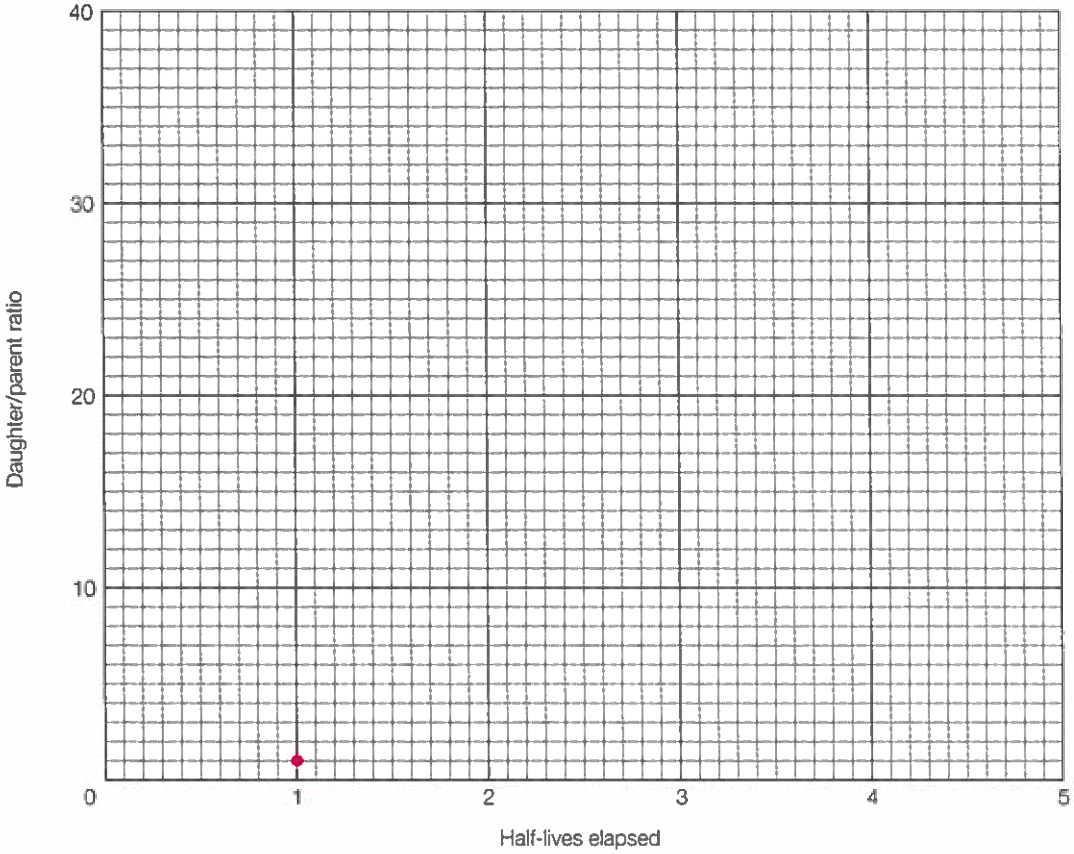

FIGURE 13.11
Graph for Problem 2c.

b. The half-life, $t_{1/2}$, of ^{40}K can be determined from the decay constant using the following relation:

$$t_{1/2} = 0.693/\lambda \text{ (see footnote 1)}$$

What is the half-life of ^{40}K? __________

c. Using the half-life calculated in Problem 3b, complete the column labeled "Half-Lives Elapsed" in the previous table.

4. Go to *www.kaibab.org/geology/gc_layer.htm* (or link to it through *www.mhhe.com/jones7e*—see Preface) and scroll down to the schematic geological section at the bottom of the page. Concentrate on the Precambrian part of the section, that is, everything below the Tapeats Sandstone, and answer the following:
   a. Is the Zoroaster Granite older or younger than the Vishnu Schist?

      The Bass Limestone?

   b. What is the oldest sedimentary rock?

[1]*The equation* $t_{1/2} = 0.693/\lambda$ *is derived from the equation* $t = \ln(N_D/N_P + 1)/\lambda$ *as follows: If* $t = t_{1/2}$*, then* $N_D/N_P = 1$, $\ln(N_D/N_P + 1) = \ln 2 = 0.693$, *and* $\ln(N_D/N_P + 1)/\lambda = 0.693/\lambda = t_{1/2}$

c. What name is applied to the surface separating the Vishnu Schist and the Bass Limestone (be specific)?

What surface separates the Bass Limestone and the Tapeats Sandstone?

d. Knowing that the oldest Precambrian sedimentary rock in the Grand Canyon is about 1,250 m.y. (million years) old and the youngest about 825 m.y., use maximum thicknesses given for the Precambrian sedimentary rocks (that is, exclude the Cardenas Lavas) and calculate the "average" rate of accumulation in feet/m.y.

Evaluate the significance of this number; that is, why might this number be meaningful or meaningless?

