## Steno's three principles concern sedimentary rocks

Because they form at Earth's surface, sedimentary rocks provide most of our information about the history of life and environments on Earth. It is therefore important that we understand their distribution and their age relationships. The study of stratified rocks and their relationships in time and space is known as **stratigraphy**.

In the seventeenth century, Nicolaus Steno, a Danish physician who lived in Florence, Italy, formulated three sensible axioms for interpreting stratified rocks. Steno's first principle, the principle of **superposition**, states that in an undisturbed sequence of strata, the oldest strata lie at the bottom and successively higher strata are progressively younger (Figure 1-8A). In other words, in an uninterrupted sequence of strata, each bed is younger than the one below it and older than the one above it. This is a simple consequence of the law of gravity, of course, as is Steno's second principle, the principle of original horizontality.

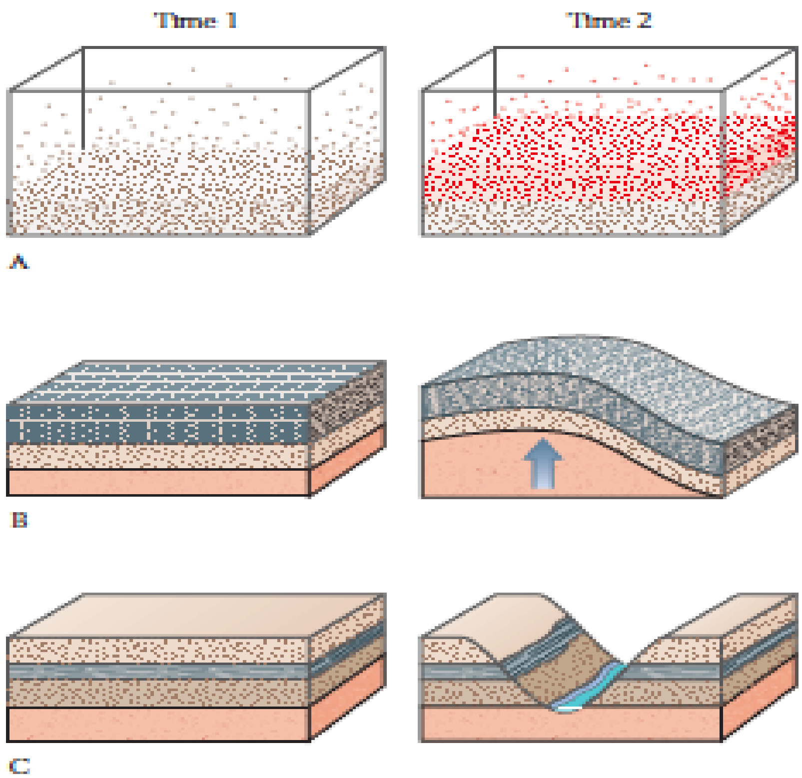


FIGURE 1–8 **Steno's three principles.** A. The principle of superposition: at time 2, sediment builds up on top of other sediment that was deposited earlier, at time 1. B. The principle of original horizontality: by time 2, strata that were horizontal at time 1, shortly after being deposited, have been uplifted and tilted. C. The principle of original continuity: by time 2, strata that were continuous at time 1 have been divided into two bodies of strata by a river that has cut through them.

The principle of **original horizontality** states that all strata are horizontal when they form. As it turns out, this principle requires some modification. We now recognize that some sediments, such as those of a sand dune, accumulate on sloping surfaces, forming strata that lie parallel to the surface on which they were deposited. Sediments seldom accumulate at an angle greater than 45° to the horizontal, however, because they slide down slopes that are steeper than that. Therefore, a reasonable restatement of Steno's second principle would be that almost all strata are initially more nearly horizontal than vertical. Thus we can conclude that any strongly sloping or folded stratum was tilted by external forces after it formed (Figure 1-8B).

Steno invoked his third principle, the principle of **original lateral continuity**, to explain the occurrence on opposite sides of a valley (or some other intervening feature of the landscape) of similar rocks that seem once to have been connected. Steno was, in effect, pointing out that strata are originally unbroken flat expanses, thinning laterally to a thickness of zero or abutting the walls of the natural basin in which they formed. The original continuity of a stratum can be broken by erosion, as when a river cuts downward to form a valley (Figure 1-8C).

