Sedimentary rocks, stratigraphy, and GST

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.

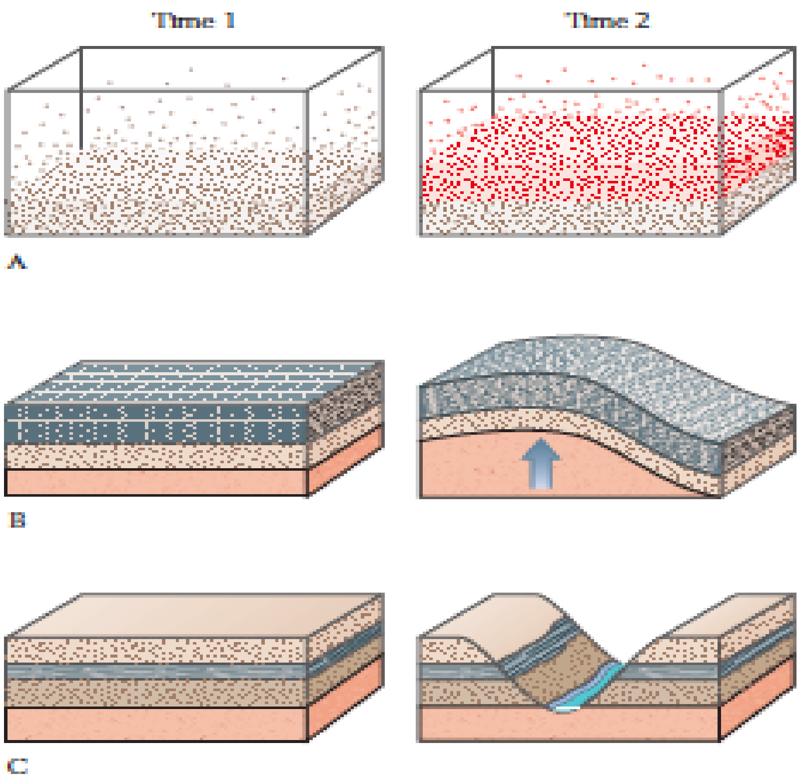

FIGURE 1-8 Steno's three principles. A. The principle of superposition: at time 2, sediment builds up on top of other sediment that was deposited earlier, at time 1. B. The principle of original horizontality: by time 2, strata that were horizontal at time 1, shortly after being deposited, have been 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.

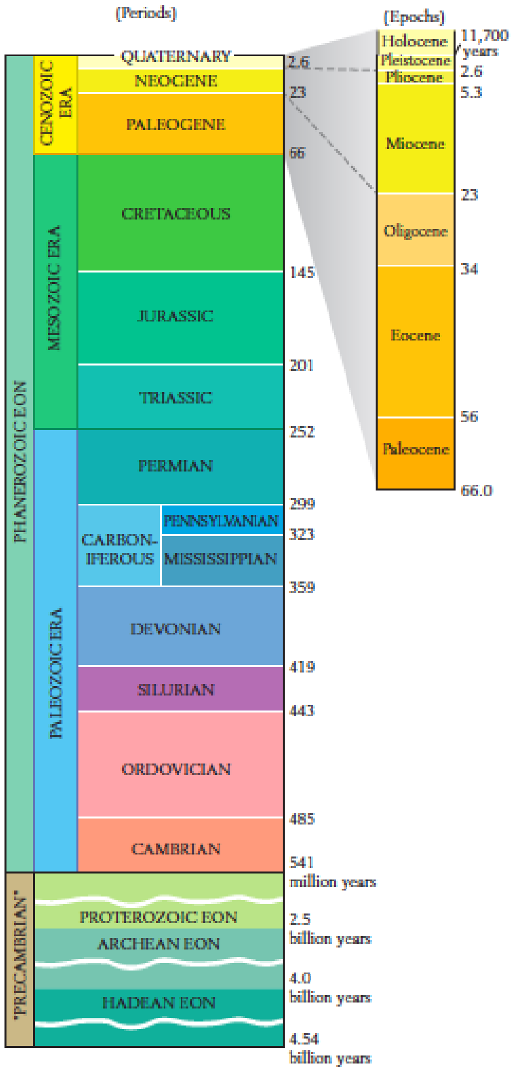

FIGURE 1-11 **The geologic time scale.** The numbers on the right represent the ages of the boundaries between periods and epochs in millions of years. The Holocene Epoch (the past 11,700 years or so) is also known as the Recent. Breaks across the "Precambrian" eons indicate compression of the time scale.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

Sedimentary Rocks

Sediments, the precursors of sedimentary rocks, are found at Earth's surface as layers of loose particles, such as sand, silt, and the shells of organisms. These particles originate in the processes of weathering and erosion. **Weathering** refers to all of the chemical and physical processes that break up and decay rocks into fragments and dissolved substances of various sizes. These particles are then transported by **erosion,** the set of processes that loosen soil and rock and move them downhill or downstream to the spot where they are deposited as layers of sediment (**Figure 3.26**).