Next go to The University of California, Berkeley Museum of Paleontology at *www.ucmp.berkeley.edu/index.php* and under *Online exhibits* click on *Tour of geologic time (www.ucmp.berkeley.edu/exhibits/geologictime.php).* Use this site to determine when the things in the following list occurred. To do this, click on *Precambrian, Paleozoic Era, Mesozoic Era,* and *Cenozoic Era*. For the three eras, you will have to further click on the *Stratigraphy* buttons to find the information needed. Write the answers below and, to get an overall sense of history, in the right-hand column of the Geologic Time Scale (Fig. 13.7).

Oldest known rocks?

Transition to atmosphere with oxygen?

Start of breakup of Pangaea?

Oldest known fossils?

First animals?

Age of dinosaurs?

First:

- Birds?
- Reptiles?
- Mammals?
- Insects?
- Fish?
- Flowering plants?

Largest mass extinction?

An excellent interactive site that will help you understand how isotopes are used to determine numerical ages is at *www.sciencecourseware.org/VirtualDating/*. Give it a try.

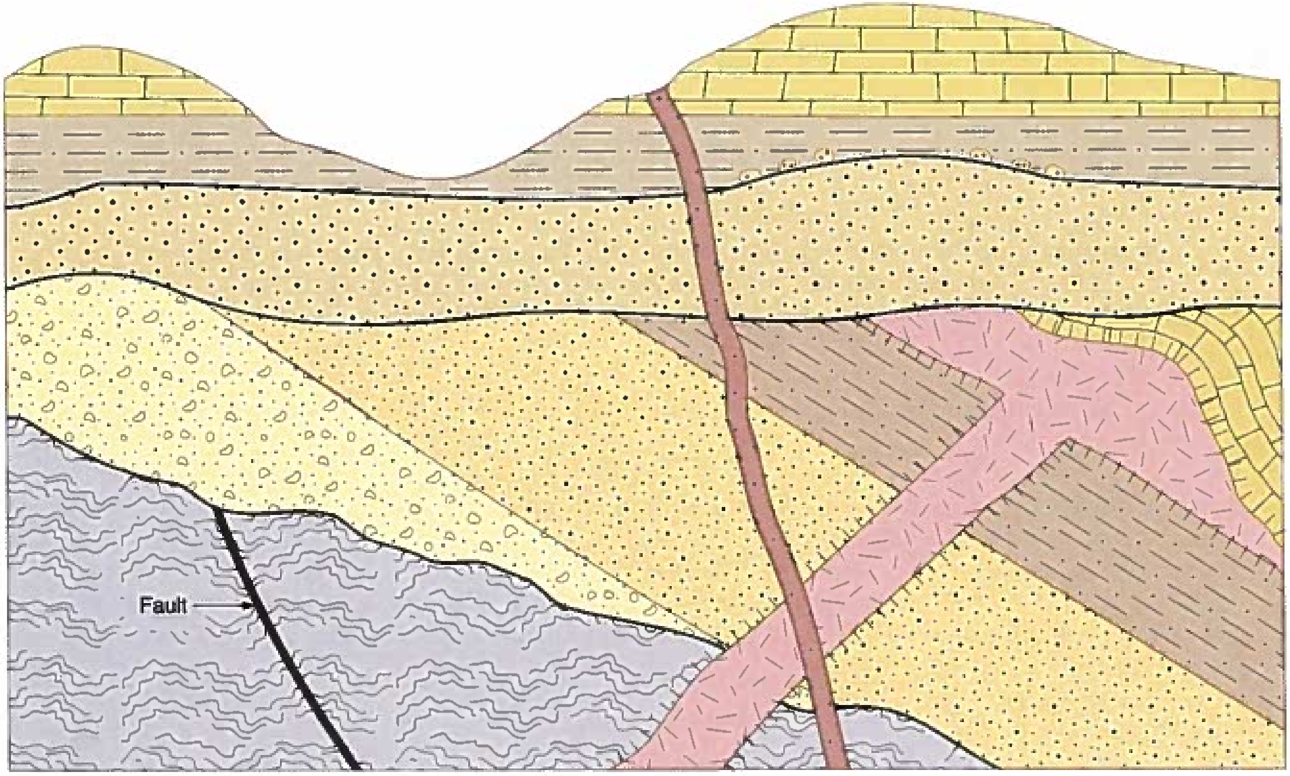

FIGURE 13.12
For Problem 5, determine the sequence of events illustrated in this cross section. Identify rock units from their symbols, and list all the events that led to the present situation.

In Greater Depth

5. Using Figure 13.12, identify rock units from their symbols, and identify and list in sequence *all* the events that led to the present situation. On the cross section, write number 1 on the oldest rock or event, number 17 on the youngest, and intermediate numbers on rocks or events in between. If you cannot determine which of two or more rocks/events is the older, explain why not.

6. Refer to Figure 13.9.
   a. The daughter-parent isotope ratios (N_D/N_P) for rocks F and C are 16.0 and 9.2, respectively. Assume that the half-life of the parent is 6.5×10^7 years, and use the curve you derived for Problem 2 to determine the numerical ages of each of these rocks.
   b. During what geologic periods were these rocks intruded (see Figure 13.7)?
   c. Assume, for illustrative purposes, the highly unlikely scenario in which each of the lettered rock units A through I represents a geologic period of the Phanerozoic. What period (or periods, if more than one answer is possible) does each represent?
   d. During what geologic period or periods did folding and erosion occur?