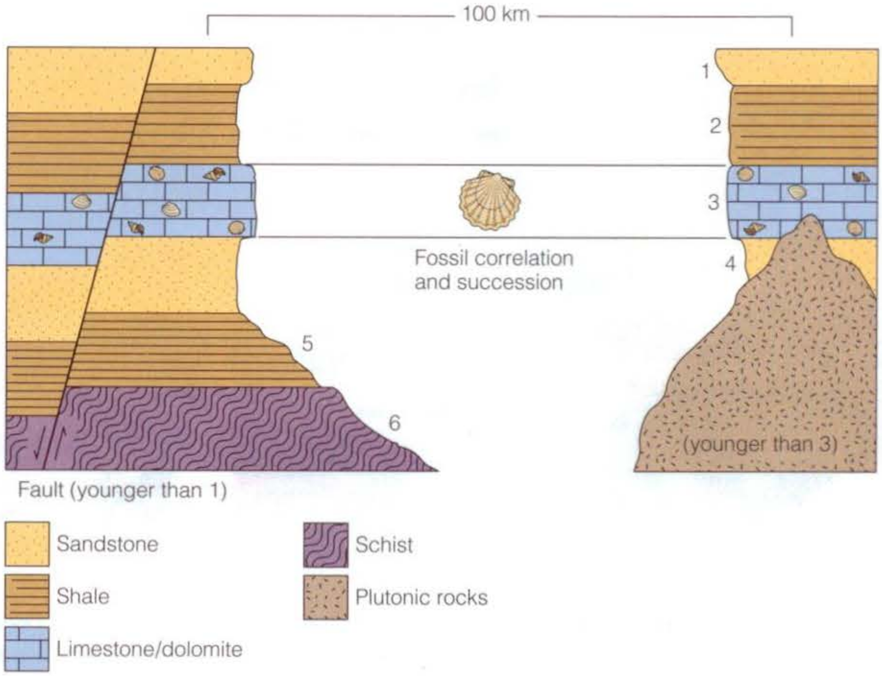
Geologic Time

Interest in extremely long periods of time sets geology and astronomy apart from other sciences. Geologists think in terms of billions of years for the age of the earth and its oldest rocks—numbers that, like the national debt, are not easily comprehended. Nevertheless, the time scales of geologic activity are important for environmental geologists because they provide a way to measure human impacts on the natural world. For example, we would like to know the rate of natural soil from solid rock to determine whether topsoil erosion from agriculture is too great or not. Likewise, understanding how climate has changed over millions of years is vital to properly assess current global warming trends. Clues to past environmental change are well-preserved in many different kinds of rocks.

Geologists evaluate the age of rocks and geologic events using two different approaches. **Relative age dating** is the technique of determining *a sequence of geological events,* based upon the structural relations of rocks. **Absolute age dating** provides the *actual ages* for rocks in years before the present. Relative age is determined by applying geologic laws based upon the structural relations of rocks. For instance, the Law of Superposition tells us that in a stack of undeformed sedimentary rocks, the stratum (layer) at the top is the youngest. The Law of Cross-cutting Relationships tells us that a fault is younger than the youngest rocks it displaces or cuts. Similarly, we know that a pluton is younger than the rocks it intrudes (◆Figure 2.24).

Using these laws, geologists arranged a great thickness of sedimentary rocks and their contained fossils representing an immense span of geologic time. The geologic age of a particular sequence of rock was then determined by applying the Law of Fossil Succession, the observed chronologic sequence of life-forms through geologic time. This allows fossiliferous rocks from two widely separated areas to be correlated by matching key fossils or groups of fossils found in the rocks of the two areas (Figure 2.24). Using such indicator fossils and radioactive dating methods, geologists have developed the geologic time scale to chronicle the documented events of earth history (◆Figure 2.25). Note that the scale is divided into units of time during which rocks were deposited, life evolved, and significant geologic events such as mountain building occurred. Eons are the longest time intervals, followed, respectively, by eras, periods, and epochs. The Phanerozoic ("revealed life") Eon began 570 million years ago with the Cambrian Period, the rocks of which contain the first extensive fossils of organisms with hard skeletons. Because of the significance of the Cambrian Period, the informal term *Precambrian* is widely used to denote the time before it, which extends back to the formation of the earth 4.6 billion years ago. Note that the Precambrian is