Sediments are deposited in two ways:

- **Siliciclastic sediments** are made up of physically deposited particles, such as grains of quartz and feldspar derived from weathered granite. (*Clastic* is derived from the Greek word *klastos,* meaning "broken.") These sediments are laid down by running water, wind, and ice.
- **Chemical sediments** and **biological sediments** are new chemical substances that form by precipitation. Weathering dissolves some of a rock's components, which are carried in stream waters to the ocean. Halite is a chemical sediment that precipitates directly from evaporating seawater. Calcite is precipitated by marine organisms to form shells or skeletons, which form biological sediments when the organisms die.

FROM SEDIMENT TO SOLID ROCK **Lithification** is the process that converts sediments into solid rock. It occurs in two ways:

- In *compaction,* particles are squeezed together by the weight of overlying sediments into a mass denser than the original.
- In *cementation,* minerals precipitate around deposited particles and bind them together.

Sediments are compacted and cemented after they are buried under additional layers of sediments. Sandstone forms by the lithification of sand particles, and limestone forms by the lithification of shells and other particles of calcite.

LAYERS OF SEDIMENT Sediments and sedimentary rocks are characterized by **bedding,** the formation of parallel layers of sediment as particles are deposited. Because

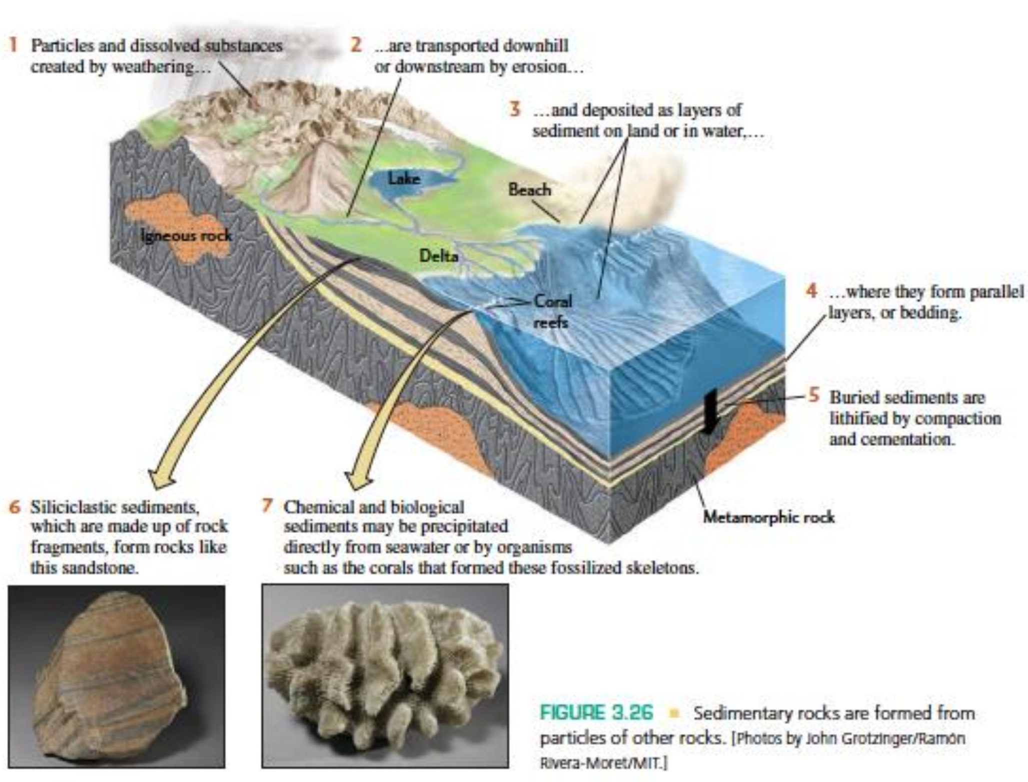

FIGURE 3.26 ■ Sedimentary rocks are formed from particles of other rocks. [Photos by John Grotzinger/Ramón Rivera-Moret/MIT.]

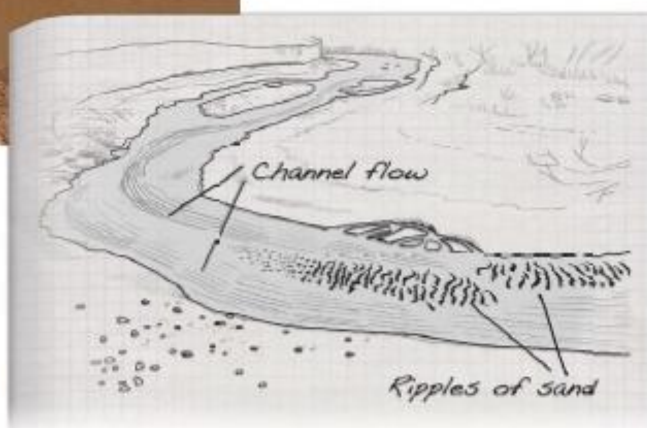

FIGURE 5.5 ▪ Sediments are easily transported by flowing water. In this photo, small ripples of sand in the channel are evidence of sediment transportation. [John Grotzinger.]

