such as clams, mussels, and shrimp gain nutrition from chemoautotrophic bacteria. When they were first discovered, hydrothermal vent communities excited scientists because they were novel and unexpected, and they showed just how much we still have to learn about the workings of our planet.

Geology: The Physical Basis for Environmental Science

A good way to understand how our planet functions is to examine the rocks, soil, and sediments beneath our feet. The physical processes that take place at and below Earth's surface shape the landscape and lay the foundation for most environmental systems and for life.

Understanding the physical nature of our planet also benefits our society, because without the study of Earth's rocks and the processes that shape them, we would have no metals for consumer products, no energy from fossil fuels, and no uranium for nuclear power plants. Our planet is dynamic, and this dynamism is what motivates **geology**, the study of Earth's physical features, processes, and history. A human lifetime is just a blink of an eye in the long course of geologic time, and the Earth we experience is merely a snapshot in our changing planet's long history. We can begin to grasp this long-term dynamism as we consider two processes of fundamental importance—plate tectonics and the rock cycle.

Earth consists of layers

Our planet consists of multiple layers (**FIGURE 2.12**). At Earth's center is a dense **core** consisting mostly of iron, solid in the inner core and molten in the outer core. Surrounding the core is a thick layer of less dense, elastic rock called the **mantle.** A portion of the upper mantle called the **asthenosphere** contains especially soft rock, melted in some areas. The harder rock above the asthenosphere is the **lithosphere.** The lithosphere includes both the uppermost mantle and the entirety of Earth's third major layer, the **crust,** the thin, brittle, low-density layer of rock that covers Earth's surface. The intense heat in the inner Earth rises from core to mantle to crust, and it eventually dissipates at the surface.

The heat from the inner layers of Earth also drives convection currents that flow in loops in the mantle, pushing the mantle's soft rock cyclically upward (as it warms) and downward (as it cools), like a gigantic conveyor belt system. As the mantle material moves, it drags large plates of lithosphere along its surface. This movement is known as **plate tectonics,** a process of extraordinary importance to our planet.

Plate tectonics shapes Earth's geography

Our planet's surface consists of about 15 major tectonic plates, which fit together like pieces of a jigsaw puzzle (**FIGURE 2.13**). Imagine peeling an orange and then placing the pieces back onto the fruit; the ragged pieces of peel are like the lithospheric plates riding atop Earth's surface. However, the plates are thinner relative to the planet's size, more like the skin of an apple. These plates move at rates of roughly 2–15 cm (1–6 in.) per year. This slow movement has influenced Earth's climate and life's evolution throughout our planet's history as the continents combined, separated, and recombined in various configurations. By studying ancient rock formations throughout the world, geologists have determined that at least twice, all landmasses were joined together in a "supercontinent." Scientists have dubbed the landmass that resulted about 225 million years ago Pangaea (see inset in Figure 2.13).

There are three types of plate boundaries

The processes that occur at each type of plate boundary all have major consequences.