## The geologic time scale divides Earth's history into formal units

During the nineteenth century, long before the discovery of radioactivity, it became apparent that very old sedimentary rocks contained no identifiable fossils. Beginning with these rocks and examining progressively younger rocks in any region, early geologists discovered that fossils became abundant at a certain level. This level became the boundary at which all of geologic time was divided into two major intervals (Figure 1-11). The oldest rocks with conspicuous fossils were designated as Cambrian in age, and still older rocks became known as Precambrian rocks. Today the Precambrian designation is still used informally, but the Precambrian interval is formally divided into three eons. The Hadean Eon is the earliest formal interval of Earth's history. It extends from the origin of the planet about 4.54 billion years ago until 4.0 billion years ago, the approximate age of the oldest bodies of rock still preserved on Earth's continents. The Precambrian interval represented by rocks that we have available to study is divided into the Archean Eon and the Proterozoic Eon, with the boundary between these two placed at 2.5 billion years ago. Subsequent geologic time, from Cambrian on, constitutes the Phanerozoic Eon, meaning the "interval of well-displayed life." An **eon** is the largest formal unit of geologic time.

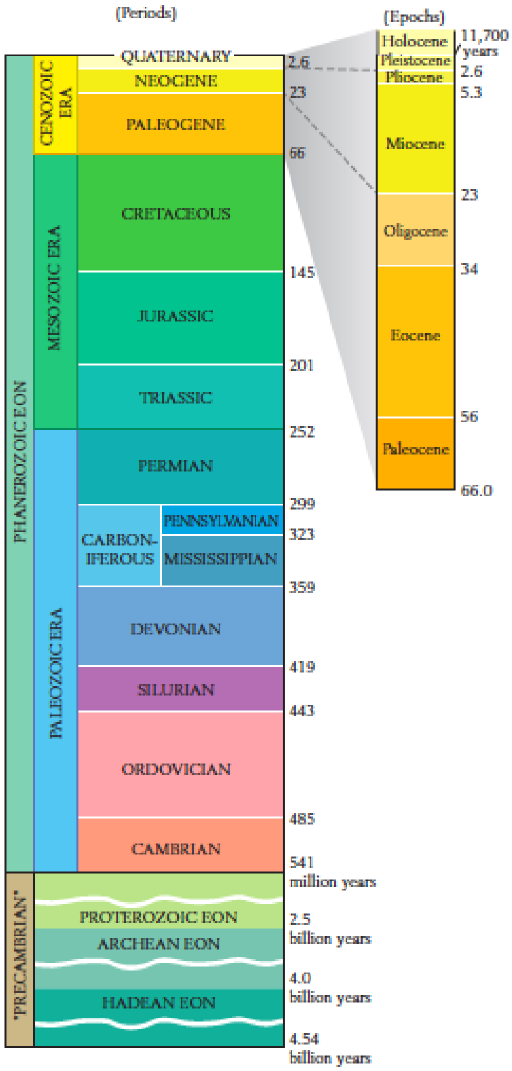


**FIGURE 1-11** **The geologic time scale.** The numbers on the right represent the ages of the boundaries between periods and epochs in millions of years. The Holocene Epoch (the past 11,700 years or so) is also known as the Recent. Breaks across the "Precambrian" eons indicate compression of the time scale. Dates are from the International Commission on Stratigraphy (January 2013).

Phanerozoic time is divided into three primary intervals, or **eras**, which the history of life on Earth serves to define. The earliest is the "interval of old life," or the Paleozoic Era. This era is followed by the "interval of middle life," or the Mesozoic Era, which is commonly called the Age of Dinosaurs, and by the "interval of modern life," or the Cenozoic Era, which is informally designated as the Age of Mammals. Figure 1-11 depicts these eras and the intervals within them, known as geologic **periods**. Periods are further divided into **epochs**. Figure 1-11 lists epochs for the Cenozoic Era.