Because all clastic particles have roughly the same density, we use particle size as the best indicator of how quickly a particle will settle. (We will take a more specific look at particle size categories later in this chapter.) In water, large particles settle faster than small ones. This is also true in air, but the difference is much smaller.

Current strength, which is directly related to current velocity, determines the size of the particles deposited in a particular place. As a wind or water current begins to slow, it can no longer keep the largest particles suspended, and those particles settle. As the current slows even more, smaller particles settle. When the current stops completely, even the smallest particles settle. Currents segregate particles in the following ways:

- *Strong currents* (faster than 50 cm/s) carry gravel (which includes boulders, cobbles, and pebbles), along with an abundant supply of smaller particles. Such currents are common in swiftly flowing streams in mountainous terrain, where erosion is rapid. Beach gravels are deposited where ocean waves erode rocky shores.
- *Moderately strong currents* (20–50 cm/s) lay down sand beds. Currents of moderate strength are common in most rivers, which carry and deposit sand in their channels. Rapidly flowing floodwaters may spread sand over the width of a river valley. Waves and currents deposit sand on beaches and in the ocean. Winds also blow and deposit sand, especially in deserts. However, because air is much less dense than water, much higher current velocities are required for it to move sediments of the same size and density.
- *Weak currents* (slower than 20 cm/s) carry muds composed of the finest clastic particles (silt and clay). Weak currents are found on the floor of a river valley when floodwaters recede slowly or stop flowing entirely. In the ocean, muds are generally deposited some distance from shore, where currents are too slow to keep even fine particles in suspension. Much of the floor of the open ocean is covered with mud particles originally transported by surface waves and currents or by wind. These particles slowly settle to depths where currents and waves are stilled and, ultimately, all the way to the bottom of the ocean.

As you can see, currents may begin by carrying particles of widely varying sizes, which then become separated as the strength of the current changes. A strong, fast current may lay down a bed of gravel while keeping sand and mud in suspension. If the current weakens and slows, it will lay

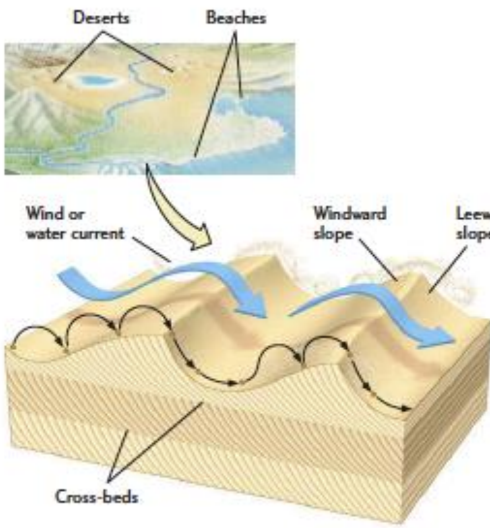

FIGURE 5.11 ■ Sediment particles transported down the steeper, downcurrent slope of a sand dune, sandbar, or ripple form cross-bedding.

particles. The grading indicates a weakening of the current that deposited the particles. A graded bed comprises one set of sediment particles, normally ranging from a few centimeters to several meters thick, that formed a horizontal or nearly horizontal layer at the time of deposition. Accumulations of many individual graded beds can reach a total thickness of hundreds of meters. A graded bed formed as a result of deposition by a turbidity current is called a *turbidite*.

Ripples

Ripples are very small ridges of sand or silt whose long dimension is at right angles to the current. They form low, narrow ridges, usually only a centimeter or two high, separated by wider troughs. These sedimentary structures are common in both modern sands and ancient sandstones (**Figure 5.12**). Ripples can be seen on the surfaces of windswept dunes, on underwater sandbars in shallow streams, and under the waves at beaches. Geologists can distinguish the symmetrical ripples made by waves moving back and forth on a beach from the asymmetrical ripples formed by currents moving in a single direction over river sandbars or windswept dunes (**Figure 5.13**).

Bioturbation Structures

In many sedimentary rocks, the bedding is broken or disrupted by roughly cylindrical tubes a few centimeters in diameter that extend vertically through several beds. These sedimentary structures are remnants of burrows and tunnels excavated by clams, worms, and other marine organisms that live on the ocean bottom. These organisms churn and burrow through muds and sands—a process called **bioturbation.** They ingest the sediment, digest the bits of organic matter it contains, and leave behind the reworked sediment, which fills the burrow (**Figure 5.14**). From bioturbation structures, geologists can determine the behavior of the organisms that burrowed in the sediment. Since the behavior of burrowing organisms is controlled partly by environmental factors, such as the strength of currents or the availability of nutrients, bioturbation structures can help us reconstruct past sedimentary environments.

(a)

(b)

FIGURE 5.12 ■ Ripples. (a) Ripples in modern sand on a beach [Courtesy of John Grotzinger.] (b) Ancient ripple-marked sandstone. [John Grotzinger/Ramón Rivera-Moret/MIT.]