1 Geologic Time

Topics

A. What is the historical basis of a 6,000-year-old Earth, and what is the apparent inaccuracy in the chronology of the Biblical six-day creation?

B. What are the 'two components' of geologic time?

C. Relative geologic time.

What was the observation made by James Hutton in 1788 at Siccar Point, Scotland, and how did he explain the rock relationships there?

What are the Principles of Original Horizontality, Superposition, Inclusions, and Cross-cutting?

What is the sequence of events that accounts for rock relationships at Grand Canyon?

How did William Smith use fossils in his work, and what was his contribution to geology?

Our geologic time scale is based on both relative time and absolute time. What's the difference?

What are 'index fossils,' and in what three ways are they used in this exercise for deciphering past geologic events?

D. Absolute geologic time.

What is the science of dendrochronology all about? How can dendrochronology build a calendar extending back in time beyond the life of a single living tree? What are some of the factors that affect variations in the development of tree rings?

How do varves develop? What is the length of time documented in the Green River Formation?

How do corals act as daily and annual'clocks?' What information have corals provided about changes in the length of an Earth day?

What is there about radioactive isotopes by which they act as geologic clocks? How does the decay curve of an hourglass differ from that of radioactive isotopes?

What is the age of Earth's oldest known rock?

What do homologous bones and vestigial organs have to say about organic evolution?

A. Judeo-Christian time.

It has been said that the greatest gift of **geology** to human thought is the concept of practically limitless time and the belief that Earth's many landforms are products of present-day processes. One of the most significant advancements in science that was made feasible by the concept of a very old Earth was the theory proposed by **Charles Darwin**—*The Origin of Species by Means of Natural Selection* (1859). Darwin's idea of natural selection would have been less than convincing had the age of Earth been a mere few thousands of years.

Various cultures have viewed the age of the Earth as measurable in human generations (i.e., lifetimes) of, say, twenty years. *Example:* In 1644, **John Lightfoot**, Vice Chancellor of the University of Cambridge, and an eminent Hebrew scholar, published his exhaustive study of human history as derived from Middle Eastern sacred texts, in which he concluded that Heaven and Earth were created on October 23, 4004 B.C. at 9:00 am. (Dr. Lightfoot failed to specify the time zone.) From this dubious beginning, along with similar calculations made by others, there continue to be references to a 6,000-year-old Earth.

Still other accounts focused not on *when*—but on *how*—Heaven and Earth were created. *Example:* A 16th-century French Bible included a pictorial of the six-day creation portrayed in the *Book of Genesis* that ended with an Earth much as it appears today (Fig. 1.1 on the following page).

For the history of John Lightfoot and others:
http://www.lhup.edu/~dsimanek/ussher.htm

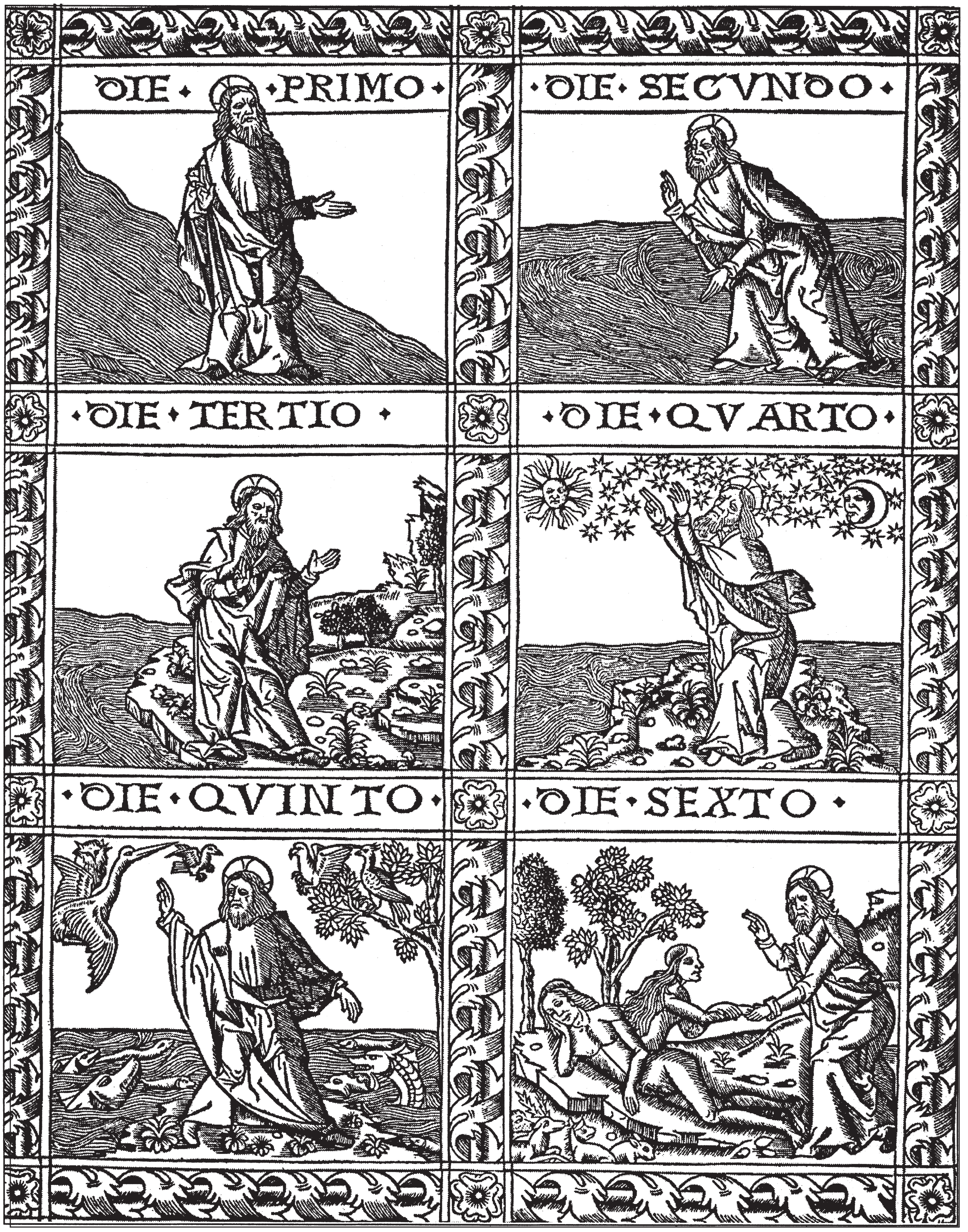


Figure 1.1 A 16th-century French Bible graphically depicted the six-day Creation described in the *Book of Genesis*. *(From* Scientific American*, August 1954.)*

On the first day (*die primo*) God created heaven and earth.
On the second day (*die secundo*) He separated firmament from water.
On the third day (*die tertio*) He made dry land and plants.
On the fourth day (*die quarto*) He made sun, moon, and stars.
On the fifth day (*die quinto*) He made birds and fishes.
On the sixth day (*die sexto*) He made land animals and man.

B. The two components of geologic time.

In this exercise we will deal with geologic time in two ways:

1. **Relative geologic time**—We will interpret past geologic events in their order of occurrence—i.e., *sequence of events*.

2. **Absolute geologic time**—We will solve for ages*, in years*, of past geologic events as recorded by 'geological clocks.'

This bipartite view of geologic time is not all that different from the way in which we view human history. *Example:* We might refer to the Renaissance chronologically as that period between medieval and modern periods (i.e., relative time). Or, we might refer to the Renaissance as having encompassed the time of certain events that occurred within the 14th century to the time in which certain events occurred within the 17th century (i.e., absolute time).

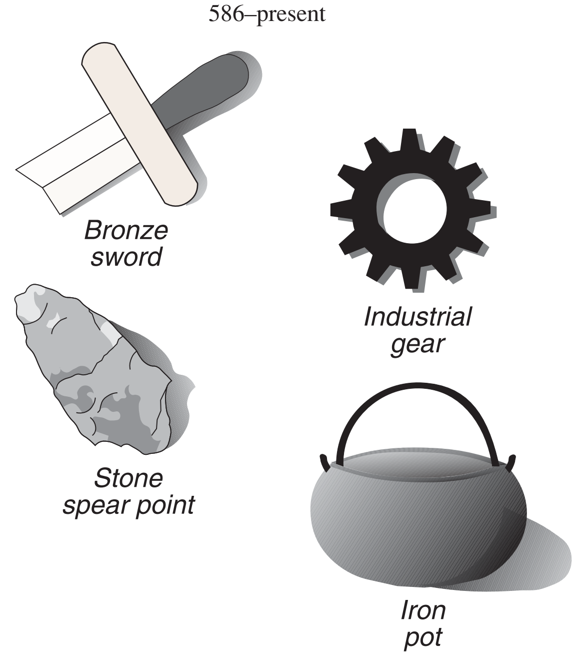
Q1.1 In Figure 1.1 (facing page), the sequence of events portrayed in the third and fourth days should raise a question in the minds of students of natural science. What is that question?

Beliefs by some in a 6,000-year-old Earth and a six-day creation persist today, but advancements in arts and sciences that define the Renaissance were accompanied by a revolution in thinking about Earth history.

Another example of the chronology of events:

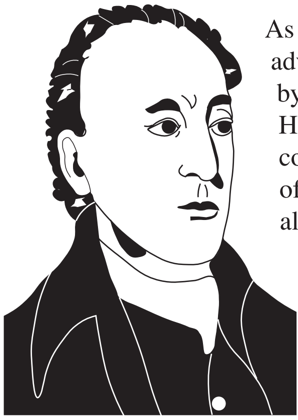
Q1.2 (A) List the four Age icons in Figure 1.2 in their proper chronological order—oldest first. (B) Does this question deal with relative time or with absolute time?

Figure 1.2 These four familiar anthropological Age icons are shown here in random order. Dates for the four ages are (in years before present):
2,000,000–3,300
3,300–1,200
1,200–586
586–present



For the history of industrial developments:
http://www.bergen.org/technology/techis.html

C. Relative geologic time.



As with most human endeavor, an advancement in science is made not by a single person, but by many. However, in the development of the concept of an Earth many millions of years old, one man stands above all others—**James Hutton**, an Edinburgh physician and geologist (1726–1797). Living at the time of other Scottish great thinkers (e.g., Adam Smith and James Watt), Hutton has been called the *Father of Modern Geology*. His study of rock outcrops in Britian led to his understanding of the immensity of geologic time, prompting him to once exclaim (about the Earth), *"No vestige of a beginning, no prospect of an end."*

Nicolaus Steno (1637–1687) observed that sediments (e.g., sand, silt, clay) are deposited in horizontal layers, much like sleet and snow. Therefore, layers of sedimentary rocks that are now tilted must record some sort of 'crustal upheaval.' But James Hutton unraveled a more complex history than that of simple deposition followed by upheaval. At Siccar Point, Scotland, Hutton observed that layers of sedimentary rocks appear to be standing on-end and that these vertical layers are truncated above by less steeply inclined layers of sedimentary rocks (Fig. 1.3). Like a good detective, Hutton reconstructed a *sequence of events* that consisted not of only three events (i.e., deposition, upheaval, and present-day erosion), but of six events (Fig. 1.4, facing page). Some years later, any similar buried surface of erosion recording a history of (a) deposition, (b) erosion, and (c) renewed deposition, came to be called an **unconformity**—a critically important feature in the deciphering of geologic history.

Q1.3 Imagine that you pick up a magazine in a waiting room and become absorbed in an article, only to encounter an 'unconformity' of sorts within the magazine. Describe this metaphorical 'unconformity.'