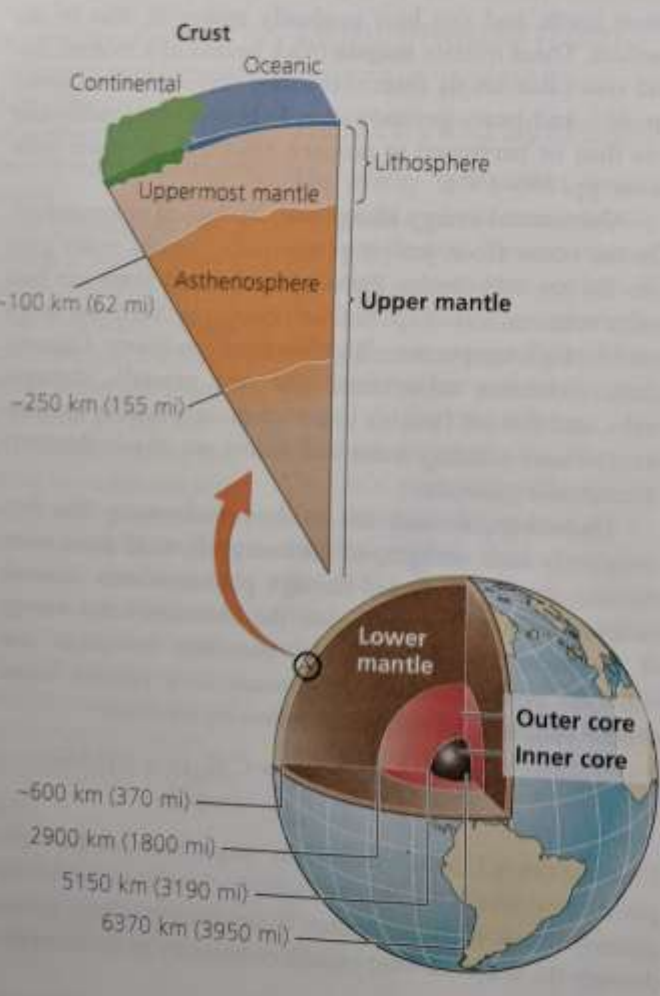


FIGURE 2.12 Earth's three primary layers—core, mantle, and crust—are themselves layered. The inner core of solid iron is surrounded by an outer core of molten iron, and the rocky mantle includes the molten asthenosphere near its upper edge. At Earth's surface, dense and thin oceanic crust abuts lighter, thicker continental crust. The lithosphere consists of the crust and the uppermost mantle above the asthenosphere.