Figure 1-11 also indicates when each period began and ended, as determined by radiometric dating of rocks whose ages approximate the period boundaries. Note that the Phanerozoic interval began about 541 million years ago. A human lifetime is so short in comparison that geologic time seems too vast for us to comprehend; experience does not permit us to extrapolate from the time scale familiar to us, measured in seconds, minutes, hours, days, and years, to a scale suitable for geologic time. Geologists therefore use a separate scale when they think about geologic time—one in which the units are millions of years. If the Phanerozoic interval of time were compressed into a year, we would find animals with backbones crawling up onto land for the first time in mid-April, dinosaurs inheriting Earth in early July but then suddenly dying out in late October, and modern humans appearing about 12 minutes before midnight on New Year's Eve.

Radiometric dating of rocks reveals that some rocks and minerals on Earth are more than 4.0 billion years old. Many major geologic events span millions of years, but on the scale of geologic time, they are only brief episodes. We now know, for example, that the Himalaya, the tallest mountain range on Earth, formed largely within the past 15 million years or so, but this interval of time represents less than one-third of 1 percent of Earth's history. Destructive processes have also yielded enormous changes within a tiny fraction of Earth's lifetime. Mountains that were the precursors of the Rockies in western North America were leveled just a few million years after they formed, and much of the Grand Canyon of Arizona was cut by erosion within just the past 2 million or 3 million years. We will examine these events in greater detail in later chapters.

### Intervals of the geologic time scale are distinctive

In the nineteenth century, when the geologic periods were first distinguished as discrete intervals of geologic time, geologists did not know even approximately how long ago each period had begun or ended. Each period was defined simply as the undetermined interval of time represented by a body of rock called a **geologic system**. The Cambrian Period, for example, was the interval of time corresponding to those rocks designated as the Cambrian System. (A geologic system is not to be confused with the Earth system, which encompasses all aspects of our dynamic planet.)

Although some geologic systems were formally recognized after others that represented earlier intervals of geologic time, the total body of rock assigned to each system was not chosen arbitrarily. Two criteria were most important in these decisions. One was the occurrence of unique groups of fossils. Most systems contain many fossils that differ considerably from the fossils found below and above them. Major extinctions have caused the most striking contrasts between systems, but newly evolved groups of organisms also characterize particular systems.

Another feature that led early geologists to recognize some bodies of rock as systems was the nature of the rocks themselves. Most of the distinctive lithological features of geologic systems have some relation to the history of life. The Cretaceous System, for example, was designated to include the thickest deposits of chalk in the world. Chalk is soft, fine-grained limestone. The abundance of chalk in the Cretaceous System reflects the fact that during the Cretaceous Period there was a great proliferation of the kinds of organisms whose skeletons produce the particles of calcium carbonate that form chalk: small, single-celled organisms whose descendants float in the sea today, but in reduced abundance.

No early scientist had the means to study the entire sequence of rocks on Earth, from the most ancient to the most modern; a single person could study only those promising rock sequences that were accessible. Thus the Cretaceous System was formally designated in 1822, whereas the much older Cambrian and Silurian systems did not gain formal recognition until 1835. Eventually, all the Phanerozoic rocks of Europe were included. It seems remarkable today that all the geologic systems of the Phanerozoic Eon were first designated during a brief interval of the nineteenth century in one small region of the world: Great Britain and nearby areas of western Europe.

Origin of life and early life

## Amino acids formed easily

In 1953 Stanley Miller and Harold Urey reported on a simple laboratory experiment in which they produced nearly all of the amino acids found in proteins. The experiment was designed to mimic the conditions under which life arose on Earth. In a closed vessel, above a pool of boiling water, the researchers created a primitive "atmosphere" of hydrogen, water vapor, methane ($CH_4$), and ammonia ($NH_3$) (Figure 11-25). To trigger chemical reactions, as lightning might have done on early Earth, they caused a spark to discharge continuously through the atmosphere in the vessel. A series of chemical reactions soon formed numerous amino acids.