◆ FIGURE 2.24 Geologic cross sections illustrating the Laws of Superposition, Cross-cutting Relationships (intrusion and faulting), and Fossil Succession. The limestone beds are correlative because they contain the same fossils. The numerals indicate relative ages, with 1 being the youngest.

divided into the Archean and Proterozoic Eons, with the Archean Eon extending back to the formation of the oldest known in-place rocks about 3.9 billion years ago. Precambrian time accounts for 88 percent of geologic time, and the Phanerozoic for a mere 12 percent. The eras of geologic time correspond to the relative complexity of life forms: Paleozoic (oldest life), Mesozoic (middle life), and Cenozoic (most recent life). Environmental geologists are most interested in the events of the past few million years, a mere heartbeat in the history of the earth.

Absolute age-dating requires some kind of natural clock. The ticks of the clock may be the annual growth rings of trees or established rates of disintegration of radioactive elements to form other elements. At the turn of the twentieth century, American chemist and physicist Bertram Borden Boltwood (1870–1927) discovered that the ratio of lead to uranium in uranium-bearing rocks increases as the rocks' ages increase. He developed a process for determining the age of ancient geologic events that is unaffected by heat or pressure—**radiometric dating.** The "ticks" of the radioactive clocks are radioactive decay processes—spontaneous disintegrations of the nuclei of heavier elements such as uranium and thorium to lead. A radioactive element may decay to another element, or to an isotope of the same element. This decay occurs at a precise rate that can be determined experimentally. The most common emissions are alpha particles ($^4_2\alpha$), which are helium atoms, and beta particles (β^-), which are nuclear electrons. New *radiogenic* "daughter" elements or isotopes result from this **alpha decay** and **beta decay** (◆ Figure 2.26).