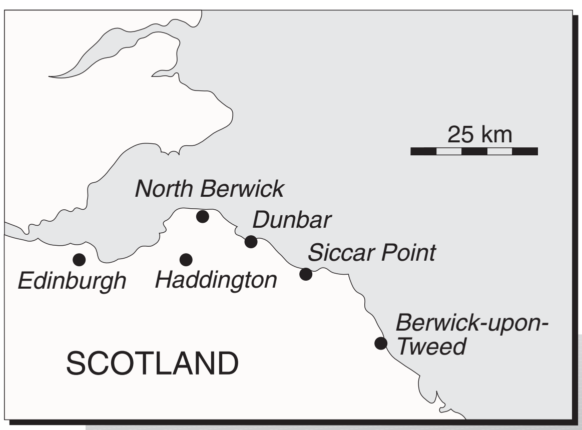


Figure 1.3 At Siccar Point, Scotland, vertically oriented layers of sedimentary rocks are truncated by less steeply inclined layers of sedimentary rocks. Note the diagonal and uneven erosional surface *(unconformity)* separating the two groups of rocks.

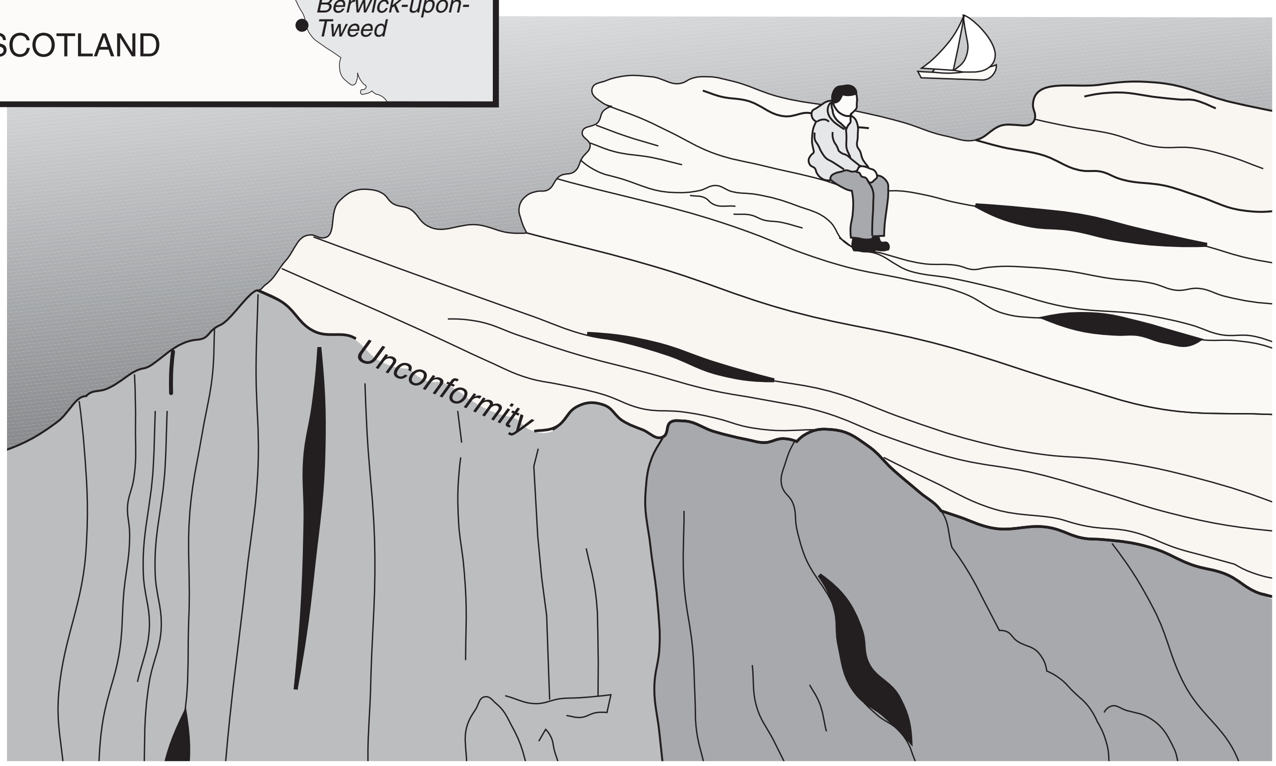
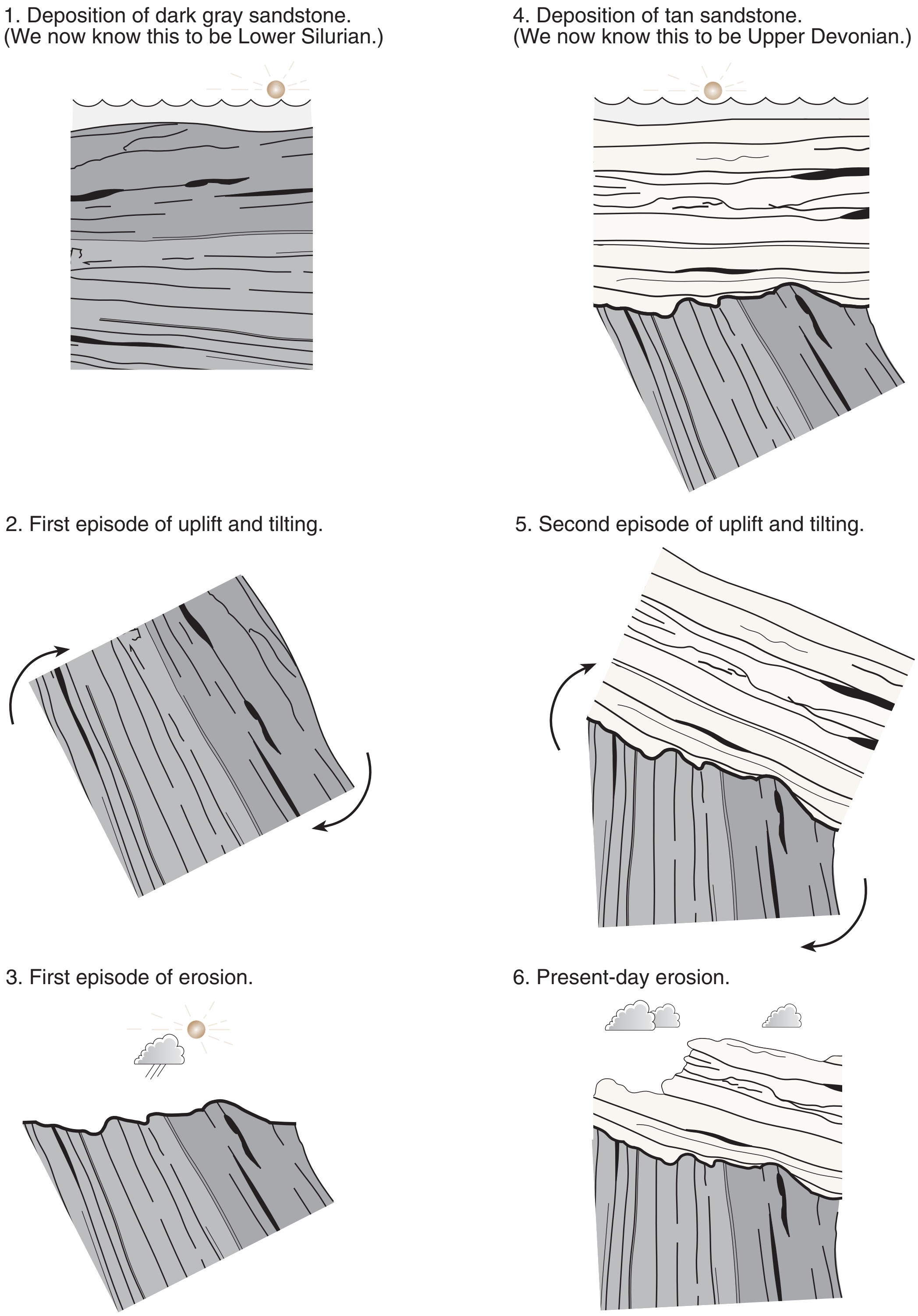


Figure 1.4 This is a graphic history of the development of the unconformity at Siccar Point, Scotland, as first envisioned by James Hutton in 1788.

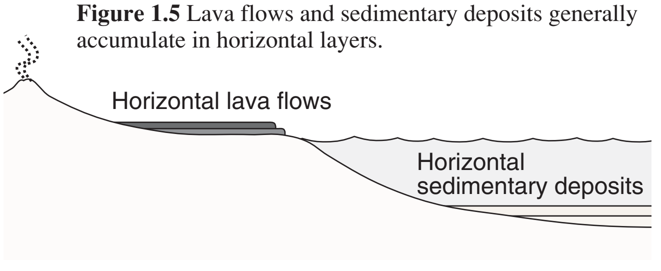


Additional principles in determining relative ages among rocks and rock features.

Geologists apply a number of physical principles in determining the relative ages of rocks and rock features. Now, in the 21st century, these principles are pretty much self-evident, but they bear illustrating for students deciphering a *sequence of geologic events* for the first time.

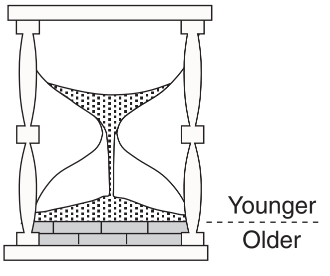
I. Principle of Original Horizontality—Volcanic and sedimentary rocks accumulate as horizontal layers, much like sleet and snow (Fig. 1.5). Therefore, most inclined rock layers have been tilted by later forces.

Figure 1.5 Lava flows and sedimentary deposits generally accumulate in horizontal layers.



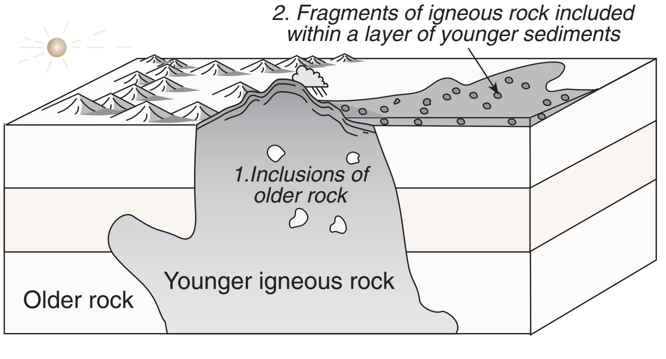
II. Principle of Superposition—When first accumulating, *younger* layers of rock overlie *older* layers of rock—like sand in an hourglass (Fig. 1.6).

Figure 1.6 An hourglass is a visual metaphor for the Principle of Superposition. Imagine the sand as the accumulating layers of sedimentary rock. (Brick pattern simulates limestone. Sand texture simulates sandstone.)



III. Principle of Inclusions—Fragments of rock that become entombed in another rock are *older* than the rock in which they become entombed. Examples (Fig. 1.7):
(1) Fragments of rock caught up in a magma or lava so as to become entombed in younger igneous rock. (2) Fragments of rock deposited as boulders or cobbles in younger sediments.

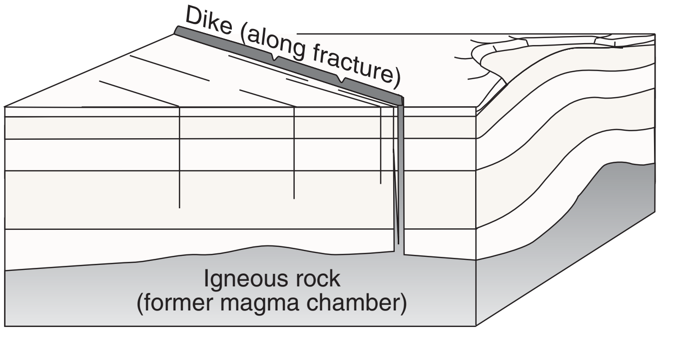
Figure 1.7 This figure illustrates two different environments for the development of inclusions.