As we will see shortly, Miller and Urey turned out to be mistaken in assuming that Earth's early atmosphere contained no free oxygen. Nonetheless, their experiment showed that amino acids can readily form from simple compounds. Amino acids have obviously formed on other bodies of the solar system as well. The carbonaceous Murchison meteorite, which fell in Australia in 1969, was found to contain the same amino acids in the same relative proportions as those produced by Miller and Urey's experiment. This discovery showed that some amino acids incorporated into pro-

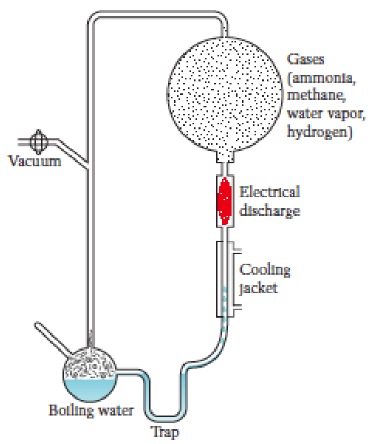


**FIGURE 11-25 The laboratory apparatus in which Miller and Urey produced amino acids.** They circulated an "atmosphere" of ammonia ($NH_3$), methane ($CH_4$), water vapor ($H_2O$), and hydrogen past an electrical discharge. Amino acids accumulated in the trap. (After G. Wald, *The Origins of Life*. © 1954 by Scientific American. All rights reserved.)

teins on Earth could have been delivered from outer space by meteorites and comets.

## Fossils and physical markers indicate the relative ages of rocks

Remnants of ancient life, called **fossils**, are useful for comparing the ages of bodies of sedimentary rock throughout the world. The term *fossil* is usually restricted to tangible remains or signs of ancient organisms that died thousands or millions of years ago. Because few fossils can survive the high temperatures at which igneous and metamorphic rocks form, almost all fossils are found in sediments and sedimentary rocks. Fossils range in size from cells of tiny bacteria to massive dinosaur bones. They include such things as shells of invertebrate animals and teeth and bones of vertebrate animals, as well as leaves of plants and impressions of soft-bodied animals.

Fossils provide one valuable means of establishing the relative ages of rocks that lie far apart. William "Strata" Smith, a British surveyor, noted late in the eighteenth century that fossils are not randomly distributed in rocks. When Smith studied large areas of England and Wales, he found that fossils in sedimentary rocks throughout those areas occurred in a particular vertical order ("vertical" in terms of the succession of one layer above another). To the surprise of less experienced observers, Smith could predict the vertical ordering of fossils in areas he had never visited. We now recognize that this ordering, known as **fossil succession**, reflects organic evolution and extinction—the natural appearance and disappearance of species through time. Figure 1-10 illustrates fossil

In the course of geologic time, many of the organisms that have inhabited Earth have left a partial record in rock of their presence and their activities. This record reveals that life has changed dramatically since it first arose. At times of sudden environmental change, many forms of life have died out. After each such crisis, evolution has produced many new forms of life. This chapter introduces the major groups of organisms that have evolved on Earth, some extinct and others still alive.

It is not easy to define life precisely, but two attributes that are generally regarded as essential to life are the capacity for self-replication and the capacity for self-regulation (criteria that viruses do not meet). On Earth today, all entities that are self-replicating and self-regulating are also cellular: they consist of one or more discrete units called cells. A living **cell** is a membrane-bounded module with a variety of distinct features, including structures in which certain chemical reactions take place. The chemical "blueprint" for a cell's operation is encoded in the chemical structure of its genes. Essential to this blueprint is the cell's built-in ability to duplicate its genes so that a replica of the blueprint can be passed on to another cell or to an entirely new organism. The fossil record reveals that life existed 3.8 billion years ago, and it may have originated hundreds of millions of years earlier.

## Fossils and Chemical Remains of Ancient Life

Most of our knowledge about the life of past intervals of geologic time is derived from **fossils**, the tangible remains or signs of ancient organisms that died thousands or millions of years ago. Few fossils consist of materials that can survive the high temperatures at which igneous and metamorphic rocks form. Consequently, almost all fossils are found in sediments or sedimentary rocks. Fossils are especially abundant in sedimentary rocks that were formed in the ocean, where animals with skeletons abound.