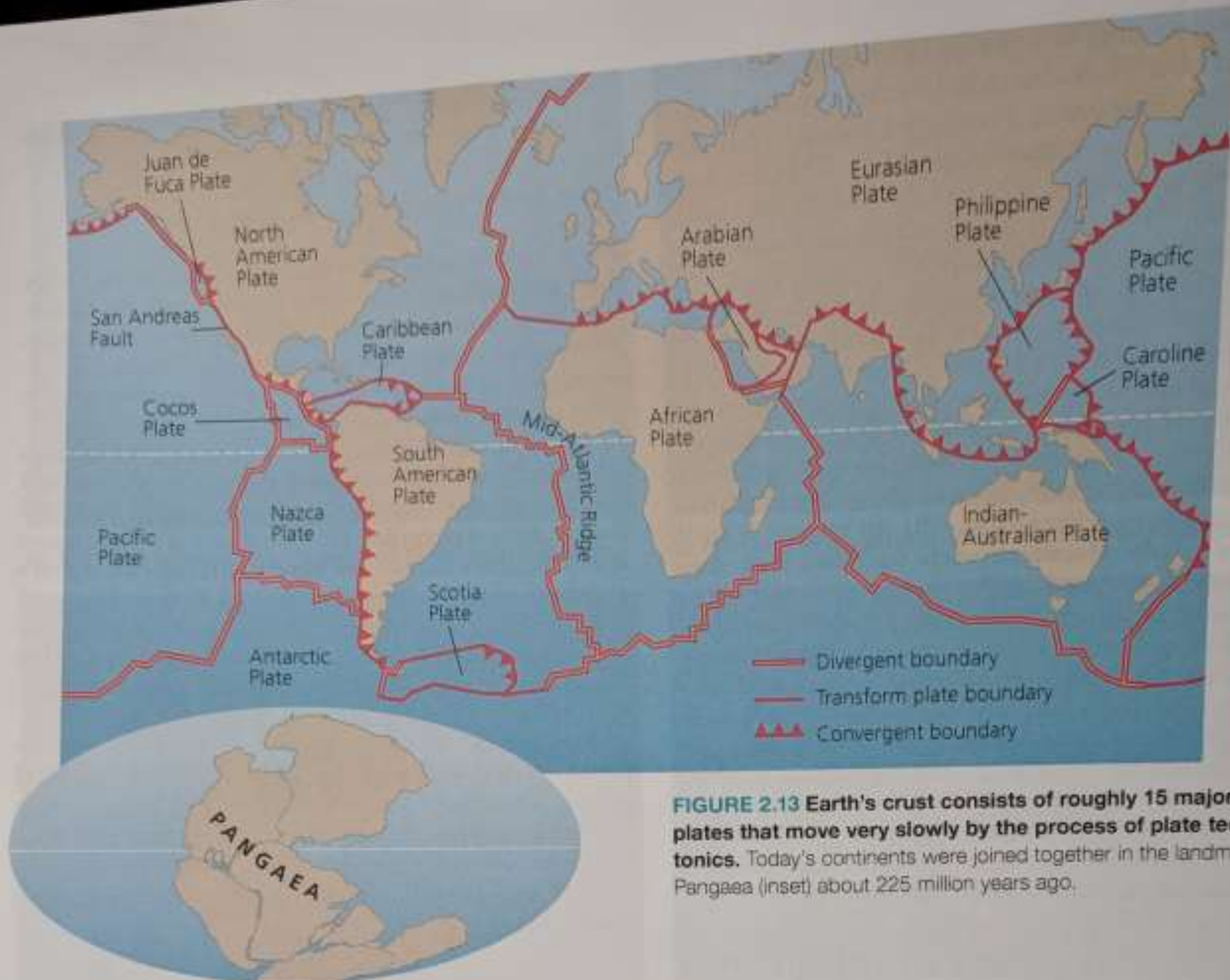
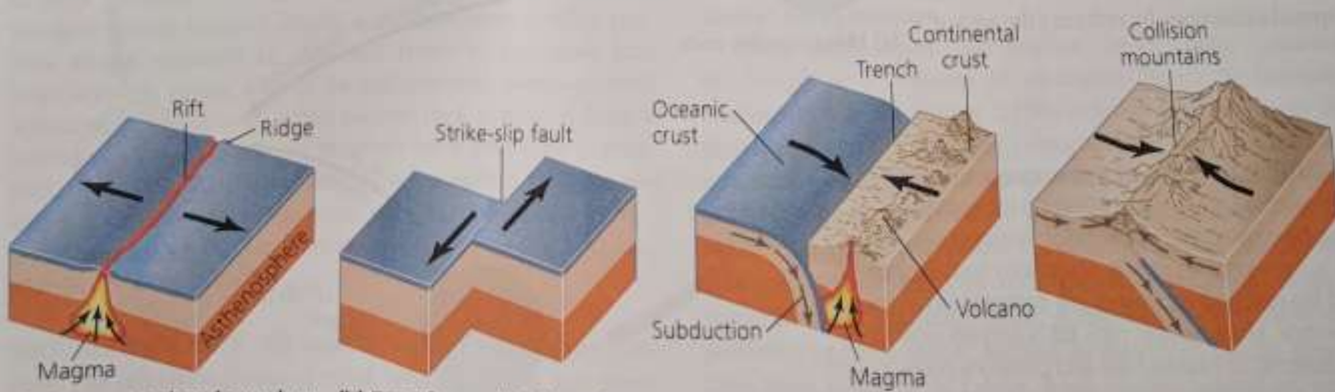


FIGURE 2.13 Earth's crust consists of roughly 15 major plates that move very slowly by the process of plate tectonics. Today's continents were joined together in the landmass Pangaea (inset) about 225 million years ago.

At **divergent plate boundaries,** tectonic plates push apart from one another as magma rises upward to the surface, creating new lithosphere as it cools (FIGURE 2.14a). An example is the Mid-Atlantic Ridge, part of a 74,000-km (46,000-mi) system of divergent plate boundaries slicing across the floors of the world's oceans.