IV. Principle of Cross-cutting—A rock feature that cuts across a body of rock is younger than the body across which it cuts. Cross-cutting rock features include bodies of magma that cut across older rock (see III. Principle of Inclusions), fractures, and faults.

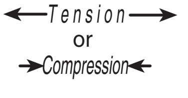
Fractures—Not only do fractures cut across older rocks, but in areas of magmatic activity, magma can intrude fractures, so that, upon cooling, the magma crystallizes to form rock bodies called **dikes** (Fig. 1.8).

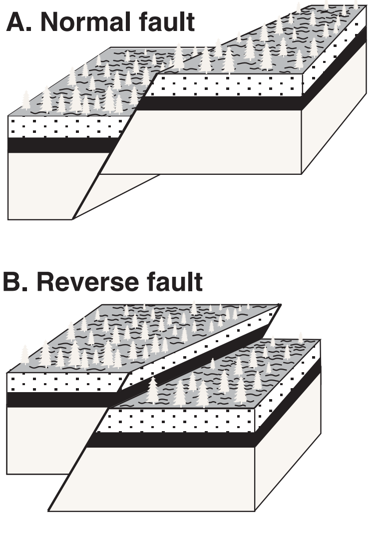
Figure 1.8 In the arid American West erosion is such that harder igneous dikes commonly stand higher than softer sedimentary rocks so as to appear like fences on the landscape.



Faults—Faults are fractures in Earth's crust along which dislocation (i.e., 'offset') occurs. Within Earth's crust there is a wide range of stresses, each of which produces a particular type of fault (Fig. 1.9).

Figure 1.9 These two kinds of faults result from two different kinds of stresses within Earth's crust. One is 'push' (compression), one is 'pull' (tension).





Q1.4 (A) In Figure 1.9A, does the geometry of the *normal fault* appear to be the result of tension, or does it appear to be the result of compression? (B) How about the *reverse fault* in Figure 1.9B? *Hint:* In one case the crust appears to have lengthened, whereas in the other case the crust appears to have shortened.

One last wrinkle (no pun intended).

The situation at Siccar Point (Fig. 1.3) is a close-up view of one **limb** of a larger **fold** such as that in Figure 1.10. Keeping it simple, in the following cases we will apply the term *'tilting'* where only one limb of a fold is within view, and the term *'folding'* where both limbs of a fold are within view.

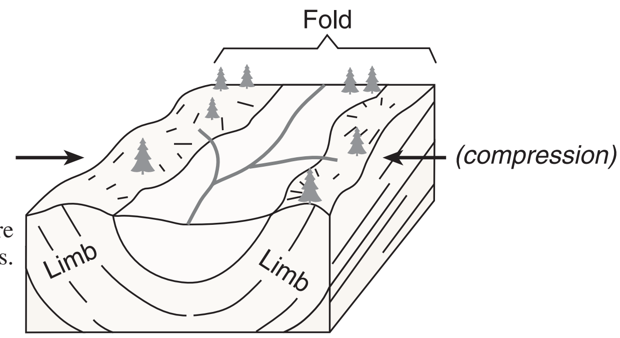
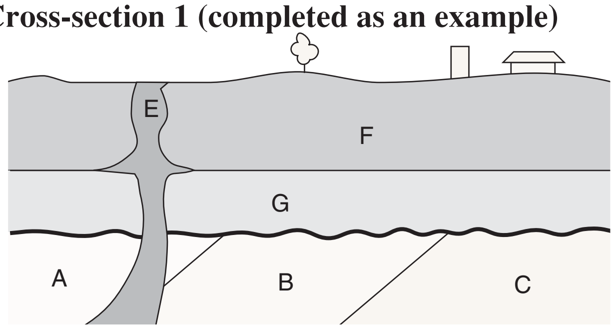


Figure 1.10 Folds such as this were produced by compressional forces.

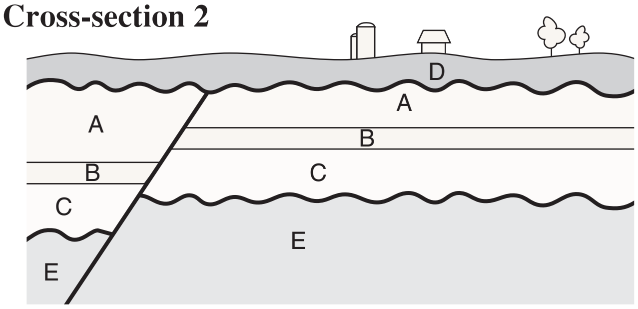
Instructions—Using **cross-section 1** (below) as an example, list events illustrated in **cross-sections 2**, **3**, and **4**, with first (earliest) event first. You need not include (as the last event) present-day erosion. Unconformities are indicated with bold wiggly lines. Faults are indicated with bold straight lines. After finishing, turn the page and work out the sequence of events for America's popular national park, Grand Canyon.

Cross-section 1 (completed as an example)



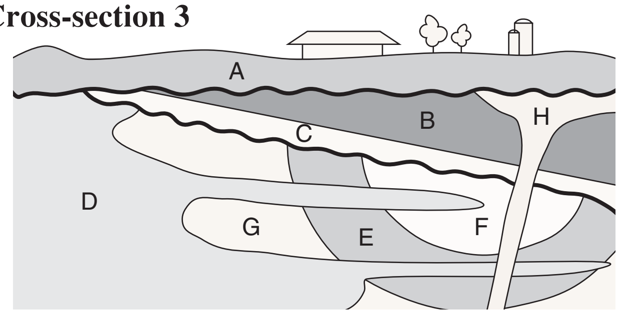
1 deposition of C
2 deposition of B
3 deposition of A
4 tilting (down to left)
5 erosion
6 deposition of G
7 deposition of F
8 intrusion of E

Cross-section 2



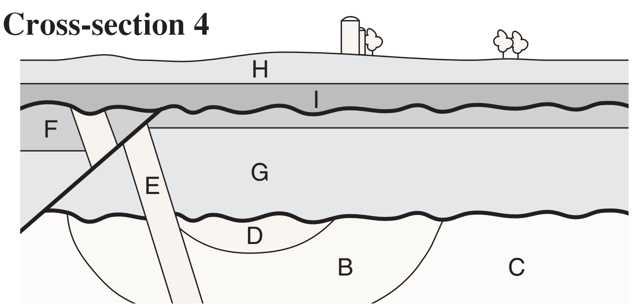
1 ________
2 ________
3 ________
4 ________
5 ________
6 ________
7 ________
8 ________

Cross-section 3



1 ________
2 ________
3 ________
4 ________
5 ________
6 ________
7 ________
8 ________
9 ________
10 ________
11 ________
12 ________

Cross-section 4



1 ________
2 ________
3 ________
4 ________
5 ________
6 ________
7 ________
8 ________
9 ________
10 ________
11 ________
12 ________

8 Geologic Time

Decipher the sequence of events from this cross-section (Fig. 1.11) **of Grand Canyon National Park.**

The existence of the Vishnu Schist is the oldest event recorded, so insert ‘Vishnu Schist’ on line no. 1, and then proceed from there. Stop with deposition of the Redwall Limestone. Unconformities are indicated with bold wiggly rock boundaries.

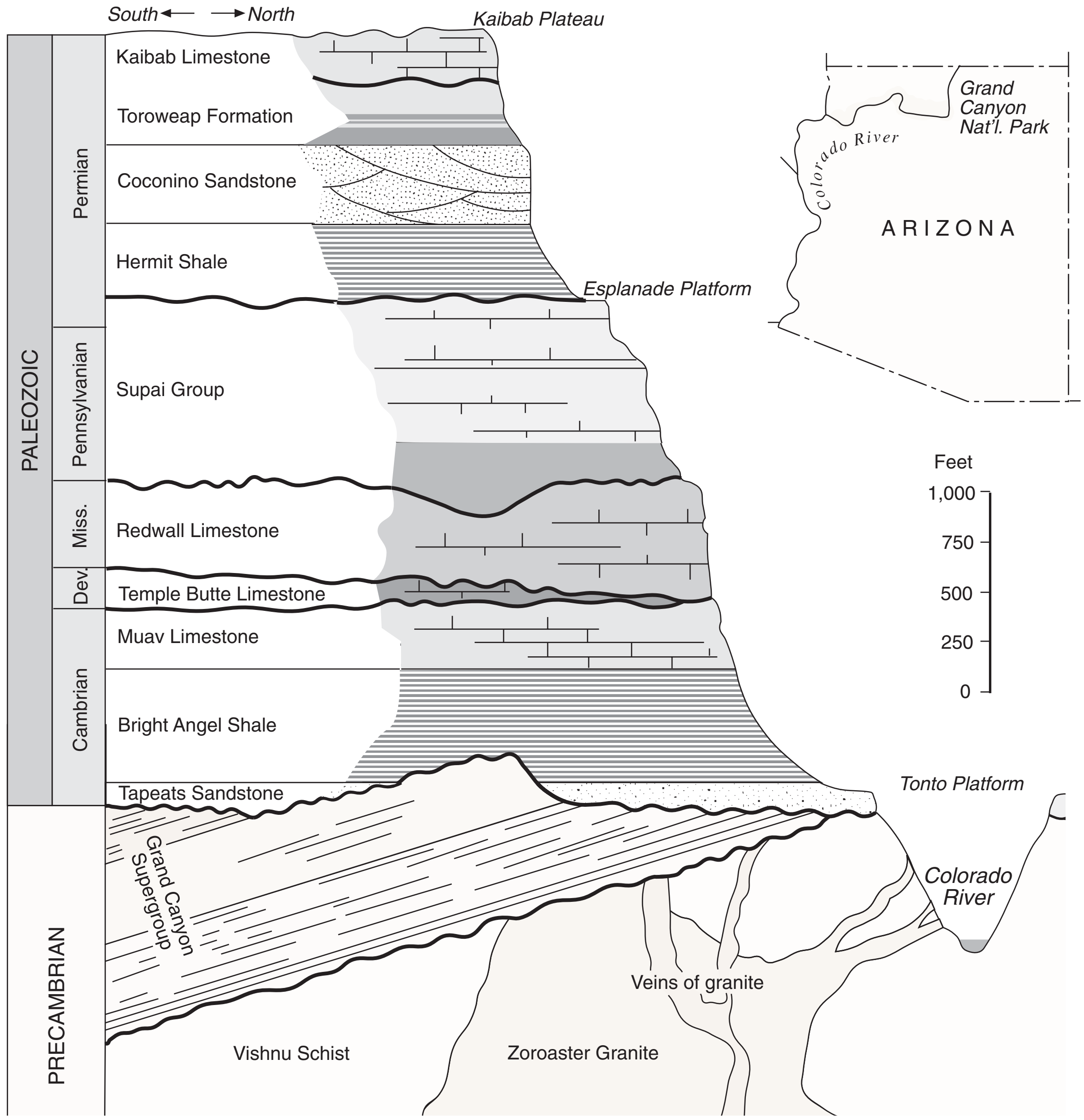


Figure 1.11 This is a geologic section of Grand Canyon, complete with geologic ages and names of rock bodies and topographic features. *(From McKee, E.D., U.S. Geological Survey Professional Paper 1173.)*

1 Vishnu Schist ______________________

2 ______________________

3 ______________________

4 ______________________

5 ______________________

6 ______________________

7 ______________________

8 ______________________

9 ______________________

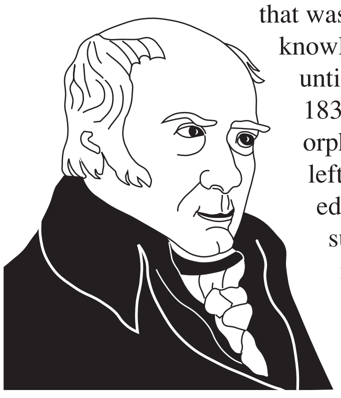
10 ______________________

11 ______________________

12 ______________________

The Map That Changed the World (a book by Simon Winchester, 2001).