### Hard parts are the most commonly preserved features of animals

The most readily preserved features of animals are "hard parts": teeth and bones of vertebrate animals and comparable solid, mineralized skeletal structures of invertebrate animals. Many groups of invertebrates lack skeletons and have therefore left poor fossil records, or none at all. Some, however, have internal skeletons embedded in soft tissue; among them are some relatives of sea stars, called crinoids (Figure 3-1A). External skeletons protect other invertebrates, among them bivalve and gastropod mollusks, whose tissues are housed inside skeletons popularly known as seashells. Hard parts are often preserved with only a modest amount of chemical alteration, but at times they are completely replaced by minerals that are unrelated to the original skeletal material (Figure 3-1B).

### Soft parts of animals are rarely preserved

Fleshy parts of animals, or "soft parts," are occasionally found in the fossil record, but only in an altered state and only in sediments that date back a few millions or tens of millions of years. In older rocks, nothing but chemical residues of organisms remain.

One deposit that is famous for preservation of soft parts is the Messel Shale of Germany, which is about 47 million years old. In organic-rich portions of these sediments, which are nearly impermeable to air and water because they are rich in oily plant debris, an array of

A B

**FIGURE 3-1 Fossil crinoids of Paleozoic age.** A. In life, each of these animals was attached to the seafloor by a flexible stalk. B. The calcium carbonate skeleton of this specimen has been altered chemically to pyrite, a mineral that consists of iron sulfide and is known as "fool's gold." The stalks of these animals are several millimeters in diameter. (A and B, © 2013 National Museum of Natural History, Smithsonian Institution.)

A B

**FIGURE 3-2 Remarkable preservation of soft parts.** A. This Eocene mammal, *Darwinius masillae*, is one of the most complete ancient primate fossils known from the fossil record. It became buried at the bottom of a lake, preserving a nearly intact skeleton, along with outlines of skin and fur and even the preserved contents of the animal's stomach. This fossil, from the Messel Shale in Germany, is about 47 million years old and is 58 centimeters (24 inches) long. B. Preserved skin of a Sauropod dinosaur embryo discovered at a dinosaur nesting site in Argentina. The width of the photo is about 8.8 millimeters (1/3 inch.) (A, Mike Segar/Reuters/Corbis; B, epa/Corbis.)

delicately preserved fossils can be found that include plants, mammals, birds, fish, and insects, some of which retain parts of their original color. Some animals are preserved here with their last meals remaining only partly decomposed in their stomachs, and some have fur still intact (Figure 3-2A). In other, older rocks, impressions of skin and other soft tissues of dinosaurs have also been found (Figure 3-2B). Protection from oxygen is the secret for fossilization of soft tissue: it is most likely to be preserved when organisms are buried in fine-grained, relatively impermeable sediment, especially if oily, water-repellent organic matter is also present.

Some sedimentary deposits that contain exceptionally well-preserved fossils, often with delicate soft parts preserved, are known as *lagerstätten* (plural of *lagerstätte*, which means "resting place" in German). These deposits form under a variety of unusual conditions, but require either low oxygen, rapid burial, or both. Dozens of famous lagerstätten have been found, including the Burgess Shale, the Ediacara Hills, the Green River Formation, and the La Brea Tar Pits. Despite their rare occurrence in the geologic record, lagerstätten provide us with a critical understanding of many important fossils.

### Permineralization produces petrified wood

Terrestrial plants do not generally have mineralized skeletal structures, but the cellulose walls of their cells are so rigid that woody tissue, and even leaves, are much more commonly preserved in the fossil record than is the flesh of animals. After plants are buried in sediment, the spaces left inside the cell walls of woody tissue may be filled with inorganic materials—most commonly chert (finely crystalline quartz). This process, known as **permineralization**, produces what is informally called petrified wood, and it also fills the pores in bones with minerals.

### Molds and impressions are imprints

Sometimes solutions percolating through rock or sediment dissolve fossil skeletons, leaving a space within the rock that is a three-dimensional negative imprint of the organic structure, called a **mold** (Figure 3-3). If it has not been filled secondarily with minerals, a paleontologist can fill the mold with wax, clay, or liquid rubber to produce a replica of the original object.