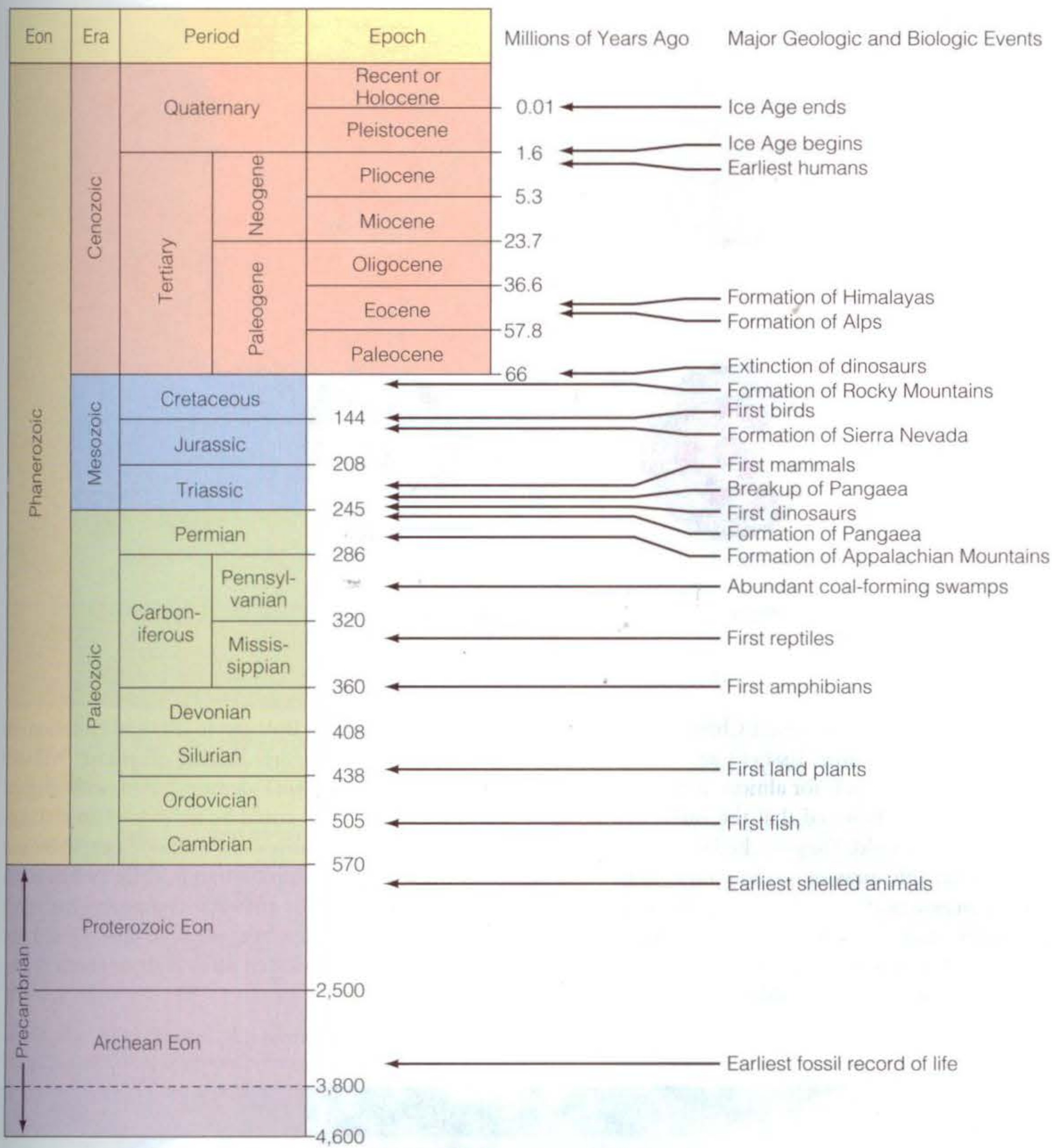
For example, of the three isotopes of carbon, ^{12}C, ^{13}C, and ^{14}C, only ^{14}C is radioactive, and this radioactivity can be used to date events between a few hundred and a few tens-of-thousands of years ago. Carbon-14 is formed continually in the upper atmosphere by neutron bombardment of nitrogen, and it exists in a fixed ratio to the common isotope, ^{12}C. All plants and animals contain radioactive ^{14}C in equilibrium with the atmospheric abundance until they die, at which time ^{14}C begins to decrease in abundance and, along with it, the object's radioactivity. Thus by measuring the radioactivity of an ancient parchment, log, or piece of charcoal and comparing the measurement with the activity of a modern standard, the age of archaeological materials and geological events can be determined (◆ Figure 2.27). Carbon-14 is formed by the collision of cosmic neutrons with ^{14}N in the atmosphere, and then it decays back to ^{14}N by emitting a nuclear electron (β^-).

$$^{14}_{7}N + \text{neutron} \rightarrow {}^{14}_{6}C + \text{proton}$$
$$^{14}_{6}C \rightarrow {}^{14}_{7}N + \beta^-$$

Both carbon—the radioactive "parent" element—and nitrogen—the radiogenic "daughter"—have 14 atomic mass units. However, one of ^{14}C's neutrons is converted to a proton by the emission of a beta particle, and the carbon changes (or *transmutes*) to nitrogen. This process proceeds at a set rate that can be expressed as a **half-life,** the time required for half of a population of radioactive atoms to decay. For ^{14}C this is about 5,730 years.

Radioactive elements decay exponentially; that is, in two half-lives one-fourth of the original number of atoms remain, in three half-lives one-eighth remain, and so on (◆ Figure 2.28). So few parent atoms remain after seven or eight half-lives (less than 1 percent) that experimental uncertainty creates limits for the various radiometric dating methods.