As we saw earlier, Nicolaus Steno and James Hutton established the fundamental principles for understanding physical relationships among rocks and rock features, but there remained another vast world in the fledgling science of geology that had hardly been noticed during their times—the world of **fossils** (from Latin *fodere*, 'to dig up'). Although a few amateur collectors of these curious objects correctly inferred that fossils are the remains of once-living animals, that was about the extent of the knowledge of the time. That is, until **William Smith** (1769–1839) came along. Smith, the orphaned son of a blacksmith, left school at age 12 and educated himself in geometry, surveying, and mapping. His interest in rocks and fossils prompted him to apply for the job of supervising the digging of the Somerset Canal in southern England—only one of many canals that were being constructed for the purpose of moving coal from Midland mines to furnaces all over England.



The surveying and excavating of canal routes required an understanding of **strata** (i.e., layers of rock) through which canals were dug—which led to Smith's discovery that different kinds of fossils within strata invariably occur in the same vertical order (Fig. 1.12), which enabled him to predict, on the basis of fossils, which strata would occur higher or lower at any excavation. Thus was born Smith's **principle of faunal succession**, the documentation of which was a composite vertical succession of some 22 strata—from (Carboniferous) coal at its base to (Cretaceous) chalk at its top. Smith exhibited such a passion for rocks and fossils that he acquired the nickname *'Strata' Smith* from his friends.

William Smith's grand **geologic column** proved to be the prototype of our modern **Geological Time Scale** (page 11). By 1815 he had plotted his many local geologic sections onto a base map of 15 sheets drawn by cartographer John Carey, producing what has been referred to as *"an incomparably beautiful geological map."* The map, which measures 8' 9" by 6' 2", now hangs covered with blue velvet drapes in Burlington House near London's Picadilly.

Postscript: Perhaps equally important was Smith's theory that the partitioning of varieties of fossils in vertical *space* (within strata) recorded their having been partitioned in *time* as well—thereby documenting the empirical evidence of organic evolution.

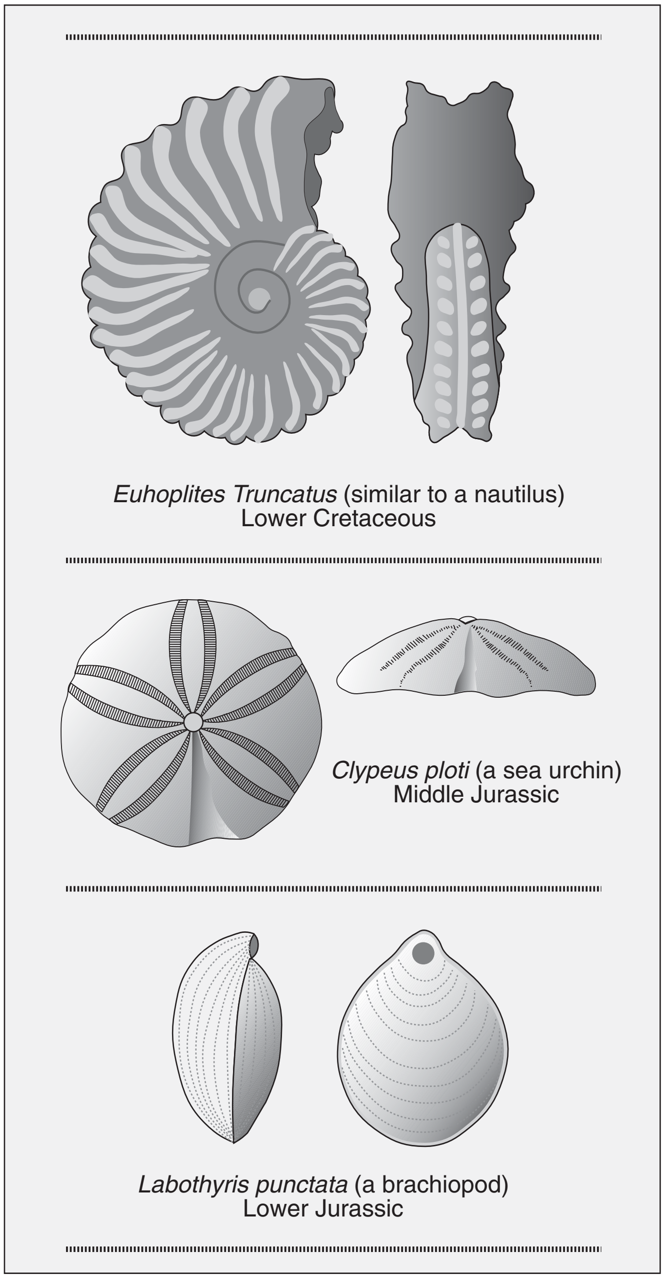


Figure 1.12 These are only three of the countless Jurassic and Cretaceous fossils that enabled William Smith to catalog the rock strata of England. *(All actual size)*

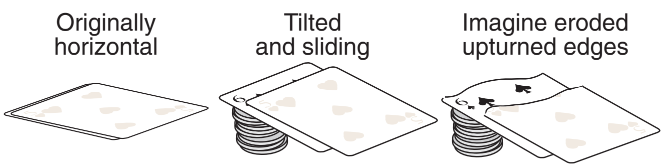
For a history of William Smith's ideas:
http://www.unh.edu/esci/tableexplan.html

The Map That… (cont.)

William Smith's successes in establishing the **stratigraphy** (i.e., the disposition of strata) of the sedimentary rocks of England derived from…

- His curiosity and remarkable powers of observation
- His facility with processing information
- Hhe relative simplicity of the geology of the region

Figure 1.13 is taken from a part of Smith's map, showing only the principal outcrops of Jurassic and Cretaceous rocks. Strata in this part of England are gently inclined downward toward the southeast, overlapping one another like cards sliding off of a stack of poker chips.



In addition to coloring each stratum with a different color on his map—which was common practice even in those days—Smith meticulously shaded each stratum's color darker on its upturned edge, giving the map a shaded-relief effect (again, Fig. 1.13).

Notice in Figure 1.13 that the southeastward inclination of Cretaceous strata reverses direction so as to be inclined toward the northwest a few miles southeast of London. You can simulate this structural grain by doing the following: With your palms upturned and your fingers pointing away from you, cup both hands and—with fingers of both hands pointing directly away from your body (so that your right fingernails are directly above your left fingernails)—nest your cupped right hand in your cupped left hand. (This will draw your elbows in to your stomach.) Your left hand now simulates the underlying Jurassic, and your right hand now simulates the overlying Cretaceous. London is in the center of your right palm, along with a bit of Tertiary strata.

Q1.5 On the Answer Page, (A) sketch the landscape *profile* along line A–E in Figure 1.13, showing ridges (shaded dark on the map) and valleys (shaded light on the map). (B) Now, beneath your profile, sketch each interval of rock—the Jurassic, the Cretaceous, and the bit of Tertiary—as a single stratum with a thickness approximately equal to that of a 25¢ piece. *Hint:* See again Figure 1.10 (top of page 7).

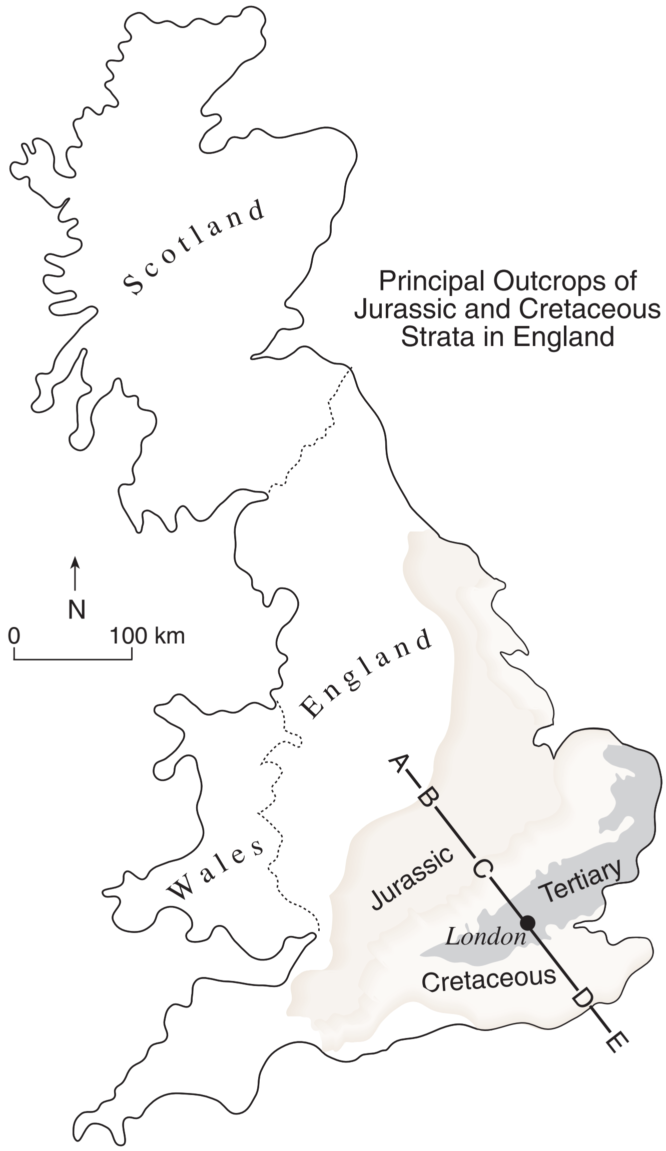


Figure 1.13 This is an excerpt of William Smith's *Geological Map of England and Wales and Part of Scotland* showing southeastward inclined Jurassic and Cretaceous strata. The Cretaceous reverses its direction of inclination southeast of London, where it is overlain by a bit of Tertiary strata. (Letters B, C, D along the line of profile A–E serve as guideposts in constructing the landscape profile called for in Question 1.5A.)

Our geologic time scale.

The beginnings of our geologic time scale in the 18th and 19th centuries developed in large measure from the successions of fossils recorded by William Smith and others. In this way, it wasn't all that different from our understanding of the succession of human cultures as documented by such things as the implements in Figure 1.2. Ages in *years*, both in anthropology and in geology, have since been added through the technology of isotopic dating.