Where two plates meet, they may slip and grind alongside one another, forming a **transform plate boundary** (FIGURE 2.14b). This movement creates friction that generates earthquakes (p. 37) along strike-slip faults. The Tohuku earthquake, for example, occurred at such a fault off the coast of Japan. Faults are fractures in Earth's crust, and at strike-slip faults, each landmass moves horizontally in opposite directions. The Pacific Plate and the North American Plate, for example, slide past one another along California's San Andreas Fault. Southern California is slowly inching its way northward along this fault, and so the site of Los Angeles will eventually reach that of modern-day San Francisco.

Convergent plate boundaries, where two plates come together, can give rise to different outcomes (FIGURE 2.14c). As plates of newly formed lithosphere push outward from divergent plate boundaries, this oceanic lithosphere gradually cools, becoming denser. After millions of years, it becomes denser than the asthenosphere beneath it and dives downward



(a) Divergent plate boundary (b) Transform plate boundary (c) Convergent plate boundary

FIGURE 2.14 There are three types of boundaries between tectonic plates, generating different geologic processes.

into the asthenosphere in a process called **subduction.** As the lithospheric plate descends, it slides beneath a neighboring plate that is less dense, forming a convergent plate boundary. The subducted plate is heated and pressurized as it sinks, and water vapor escapes, helping to melt rock (by lowering its melting temperature). The molten rock rises, and this magma may erupt through the surface via volcanoes (p. 38).

When one plate of oceanic lithosphere is subducted beneath another plate of oceanic lithosphere, the resulting volcanism may form arcs of islands, such as Japan and the Aleutian Islands of Alaska. Subduction zones may also create deep trenches, such as the Mariana Trench, our planet's deepest abyss. When oceanic lithosphere slides beneath continental lithosphere, volcanic mountain ranges form that parallel coastlines (Figure 2.14c, left). An example is South America's Andes Mountains, where the Nazca Plate slides beneath the South American Plate.

When two plates of continental lithosphere meet, the continental crust on both sides resists subduction and instead crushes together, bending, buckling, and deforming layers of rock from both plates in a **continental collision** (Figure 2.14c, right). Portions of the accumulating masses of buckled crust are forced upward as they are pressed together, and mountain ranges result. The Himalayas, the world's highest mountains, result from the Indian-Australian Plate's collision with the Eurasian Plate beginning 40–50 million years ago, and these mountains are still rising today as these plates converge.

Tectonics produces Earth's landforms

Tectonic movements build mountains; shape the geography of oceans, islands, and continents; and give rise to earthquakes and volcanoes. The topography created by tectonic processes, in turn, shapes climate by altering patterns of rainfall, wind, ocean currents, heating, and cooling—all of which affect rates of weathering and erosion and the ability of plants and animals to inhabit different regions. Thus, the locations of biomes (pp. 92–98) are influenced by plate tectonics. Moreover, tectonics has affected the history of life's evolution; the convergence of landmasses into supercontinents such as Pangaea is thought to have contributed to widespread extinctions by reducing the area of species-rich coastal regions and by creating an arid continental interior with extreme temperature swings.

The rock cycle alters rock

Just as plate tectonics shows geology's dynamism on a large scale, the rock cycle shows it on a smaller one. We tend to think of rock as pretty solid stuff. Yet over geologic time, rocks and the minerals that make them up are heated, melted, cooled, broken down, and reassembled in a very slow process called the **rock cycle** (**FIGURE 2.15**).

A **rock** is any solid aggregation of minerals. A **mineral** is any naturally occurring solid element or inorganic compound with a crystal structure, a specific chemical composition, and distinct physical properties. The type of rock in a given region affects soil characteristics and thereby influences the region's plant community. Understanding the rock cycle enables us to better appreciate the formation and conservation of soils, mineral resources, fossil fuels, groundwater sources, and other natural resources (all of which we discuss in later chapters).