Whereas the practical age limit for dating carbon-bearing materials such as wood, paper, and cloth is about 40,000 to 50,000 years, ^{238}U disintegrates to ^{206}Pb and has a

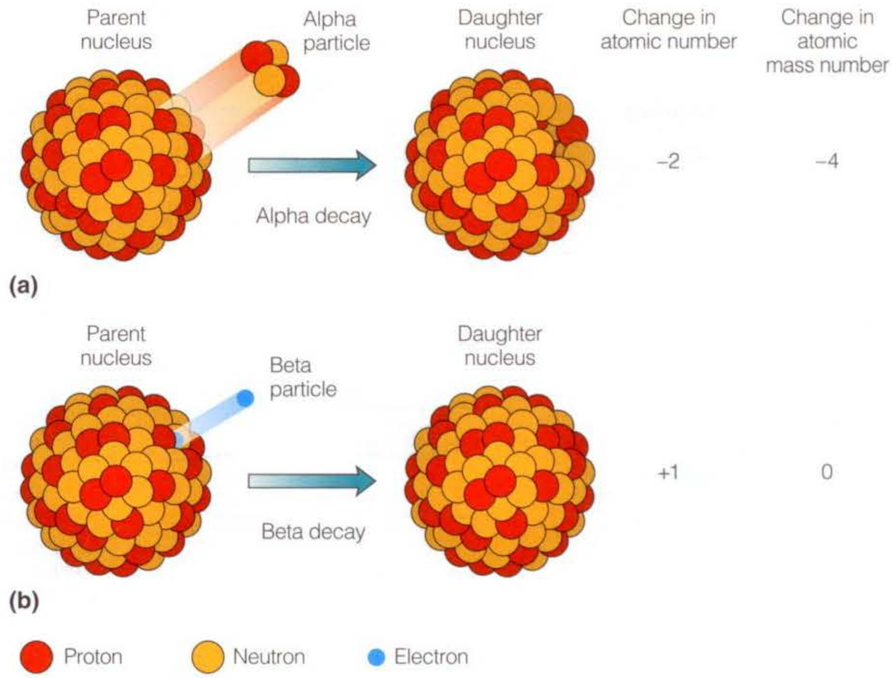


◆ FIGURE 2.25 Geologic time scale. Adapted from A. R. Palmer, Geology, 1983, 504.

half-life of 4.5×10^9 years. Uranium-238 emits alpha particles (helium atoms). Since both alpha and beta disintegrations can be measured with a Geiger counter, we have a means of determining the half-lives of a geological or archaeological sample. ✱ Table 2.6 shows radioactive parents, daughters, and half-lives commonly used in age-dating.

Age of the Earth

Before the advent of radiometric dating, determining the age of the earth was a source of controversy between established religious interpretations and early scientists. Archbishop Ussher (1585–1656), the Archbishop of Armagh and a professor at Trinity College in Dublin, declared that the earth was formed in the year 4004 B.C. Ussher provided not only the year but also the day, October 23, and the time, 9:00 A.M. Ussher has many detractors, but Stephen J. Gould of Harvard University, though not proposing acceptance of Ussher's date, was not one of them. Gould pointed out that Ussher's work was good scholarship for its time, because other religious scholars had extrapolated from Greek and Hebrew scriptures that the earth was formed in 5500 B.C. and 3761 B.C., respectively. Ussher based his age determination on the verse in the Bible that says "one day is with the Lord as a thousand years" (2 Peter 3:8). Because the Bible also says that God created heaven and earth in 6 days, Ussher arrived at 4004 years