GEOLOGIC TIME SCALE

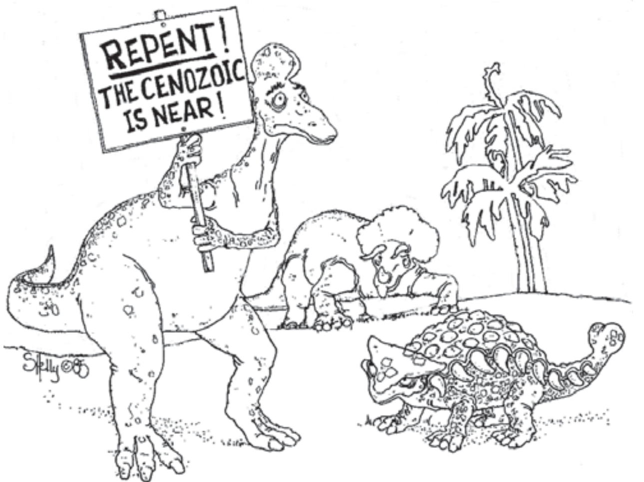
Eon	Era	Period	Epoch	million yrs.
PHANEROZOIC	CENOZOIC (Age of Mammals)	Quaternary	Holocene	0.01
			Pleistocene	1.8
		Tertiary (Neogene)	Pliocene	5.3
			Miocene	23.8
		Tertiary (Paleogene)	Oligocene	33.7
			Eocene	54.8
			Paleocene	
			Mass extinctions	65
	MESOZOIC (Age of Reptiles)	Cretaceous		144
		Jurassic		206
		Triassic		
			Mass extinctions	248
	PALEOZOIC (Age of Invertebrates and Fishes)	Permian		290
		Pennsylvanian	Carboniferous	323
		Mississippian		354
		Devonian		417
		Silurian		443
		Ordovician		490
		Cambrian		543
PROTEROZOIC	LATE	PRECAMBRIAN		900
	MIDDLE			1600
	EARLY			2500
ARCHEAN	LATE			3000
	MIDDLE			3400
	EARLY			3800?

Life ranges shown: *Invertebrates*, *Fishes*, *Land plants*, *Amphibians*, *Reptiles*, *Mammals*, *Birds*

(1) Epochs within the Paleozoic and Mesozoic Eras are not referenced to the extent that they are within the much younger Tertiary, so they are omitted here in the interest of simplicity.

(2) The Precambrian has not been subdivided into periods and epochs.

In the case of our geologic time scale, Greek and Latin roots were borrowed in naming the Phanerozoic Eon (*visible life*) and its three eras: Paleozoic (*ancient life*), Mesozoic (*middle life*), and Cenozoic (*recent life*). Mass extinctions at the ends of the Permian and Cretaceous Periods punctuated the end of the Paleozoic and Mesozoic Eras.



A Late Cretaceous landscape

Q1.6 The two mass extinctions notwithstanding, there appears to have been a developmental trend in vertebrate animals within the Phanerozoic Eon. What was that trend? *Hint:* The same descriptor is used as an ethnicity goal on some college campuses.

Mnemonic crutch: Periods Cambrian through Quaternary. (Read in ascending order.)

question!
Tough
congressmen?
junior
than
power
political
more
demand
senators
old
Can

For a more detailed account of the geologic time scale: http://www.geosociety.org/science/timescale/timescl.htm

Other mnemonic help—and much more: http://oldsci.eiu.edu/geology/jorstad/geoltime.htm

Index fossils—guides to the ages of rocks.

Beginning with the work of William Smith, fossil species have systematically been cataloged to serve as guides to particular intervals of geologic time. Some species existed for long periods of time, whereas other species weren't long for this world. This latter group of short-lived species is of greater utility as guides to the ages of rocks. Members of this distinguished group are called **index fossils**. Ages of some index fossils are diagrammed in Figure 1.14 (below), and their utility in solving geological problems is illustrated on the facing page.

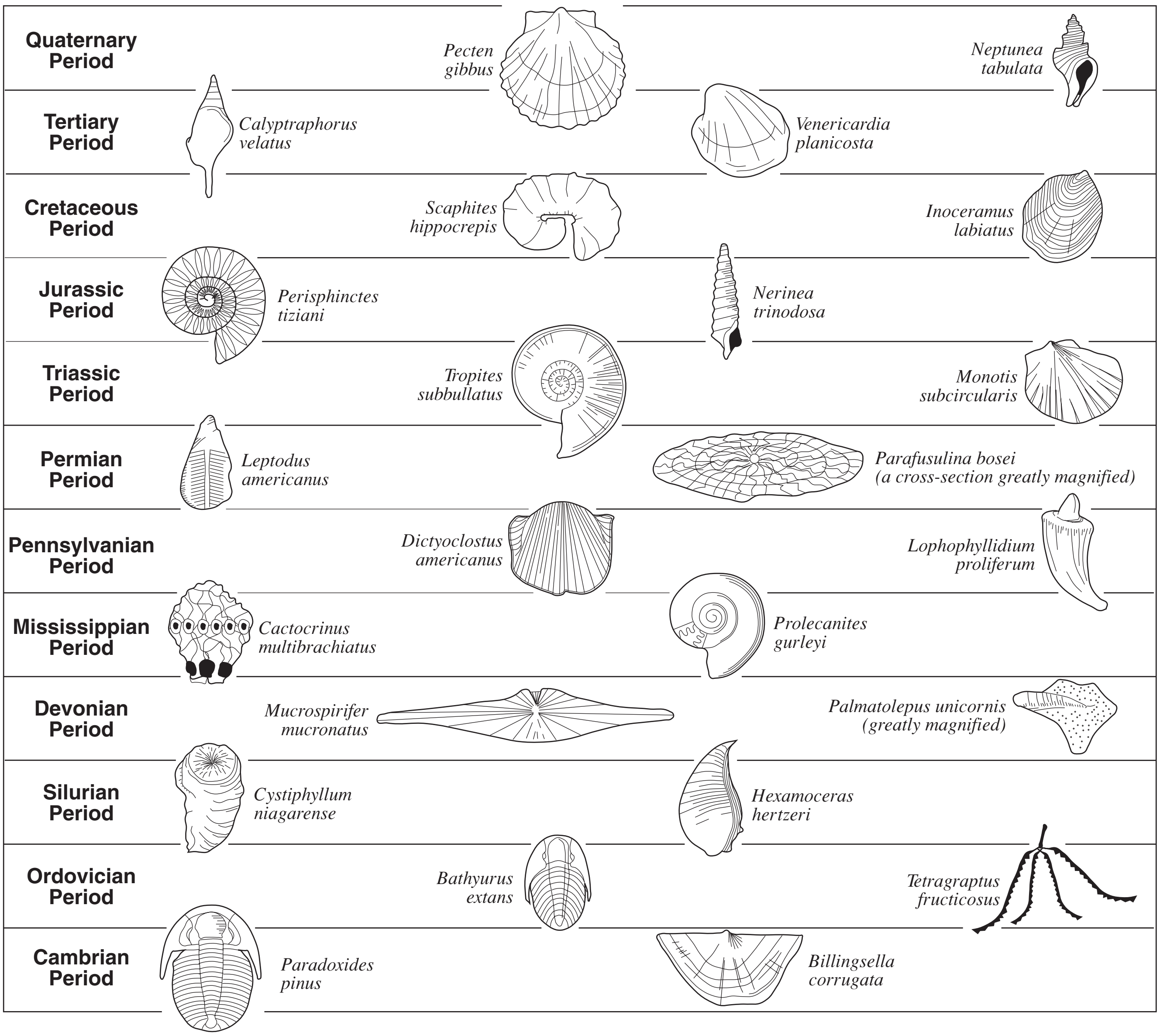


Figure 1.14 This is a *composite* catalog of index fossils, meaning that this succession has been pieced together from numerous less complete successions from around the world. No one place on Earth exhibits all of these ages of rocks with their diverse diagnostic fossils. Species shown here belong to a variety of animal groups, including trilobites, brachiopods, pelecypods, gastropods, cephalopods, echinoderms, and corals. *(From U.S. Geological Survey pamphlet,* Geologic Time.*)*

Q1.7 In the succession of strata below (Fig. 1.15), at which stratum boundary—I through VIII—does there appear to be an unconformity as indicated by the distribution of fossil species? *Suggestion:* It might be helpful to first abbreviate the name of each geologic period indicated by a fossil species on its corresponding line to the right. The lowest (Cambrian) is supplied. Then look for gap(s) within the succession.

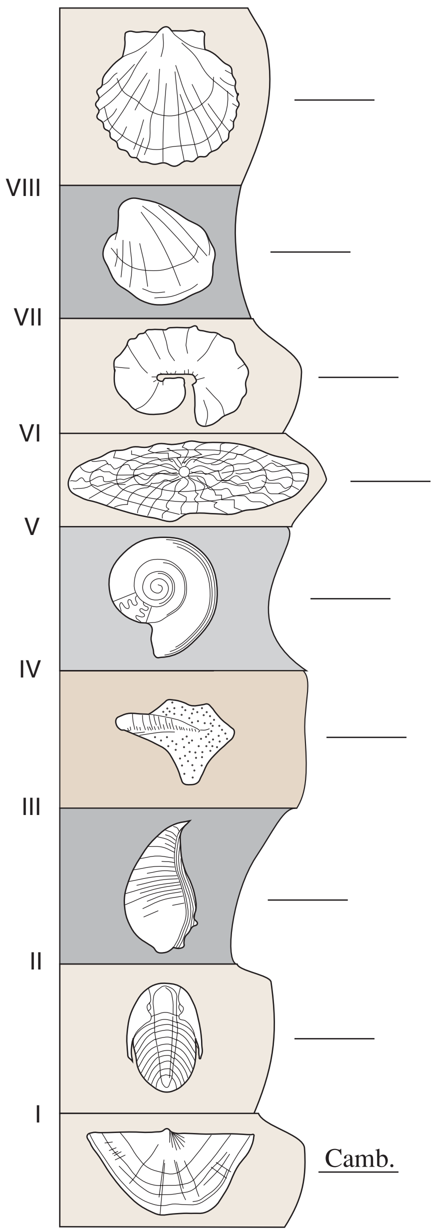


Figure 1.15 This is a vertical succession of sedimentary rocks that includes some of the index fossils illustrated on the facing page.

Q1.8 In the succession of strata below (Fig. 1.16), there is a fault. What kind of fault is indicated by the distribution of fossil species in this succession of strata—a normal fault or a reverse fault? *Hint:* You might need to review these two kinds of faults in Figure 1.9 on page 6.

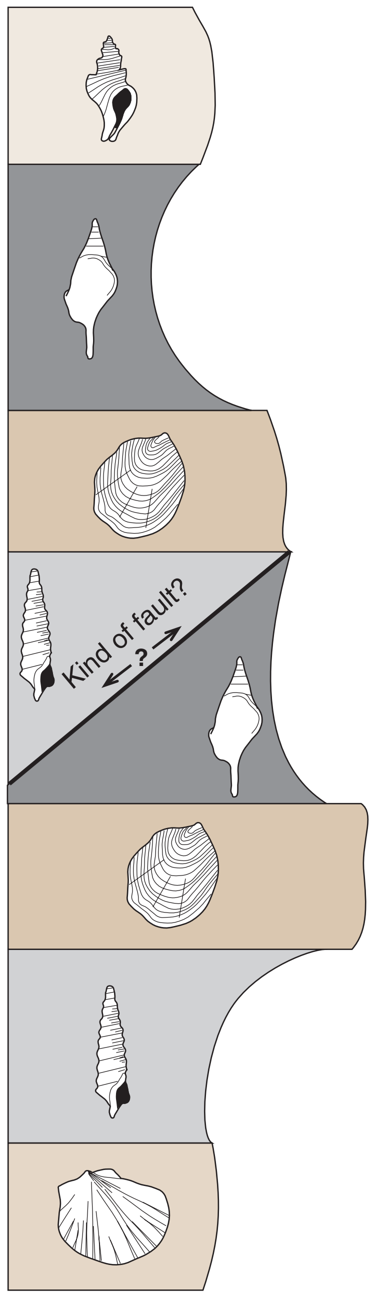


Figure 1.16 This is a vertical succession of sedimentary rocks that includes some of the index fossils illustrated on the facing page, plus a fault shown with a bold line.