Igneous rock All rocks can melt. At high enough temperatures, rock will enter the molten, liquid state called magma. If magma is released through the lithosphere (as in a volcanic eruption), it may flow or spatter across Earth's surface as **lava.** Rock that forms when magma or lava cools is called **igneous rock** (from the Latin *ignis*, meaning "fire") (Figure 2.15a).

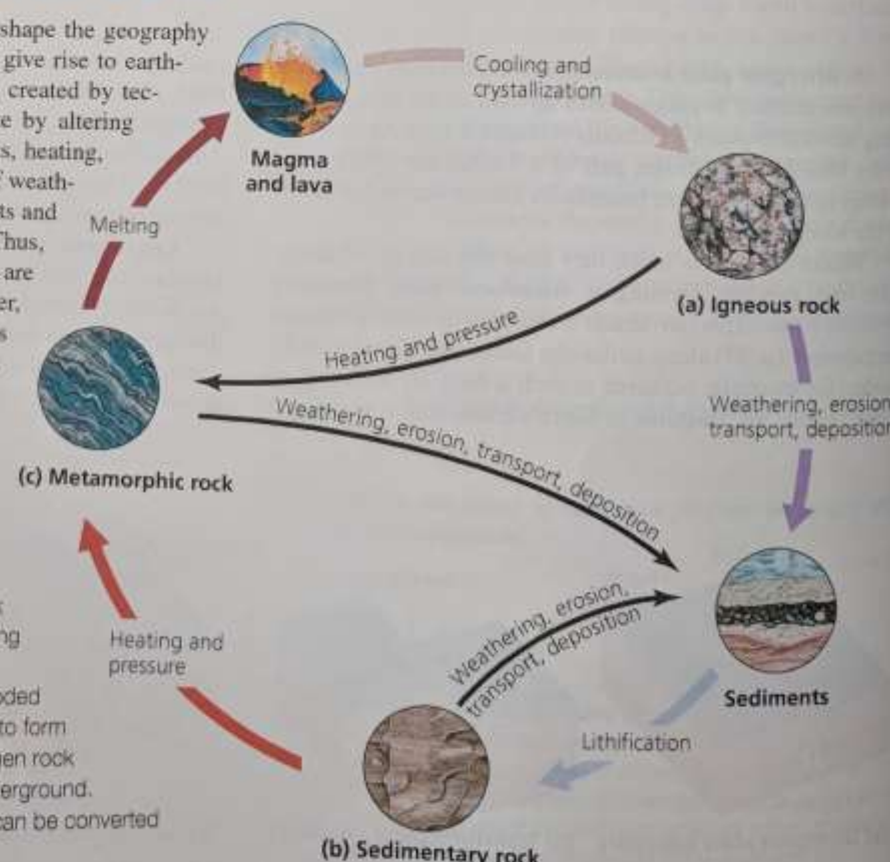
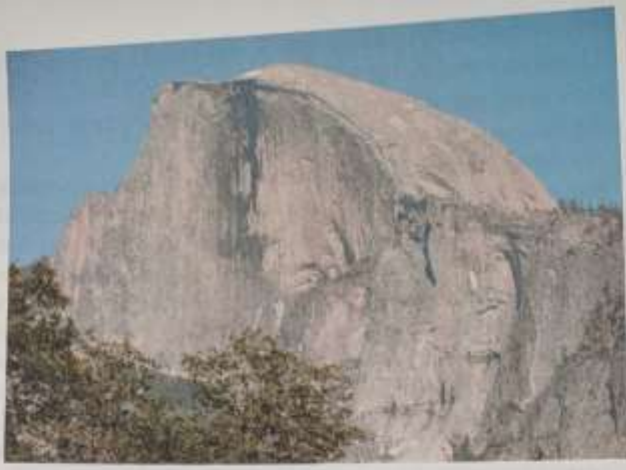