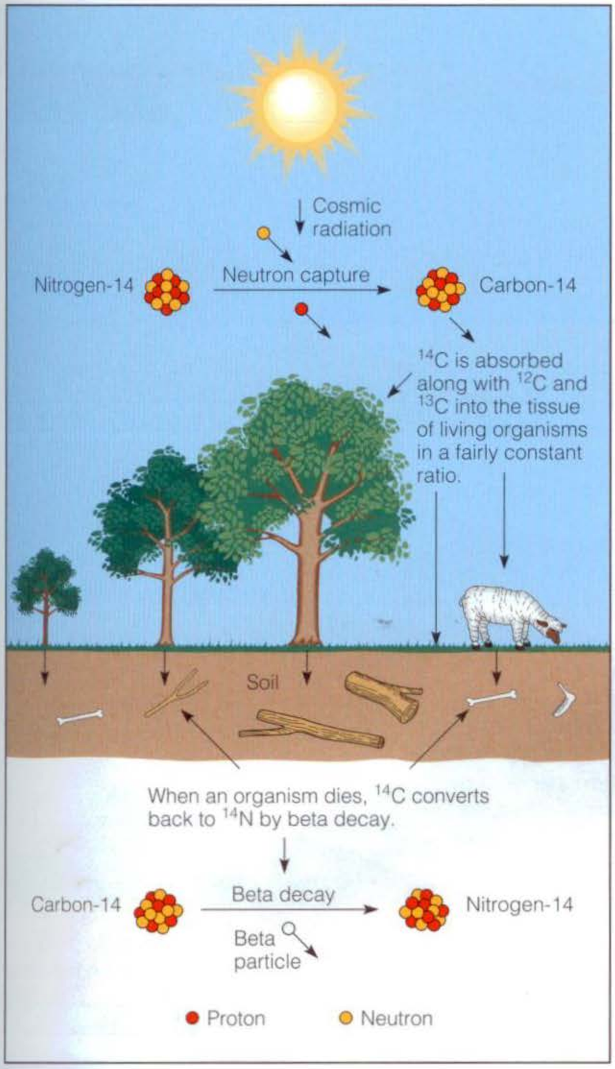
◆ FIGURE 2.26 (a) Alpha emission, whereby a heavy nucleus spontaneously emits a helium atom and is reduced 4 atomic mass units and 2 atomic numbers. (b) Emission of a nuclear electron (ß⁻ particle), which changes a neutron to a proton and thereby forms a new element without a change of mass.

B.C.—the extra four years because he believed Christ's birth year was wrong by that amount of time. Ussher's age for the earth was accepted by many as "gospel" for almost 200 years.

By the late 1800s geologists believed that the earth was on the order of 100 million years old. They reached their estimates by dividing the total thickness of sedimentary rocks (tens of kilometers) by an assumed annual rate of deposition (mm/year). Evolutionists such as Charles Darwin thought that geologic time must be almost limitless in order that minute changes in organisms could eventually produce the present diversity of species. Both geologists and evolutionists were embarrassed when the British physicist William Thomson (later Lord Kelvin) demonstrated with elegant mathematics how the earth could be no older than 400 million years, and maybe as young as 20 million years. Thomson based this on the rate of cooling of an initially molten earth and the assumption that the material composing the earth was incapable of creating new heat through time. He did not know about radioactivity, which adds heat to rocks in the crust and mantle.

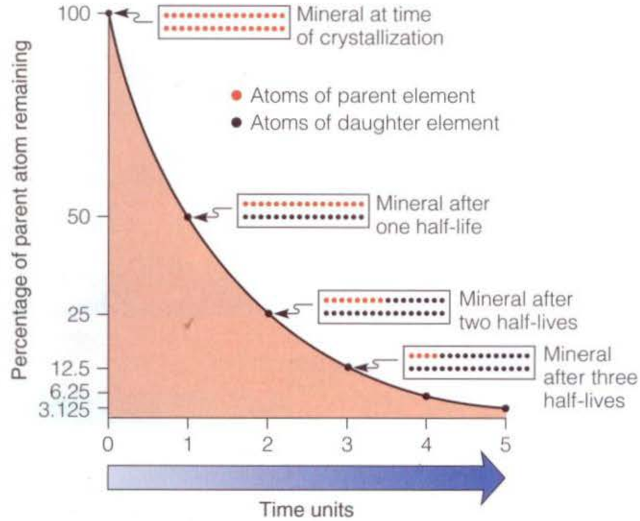
✱TABLE 2.6 Isotopes Used in Age-Dating

Isotopes: *Parent*	Isotopes: *Daughter*	Parent's Half-Life, Years	Effective Dating Range, Years	Material That Can Be Dated
Uranium-238	Lead-206	4.5 billion	10 million to 4.6 billion	Zircon Uraninite
Uranium-235	Lead-207	704 million		
Thorium-232	Lead-208	14 billion		
Rubidium-87	Strontium-87	48.8 billion	10 million to 4.6 billion	Muscovite Biotite Orthoclase Whole metamorphic or igneous rock
Potassium-40	Argon-40	1.3 billion	100,000 to 4.6 billion	Glauconite Muscovite Biotite Hornblende Whole volcanic rock
Carbon-14	Nitrogen-14	5,730 years	less than 100,000	Shell, bones, charcoal