Q1.9 In the succession of strata below (Fig. 1.17), there are no faults. Notice that in stratum #9 there is a fragment of *Parafusulina bosei* (a species that occurs in stratum #6). Explain this recurrence of *Parafusulina bosei* in stratum #9. *Hint*: You might need to review the Principle of Inclusions (Example 2) in Figure 1.7 on page 6.

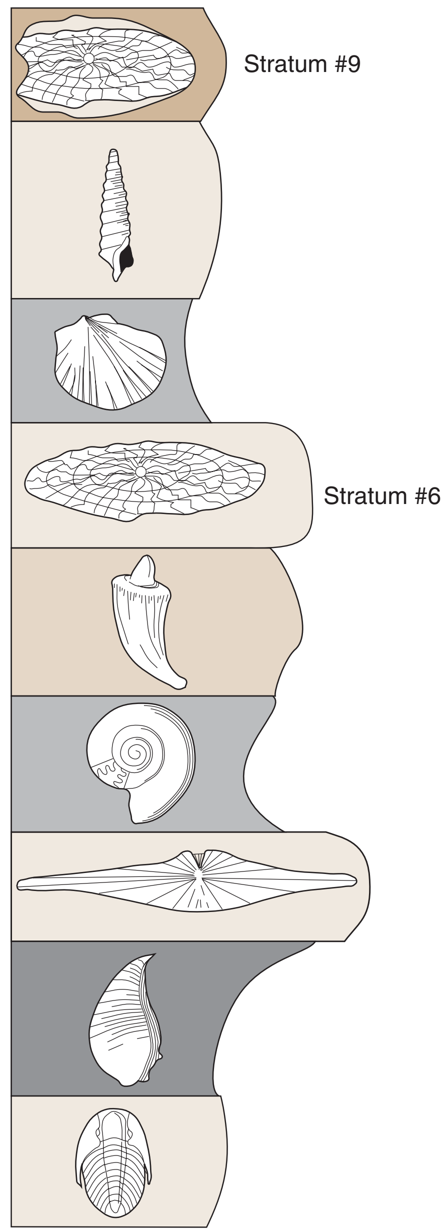


Figure 1.17 This is a vertical succession of sedimentary rocks that includes some of the index fossils illustrated on the facing page. There is no fault in this succession.

D. Absolute geologic time.

Dendrochronology

Word roots:
dendros = having to do with trees
chronos = time, sequence of events
ology = the study of

Everyone knows about tree rings—those curious bands in tree stumps and lumber that record annual increments of growth. Figure 1.18A shows a schematic cross-section of a mature tree, complete with rings, the sum of which reveals the tree's age.

Q1.10 What is the age of the tree sketched in Figure 1.18A?

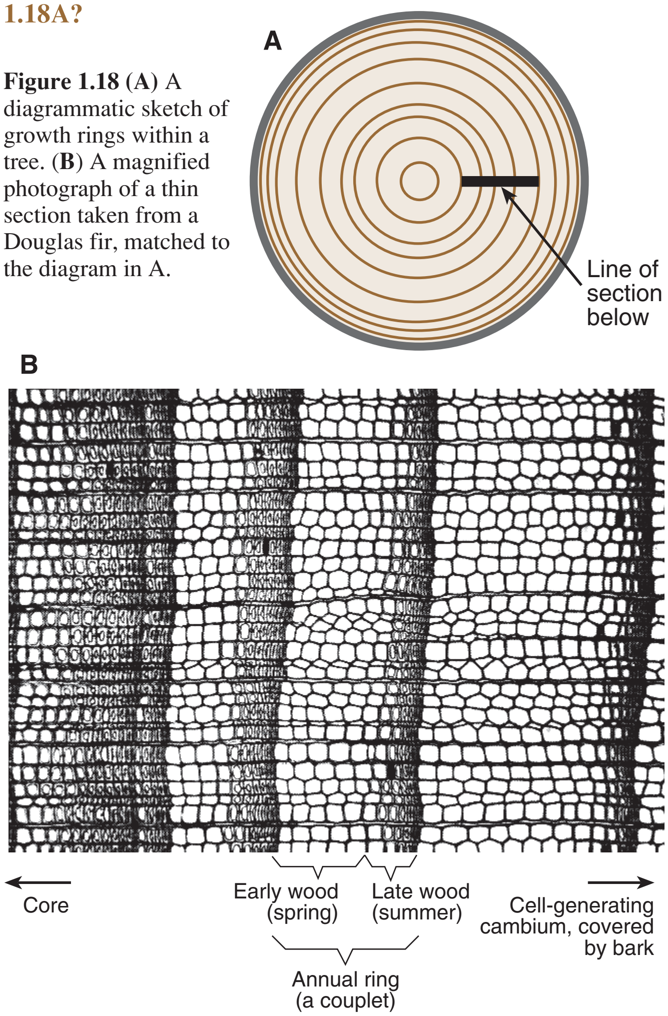


Figure 1.18 (**A**) A diagrammatic sketch of growth rings within a tree. (**B**) A magnified photograph of a thin section taken from a Douglas fir, matched to the diagram in A.

Remarkable coring devices—called **increment borers**—which are about the diameter of a soda straw, can be drilled into the heart of a tree to extract a plug of wood without threatening the life of the tree. Dendrochronologists have concluded that the bristlecone pine of California is the oldest of all living species on Earth (Fig. 1.19).

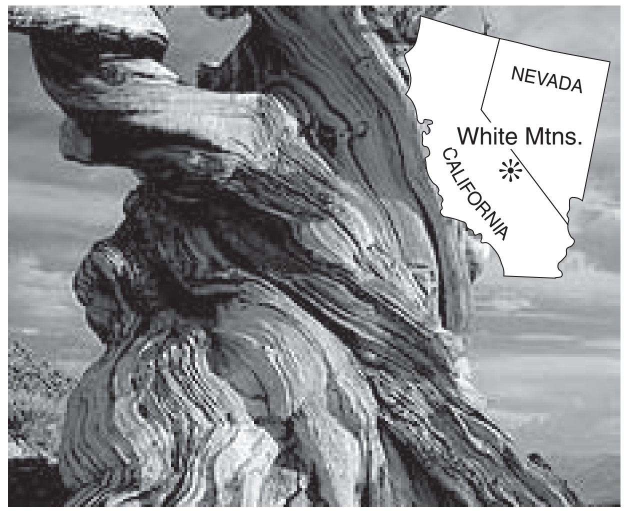


Figure 1.19 The Methuselah Tree, a bristlecone pine in the White Mountains of California, is 4,800 years old—the age of Egyptian pyramids.

But the work of *dendrochronologists* is not limited to life histories of standing trees. By coring trees, both living and dead, that overlap in time, these scientists are able to piece these 'barcodes' of Mother Nature together in a composite extending back some 9,000 years. Not only have they been able to study the life histories of living trees, standing dead trees, and fallen dead trees (Fig. 1.20), but they have also been able to determine the ages of timbers used by native Americans in the construction of prehistoric dwellings. Challenges in this exciting field include studying past climates and the effects of modern pollutants.

Q1.11 In schematic Figure 1.20, (A) How many years are recorded by the living tree? (B) How many years are recorded in the lives of the three overlapping trees?

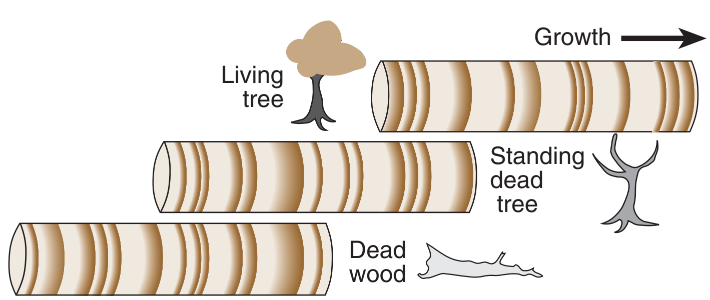


Figure 1.20 This is a simplified diagram showing cores from three trees that overlap in time. Bear in mind that many such trees must be sampled in order to arrive at statistically valid data.

Rate of growth within a tree is most generally promoted by the following four factors?

- *Moisture*
- *Sunlight*
- *Temperature*
- *Nutritious soil*

Figure 1.21 shows the effects that the environment has had on the rates of growth within the life of this tree.

Figure 1.21 In this section, two successions of broadly spaced tree rings 'sandwich' a succession of closely spaced rings.

Q1.12 What's your guess as to what accounts for the group of seven closely spaced tree rings in Figure 1.21?

Q1.13 In Figure 1.22, tree #1 grew in sparse woods and tree #2 grew in dense woods. So which of the above four factors do you imagine accounts for the difference in their sizes? *Hint*: In the field, neither competition for soil nutrients nor moisture appears to have been the reason.

Figure 1.22 These two sections are from trees that grew near each other. Notice that the two sections exhibit the same growth successions.

Varves

Varves are annual layers of sediment (or sedimentary rock) that develop because of seasonal fluctuations in the kinds of sediments accumulating on the floor of a body of water. The simplest schematic model of varve development is shown in Figure 1.23.

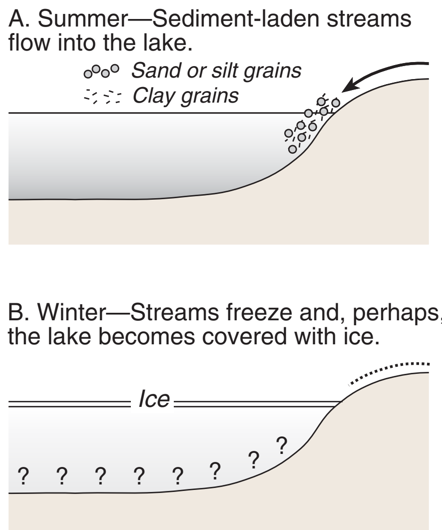
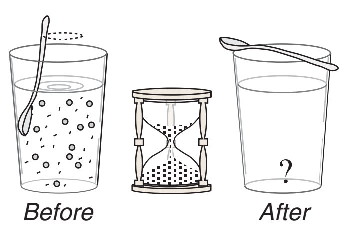


Figure 1.23 There are the two steps in varve development: (A) Summer streams bring a mix of coarse sand and fine clay to a lake. (B) Winter streams freeze and, perhaps, the lake freezes over as well.

Q1.14 On the Answer Page there's a replica of Figure 1.23B. Borrowing symbols for sand and clay in Figure 1.23A, sketch segregated layers of summer sediments and winter sediments on the floor of the lake. *Hint:* Think about the before-and-after water glasses in the demonstration below.



Q1.15 (A) For reasons of latitude, where would varves most likely be forming—in Canada, in Ecuador, or in Antarctica? (B) Why?

Like tree rings, varves come in a range of sizes—from several centimeters (Fig. 1.24) to fractions of a millimeter (Fig. 1.25).

Figure 1.24 These exceptionally thick varves accumulated in an Ice Age lake in northeastern Washington state. Each couplet of dark clay and light silt comprises the record of one year.

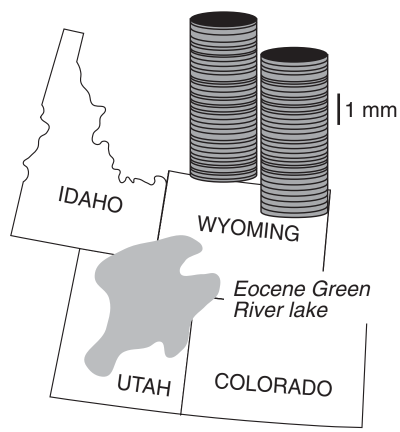


Figure 1.25 This is a sketch of two cores drilled miles apart in the Eocene Green River Formation, showing lateral integrity.

Q1.16 In what way is the *structure* of a varve like that of a tree ring?