Fossils called **impressions** might be viewed as squashed molds. Impressions usually preserve, in flattened form,

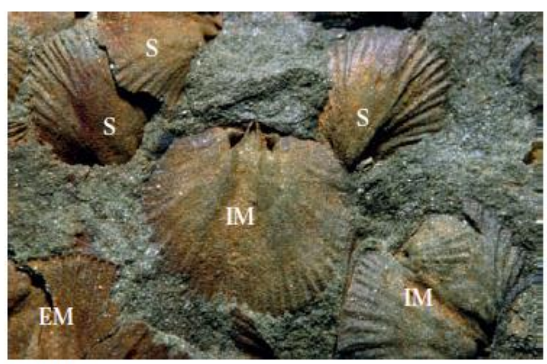


**FIGURE 3-3 Preservation of brachiopods.** The two shell halves of brachiopods meet along a hinge. This Paleozoic rock surface contains fossil brachiopod shells (S) as well as molds of the interiors (IM) and exteriors (EM) of other shells of the same species. The largest of these speciments is about 3 centimeters (1.2 inches) across. (Sinclair Stammers/Science Source.)

FIGURE 3-4 **Carbonized fossil leaf impression from the Jurassic Period.** This leaf, which is about 5 centimeters (2 inches) wide, belongs to the group of plants known as cycads. (Martin Land/Science Photo Library/Science Source.)

the outlines and some of the surface features of soft or semihard organisms such as insects or leaves (Figure 3-4). A residue of carbon remains on the surface of some impressions after other compounds have been lost through the escape of liquids and gases. This process of carbon concentration is known as **carbonization**.

### Trace fossils are records of movement

Tracks, trails, burrows, temporary resting marks, and other structures left by animal activity are known as **trace fossils**. Trace fossils can reveal aspects of the behavior of extinct animals, even though the animal that made a particular trace cannot always be identified. Trackways of dinosaurs, for example (Figure 3-5A), show that these animals were very active. Unlike modern reptiles, they customarily moved about at a fast pace. Farther back in the geologic record, preserved tracks and burrows reveal how the earliest animals colonized the floors of ancient seas at a time when very few kinds of animals left fossils that revealed the shapes of their bodies. Once burrowers were well established, however, they were able to obliterate traces of bedding in many marine sediments (see Figure 2-27). Many burrows become filled with sediment that differs enough from the surrounding sediment that they stand out on bedding planes or weathered rock surfaces (Figure 3-5B).

### The quality of the fossil record is highly variable

Although fossils are common in many sedimentary rocks, many kinds of animals and plants that have existed in Earth's history have never been discovered as fossils. Rare species and those that lack skeletons are especially unlikely to be found in fossilized form. Even most forms with skeletons have left no permanent fossil record. Several processes destroy skeletons. Animals that scavenge carcasses, for example, may splinter bones in the process. Many bones, teeth, and shells are abraded beyond recognition when they are transported by moving water before finally becoming buried. Even after burial, many fossils fail to survive metamorphism or erosion of the sedimentary rocks in which they are embedded. Finally, many kinds of fossils remain entombed in rocks that have never been exposed at Earth's surface or sampled by drilling operations.

### Biomarkers are useful chemical indicators of life

A dead organism that decays within sediment may leave a chemical residue behind. Some residues of this kind, known as **biomarkers**, provide key information about the presence of ancient life. Certain biomarkers show, for example, that organisms more complex than bacteria existed more than 1.7 billion years ago.

### Dead organisms decay to form fossil fuels

Organisms usually lose their identity in contributing to *fossil fuels*. Coal is formed by alteration of plant debris that accumulates in water as peat (see Figure 2-24). Petroleum

A B

FIGURE 3-5 **Two kinds of trace fossils.** A. Dinosaur tracks in Spain that have been artificially darkened for clarity. One or more dinosaurs formed these tracks by walking across wet mud that later hardened into rock. B. Finger-sized burrows in the Bright Angel Shale from the Grand Canyon that were formed by worm-shaped organisms in a marine setting. (A, age footstock/Superstock; B, NPS/Alamy.)