◆ FIGURE 2.27 Carbon-14 is formed from nitrogen-14 by neutron capture and subsequent proton emission. Carbon-14 decays back to nitrogen-14 by emission of a nuclear electron (β^-).

Bertram Boltwood postulated that older uranium-bearing minerals should carry a higher proportion of lead than younger samples. He analyzed a number of specimens of known relative age, and the absolute ages he came up with ranged from 410 million to 2.2 billion years old. These ages put Lord Kelvin's dates based on cooling rates to rest and ushered in the new radiometric dating technique. By extrapolating backward to the time when no radiogenic lead had been produced on earth, we arrive at an age of 4.6 billion years for the earth. This corresponds to the dates obtained from meteorites and lunar rocks, which are part of our solar system. The oldest known intact terrestrial rocks are found in the Acasta Gneiss of the Slave geological province of Canada's Northwest Territories. Analyses of lead to uranium ratios on the gneiss's zircon minerals indicate that the rocks are 3.96 billion years old. However, older detrital zircons on the order of 4.0–4.3 billion years old have been found in



◆ FIGURE 2.28 Decay of a radioactive parent element with time. Each time unit is one half-life. Note that after two half-lives one-fourth of the parent element remains, and that after three half-lives one-eighth remains.

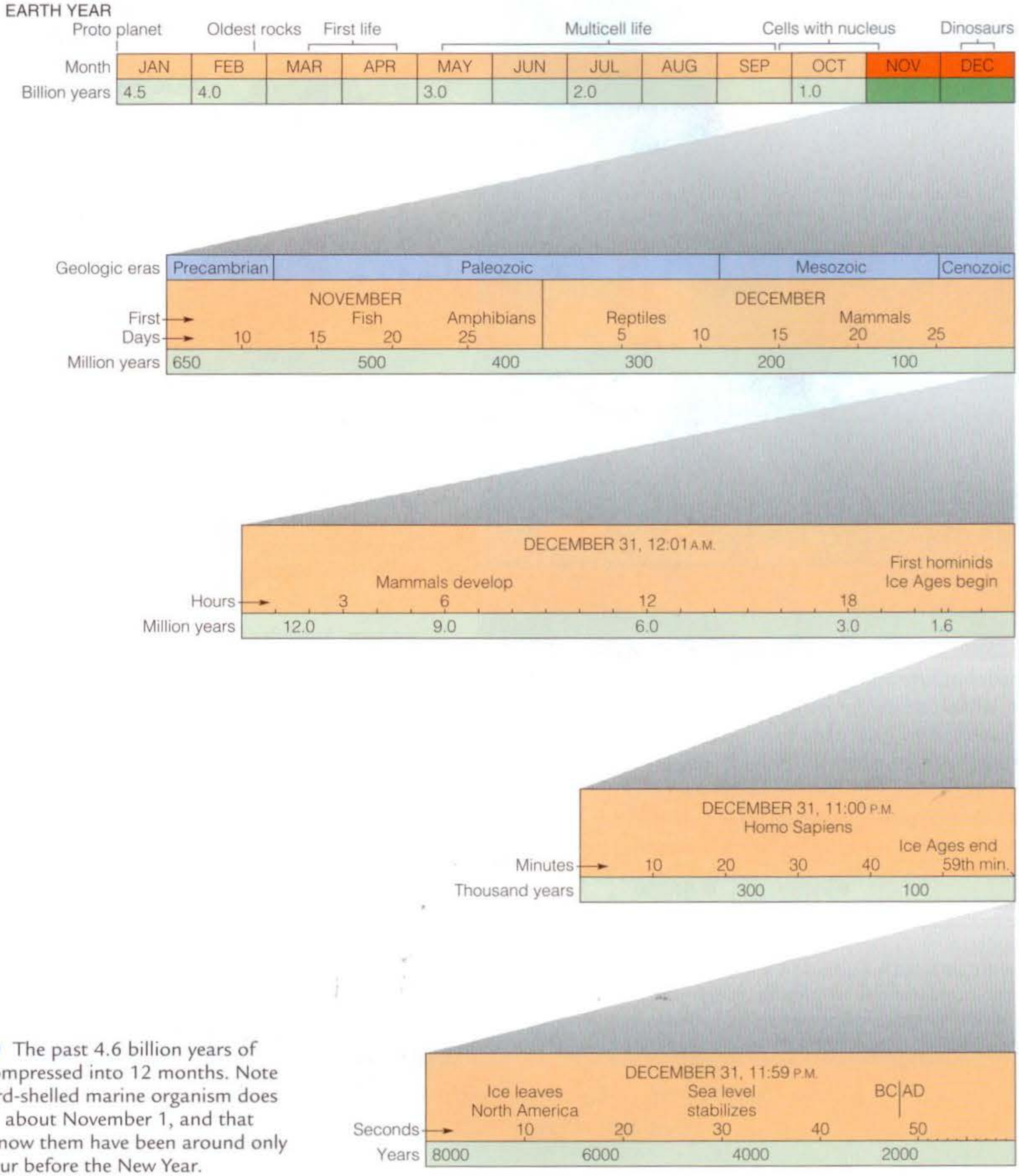
western Australia, indicating that some stable continental crust was present as early as 4.3 billion years ago (✱ Table 2.7). Suffice it to say that the earth is very old and that there has been abundant time to produce the features we see today (◆Figure 2.29).