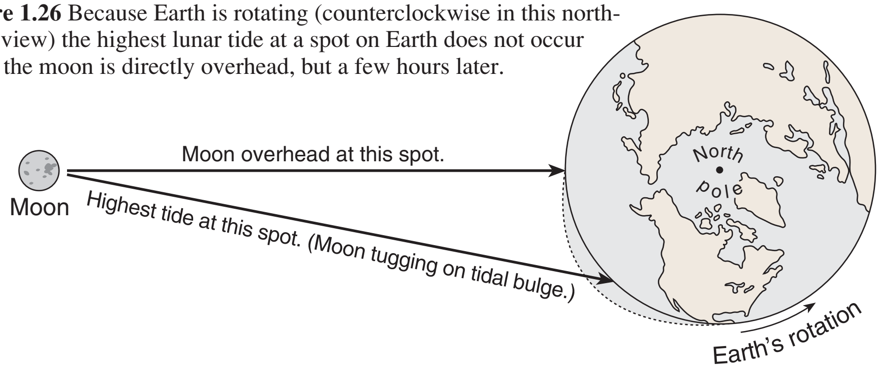
Measurements within the Green River Formation show that the average number of varves per centimeter is 70.

Q1.17 The thickest part of the Green River Formation is some 1,700 meters. So how much time is recorded by varves within this part of this Eocene formation?

Corals as clocks

The slowing of Earth's rotation—The highest lunar tide at any spot on Earth does not occur when the moon is directly overhead. Instead, the highest tide occurs a few hours later (Fig. 1.26). The reason is that it takes time for tidal currents to flow from one place to another, so the growing tidal bulge is carried eastward (via Earth's rotation) before it develops to its maximum. The mutual gravitational attraction between the moon and the 'off-centered' tidal bulge acts like a brake, thereby slowing Earth's rotation and lengthening Earth's day. Physicists and astronomers place the rate of deceleration of Earth's rotation at 0.002 second per century. This rate was first derived by comparing observations of eclipses of the sun and the moon recorded by Babylonians, Greeks, Arabs, and Chinese.

Figure 1.26 Because Earth is rotating (counterclockwise in this north-polar view) the highest lunar tide at a spot on Earth does not occur when the moon is directly overhead, but a few hours later.



The whopping rate of deceleration at 0.002 second per century doesn't sound like much, but given the immensity of geologic time, significant changes in the length of a day have developed since, say, the Paleozoic Era.

Q1.18 Using the 'slowing factor' of 0.002 second per century, what was *the length of a day* (in hours and minutes) at the beginning of the Devonian Period? (Refer to the geologic time scale—which includes years before present—on page 11.)

Decreasing days per year—Astrophysicists say there is no known reason for changes in the length of Earth's year (i.e., the time required for one trip around the sun). Therefore, as the length of a day *increases*, the number of days per year *decreases* proportionately.

Q1.19 Using the length of Earth's day that you computed in Question 1.18, what was *the number of days per year* at the beginning of the Devonian Period (rounded to the nearest one day)?

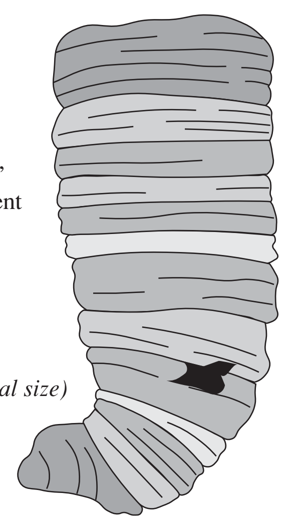
Earth's precession and deceleration are at…
http://www.crystalinks.com/precession.html

The 'calendar' within corals—Since the days of William Smith, fossils have been used to determine the *relative ages* of geologic events (as we saw on pages 9–13), but not the *absolute ages* of events, that is, until the work of **John W. Wells**, of Cornell University (*Nature*, 1963, 197:948–950).

Wells reviewed the fact that annual increments of growth occur in a variety of both fossil and living organisms (Fig. 1.27), but annual increments tell us no more about absolute time than do tree rings and varves.

Figure 1.27 Thirteen annual growth increments in this Middle Devonian 'horn coral,' *Heliophyllum halli,* are apparent with the unaided eye. Similar growth increments in living corals have been ascribed to seasonal differences in water temperature.

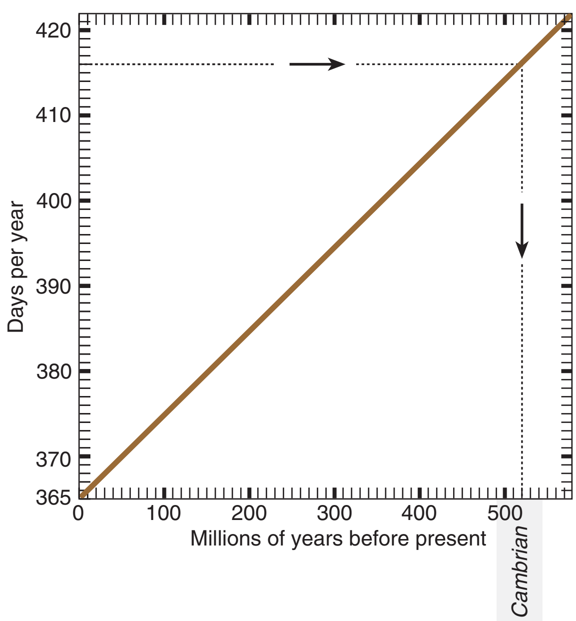
(Actual size)



Tellling time with corals—As pointed out by John Wells, if only there were some way to detect both *daily* growth increments and *annual* growth increments within a fossil, one could solve for the number of days per year at the time the animal lived. Then, using the slowing factor of 0.002 seconds per century, one could graph days per year vs. millions of years ago and graphically derive the geologic age of that fossil.

Figure 1.28 is a skeletal version of a graph made by John Wells in which he plotted the relationship between (a) days per year and (b) millions of years before the present. Using this graph, if we could determine that the number of days per year recorded by a Cambrian fossil was 416, the graph would show its age to be 520 million years, which is consistent with the age of Cambrian rocks derived through techniques of isotopic dating.

Figure 1.28 This graph by John Wells shows the relationship between increasing number of days per year and increasing geologic age. Example: A year of 416 days occurred during the Cambrian Period.



A number of people had noticed fine ridges on surfaces of coral skeletons, but the growth-time significance of the ridges went unnoticed until T.F. Goreau (1959) showed that the uptake of skeletal material from seawater by modern corals increases in daylight and decreases in darkness, thereby providing compelling evidence that these fine ridges mark daily growth increments.

Wells, in his study of West Indian corals, discovered that the number of these presumed daily growth increments per annual growth increment hovers around 360 in the space of a year's growth—approximately the current number of days per year. This observation prompted Wells to study fossil corals from Silurian, Devonian, Pennsylvanian, and Jurassic rocks (Fig. 1.29).

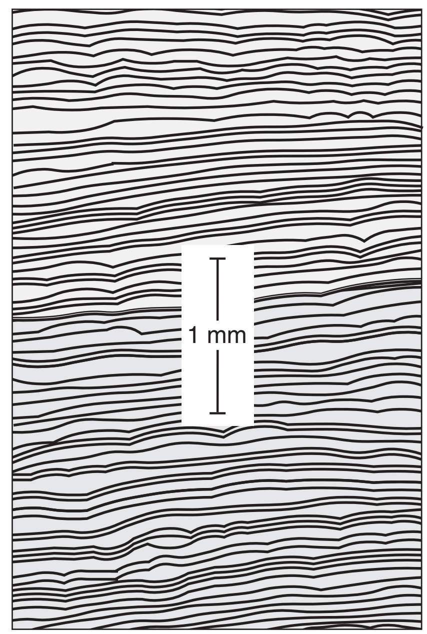


Figure 1.29 This is a schematic sketch of the Middle Devonian coral *Eridophyllum archiaci* showing what were interpreted by John Wells as daily growth increments.

Wells studied corals from rocks of known ages and, as he had expected, found that the numbers of days per year evident in these corals fell along the line in his graph when plotted vs their known ages. His work demonstrated the feasibility of illuminating the ages of rocks in which fossils exhibit daily and annual growth increments.

Q1.20 Collections of corals from three different rock formations on Mystery Island exhibit both daily and annual growth increments. On Answer Page 21, for each of the collections, give the age in millions of years and the geologic period indicated.
A. Corals in collection #1 record 407 days per year.
B. Corals in collection #2 record 396 days per year.
C. Corals in collection #3 record 382 days per year.

Isotopic (aka 'radiometric') dating of rocks.

Most chemical elements include two or more kinds of atoms that are alike in number of **protons** (thus, they are nearly identical in *chemical* behavior), but different in number of **neutrons** (thus, they behave differently in *physical* ways, such as diffusion). Different atomic species of the same element are called **isotopes** (Gr. *isotopos,* equal place—on the periodic table of chemical elements). Some isotopes are stable, whereas others are unstable (i.e., radioactive). Radioactive **parent isotopes** have nuclei that **decay** by emitting or capturing one or more kinds of subatomic particles to form daughter products (Fig. 1.30).

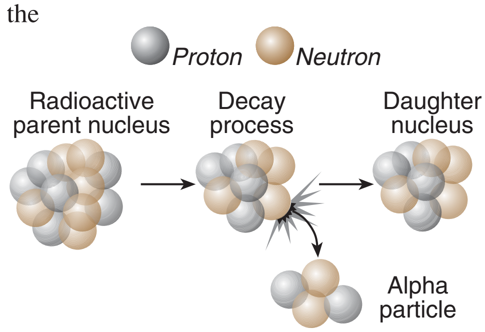


Figure 1.30 Alpha decay is one of the ways in which radioactive nuclei decay to form new isotopes. Alpha decay characterizes the decay of uranium-238, along with its family of products, ending in lead-206.

Half-lives of radioactive isotopes—The time at which a particular radioactive isotope will decay *cannot* be predicted, but the time at which a *percentage of a group* of particular isotopes will decay *can* be predicted. It's a probability thing. An analogy: An insurance company cannot predict when a particular driver will have an accident, but the company can predict when a percentage of drivers will have an accident, and, thereby, can set premium rates at levels sufficient to cover the insured.

The rate at which a particular radioactive isotope decays is known as its **half-life**, which is the time required for one-half of radioactive parent atoms in a sample to decay to daughter products, leaving one-half of the original parent atoms. The decay, in half-lives, of a radioactive element can be represented with a graph such as that in Figure 1.31.