Environmental geology deals mostly with the present and the recent past—the time interval known as the *Holocene Epoch* (10,000 years ago to the present) of the *Quaternary Period.* However, because the Great Ice Age advances of the Pleistocene Epoch of the Quaternary Period (which preceded our own Holocene Epoch) had such a tremendous impact on the landscape of today, we will investigate the probable causes of the "ice ages" in order to speculate a bit about what the future might bring. In addition, Pleistocene glacial deposits are valuable sources of underground water, and they have economic value as sources of building materials. We will see that "ice ages" have occurred several times throughout geologic history (see Chapter 11).

What is most impressive about geologic time is how short the period of human life on earth has been. If we could

✱TABLE 2.7 Earth's Oldest Known Materials

Material	Location	Age, Billions of Years
Crust	Zircon minerals in rocks of western Australia	4.0–4.3
Rock	Zircon minerals in the Acasta Gneiss, N.W. Terr., Canada	3.96
Sedimentary rock	Isua Greenstone Belt, Greenland	3.7–3.75
Fossils	Algae and bacteria	3.5



◆ FIGURE 2.29 The past 4.6 billion years of geologic time compressed into 12 months. Note that the first hard-shelled marine organism does not appear until about November 1, and that humans as we know them have been around only since the last hour before the New Year.

compress the 4.6 billion years since the earth formed into one calendar year, *Homo sapiens* would appear about 30 minutes before midnight on December 31 (see Figure 2.29). The last ice-age glaciers would begin wasting away a bit more than 2 minutes before midnight, and written history would exist for only the last 30 seconds of the year. Perhaps we should keep this calendar in mind when we hear that the dinosaurs were an unsuccessful group of reptiles. After all, they endured 50 times longer than hominids have existed on the planet to date. At the present rate of population growth, there is some doubt that humankind as we know it will be able to survive anywhere near that long.

The earth we see today is the product of earth processes acting on earth materials over the immensity of geologic time. The response of the materials to the processes has been the formation of mountain ranges, plateaus, and the multitude of other physical features found on the planet. Perhaps the greatest of these processes has been the formation and movement of platelike segments of the earth's surface, which influence the distribution of earthquakes and volcanic eruptions, global geography, mineral deposits, mountain ranges, and even climate. These *plate tectonic* processes are the subject of the next chapter.