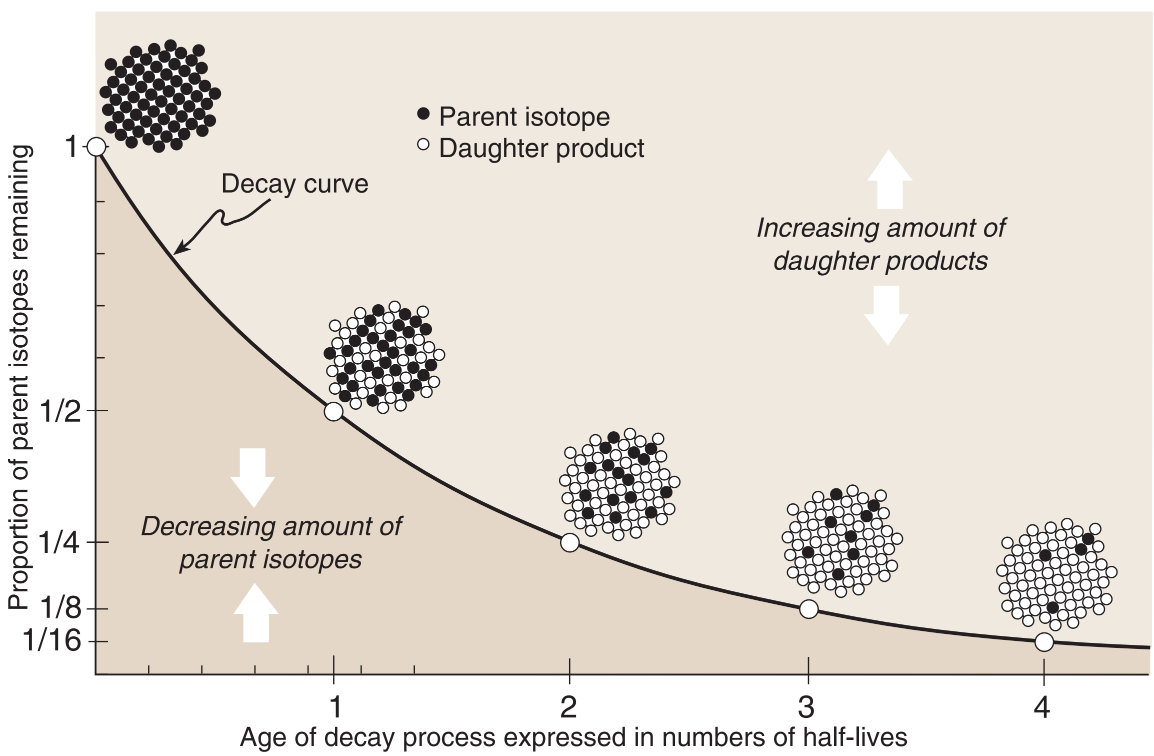


Figure 1.31 This is a graphic representation—in half-lives—of the decay of a radioactive isotope. (The tiny tick-marks along the base line near 1 half-life have been added to assist with the answering of Questions 1.23 and 1.24.)

Q1.21 What proportion (expressed as a fraction) of parent isotopes would remain after seven half-lives (Fig. 1.31)?

You be the judge—Numerous textbooks and lab manuals portray the decay of radioactive isotopes with an hourglass (Fig. 1.32).

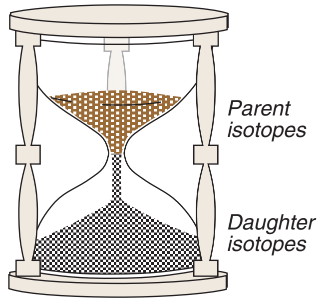


Figure 1.32 In this metaphor of radioactive decay, parent isotopes in the upper chamber magically decay to daughter isotopes as they pass through the orifice between the two chambers. Voilá.

While this visual metaphor conveys a sense of the simple passage of time, it fails to correctly simulate the *rate* of radioactive decay. What do you think? You be the judge.

Q1.22 On the skeletal framework below (Fig. 1.33), graph the flow of sand grains in this 4-minute 'hour-glass' timer. Construct your graph, and then answer the following question on the Answer Page: How does your graph differ from the graph of radioactive decay illustrated in Figure 1.31—in appearance and in substance?

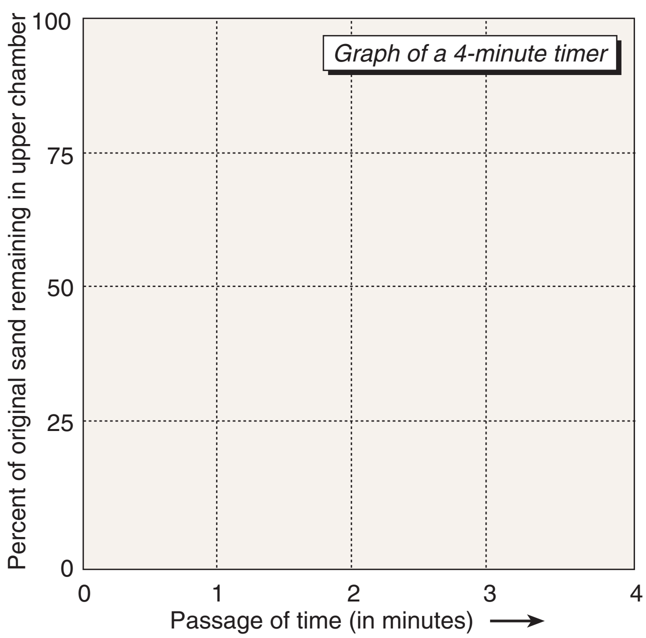


Figure 1.33 This is the skeletal framework on which you are asked to construct a graph depicting the flow of sand grains in a 4-minute 'hourglass' timer.

In 1907, **Bertrum Boltwood**, of Yale University, *observed* that in cases of uranium-bearing minerals of different relative ages—the older the rock, the more lead it contains. This observation led him to the *hypothesis* that the element lead is the eventual stable end product of uranium decay and that the ratio of uranium-to-lead in a rock is a measure of that rock's age. Boltwood's hypothesis has been *tested* thousands of times with countless isotopic analyses that have been consistent with relative-age determinations.

You might have recognized (in the above paragraph) the triad—*observation, hypothesis, and testing*—as components of the **scientific method**. A brief outline of '*scientific method lite*' follows:

(a) Observation of natural phenomena
(b) Shaping a hypothesis that explains that observation
(c) Testing of that hypothesis

The oldest rock—This is a moving target, but, at this writing, the oldest rock yet studied contains isotopes of uranium (uranium-238) that decay to stable isotopes of lead (lead-206). Judging from the amounts of uranium-238 and lead-206 in that rock, we find that approximately 54 percent of the original uranium remains. (The half-life of uranium-238 is 4.5 billion years.)

Q1.23 Using Figure 1.31, solve for the age of the oldest rock yet studied. *Hint:* Count each of the tiny tick-marks in Figure 1.31 as one billion years in the case of uranium-238.

The oldest meteorite—The oldest meteorites yet studied contain equal amounts of uranium-238 and lead-206.

Q1.24 How old are the oldest meteorites yet studied?

The age of Earth—Geoscientists assume that Earth is at least as old as the oldest meteorites. So…

Q1.25 So what's the minimum age of Earth?

P.S.
If the age of Earth were equal to one calendar year, the 1492 arrival of Christopher Columbus in America would have occurred at five seconds before midnight on December 31.

Another application of the scientific method.

Charles Darwin, during his five-year exploration of Pacific islands (1831–1836), *observed* three dynamics having to do with species:

- *Variation among individuals within a species*
- *Greater survival of the more fit individuals*
- *Inheritance of the more fit characteristics*

These observations led to his *theory* of organic evolution through **natural selection**.

Darwin's theory has been *tested* many times, in many ways. A couple of examples follow:

Homologous bones—(Gr. *homologous*, matching in structure, position, and character.) It was discovered early on that different animals share similar organizations of bones as concerns form and function (Fig. 1.34). This led naturalists to hypothesize that there exists a common ancestry among animals. The testing of this hypothesis led to additional discoveries that, for example, include the fact that the five digital bones in the human hand occur in the limbs of such diverse creatures as mammals, reptiles, and birds.

Q1.26 In the bat skeleton, which bone is the humerus, A, B, or C?

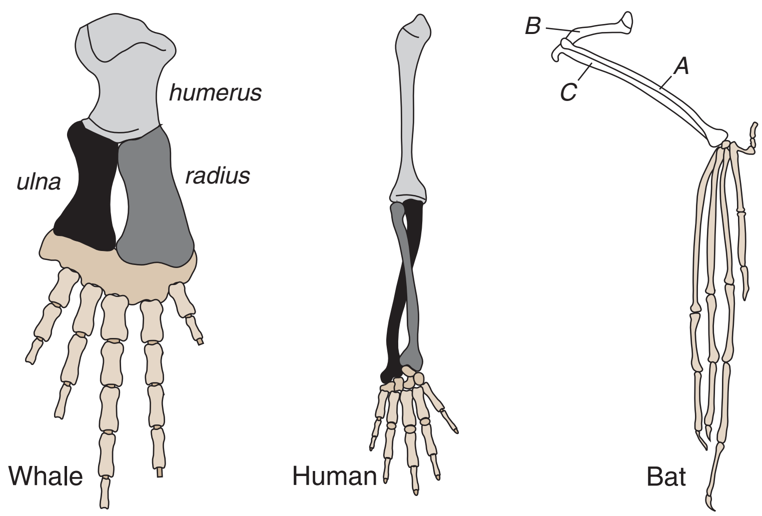


Figure 1.34 Right forelimbs of whale, human, and bat. These examples, plus myriad other mammals, share similar bone structures.

Vestigial organs—(L. *vestigium*, of the past.) Evidence for common ancestry among animals also occurs in **vestigial organs**—which are structures within an organism that no longer serve a useful purpose but appear to be diminutive analogs of functioning structures in other organisms.

The 'flipper' that no longer exists—One of many examples of vestigial organs occurs in the whale, which appears to have evolved from a four-legged animal. The evidence: vestigial limb elements that are now deeply buried within the whale's flesh (Fig. 1.35).

Q1.27 Can you name a rather obvious vestigial structure in the human skeleton? *Hint:* This structure has both a proper anatomical name and a vernacular (common) name.

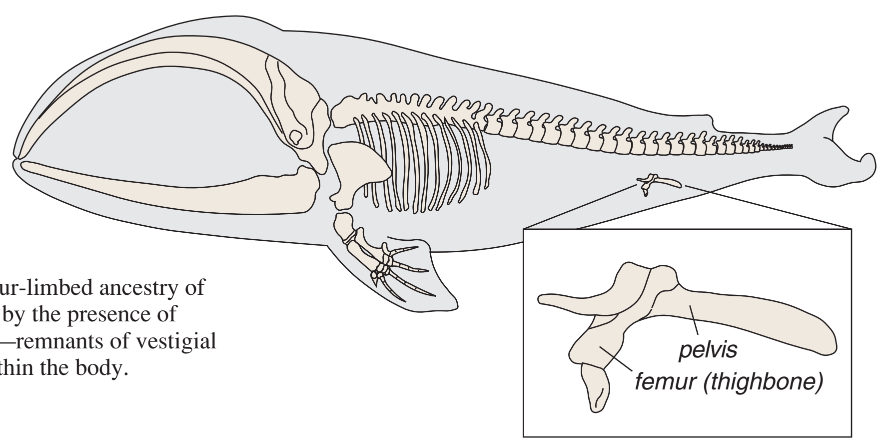


Figure 1.35 The four-limbed ancestry of whales is indicated by the presence of small pelvic bones—remnants of vestigial limb elements—within the body.

______________________ ______ ______
(Student's name) (Day) (Hour)

____
(Lab instructor's name)

ANSWER PAGE

1.1 ______________________

1.2 (A) ______________________ (B) ______________________

1.3 ______________________

1.4 (A) ______________________

(B) ______________________

1.5 A—B——C————D—E

1.6 ______________________

1.7 ______________________

1.8 ______________________

1.9 ______________________

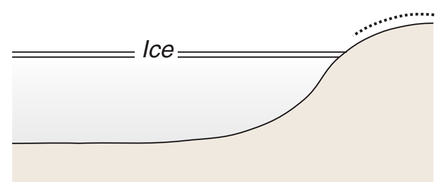
1.10 ______________________

1.11 (A) ______________________ (B) ______________________

1.12 ______________________

1.13 ______________________

1.14



1.15 (A) ______________________ (B) ______________________

1.16 ______________________

1.17 ______________________

1.18 ______________________

1.19 ______________________

1.20 (A) ______________________

(B) ______________________

(C) ______________________

1.21 ______________________

1.22

1.23

1.24

1.25

1.26

1.27