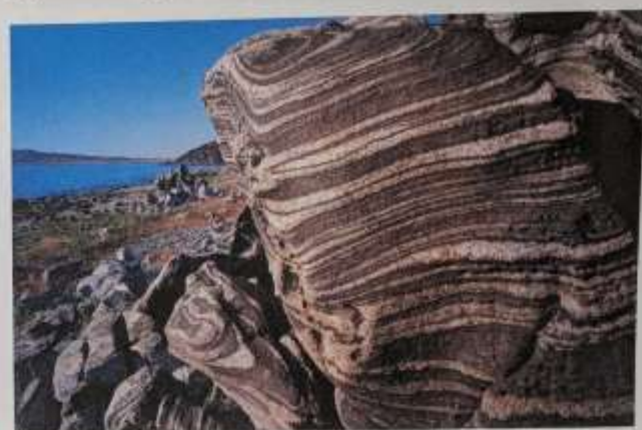
FIGURE 2.15 The rock cycle. Igneous rock **(a)** is formed when rock melts and the resulting magma or lava then cools. Sedimentary rock **(b)** is formed when rock is weathered and eroded and the resulting sediments are compressed to form new rock. Metamorphic rock **(c)** is formed when rock is subjected to intense heat and pressure underground. Through these processes, each type of rock can be converted into either of the other two types.



(a) Intrusive igneous rock: Granite at Yosemite National Park

(b) Extrusive igneous rock: Basalt in the Canary Islands

(c) Sedimentary rock: Sandstone in Arizona



(d) Metamorphic rock: Gneiss in Utah

FIGURE 2.16 **Examples of rock types.** The towering rock formations of Yosemite National Park are made of granite **(a)**, a type of intrusive igneous rock. The lava flows on the Canary Islands form basalt **(b)**, a type of extrusive igneous rock. The layered formation in Paria Canyon, Arizona, is an example of sandstone **(c)**, a type of sedimentary rock. Gneiss (pronounced "nice") **(d)**, at Antelope Island, Utah, is a type of metamorphic rock.

Igneous rock comes in two main classes because magma can solidify in different ways. When magma cools slowly and solidifies while it is below Earth's surface, it forms intrusive igneous rock. This process created the famous rock formations at Yosemite National Park (FIGURE 2.16a). Granite is the best-known type of intrusive rock. A slow cooling process allows minerals of different types to aggregate into large crystals, giving granite its multicolored, coarse-grained appearance. In contrast, when molten rock is ejected from a volcano, it cools quickly, so minerals have little time to grow into coarse crystals. This quickly cooled molten rock is classified as extrusive igneous rock, and its most common representative is basalt, the principal rock type of the Japanese islands (FIGURE 2.16b).

Sedimentary rock All exposed rock weathers away with time. The relentless forces of wind, water, freezing, and thawing strips off one tiny grain (or large chunk) after another. Through weathering (p. 213) and erosion (pp. 221–222), particles of rock blown by wind or washed away by water come to rest downhill, downstream, or downwind from their sources, eventually forming **sediments.** Alternatively, some sediments form chemically from the precipitation of substances out of solution.

Sediment layers accumulate over time, causing the weight and pressure of overlying layers to increase. **Sedimentary rock** (Figure 2.15b) is formed as sediments are physically pressed together (compaction) and as dissolved minerals seep through sediments and act as a kind of glue, binding sediment particles together (cementation). The formation of rock through these processes is termed lithification. Examples of sedimentary rock include sandstone, made of cemented sand particles; shale, comprising still smaller mud particles; and limestone, formed as dissolved calcite precipitates from water or as calcite from marine organisms settles to the bottom.

These processes also create the fossils of organisms (p. 56) we use to learn about the history of life on Earth and the fossil fuels we use for energy. Because sedimentary layers pile up in chronological order (FIGURE 2.16c), scientists can assign relative dates to fossils they find in sedimentary rock.

Metamorphic rock Geologic forces may bend, uplift, compress, or stretch rock. When any type of rock is subjected to great heat or pressure, it may alter its form, becoming **metamorphic rock** (from the Greek for "changed form") (Figure 2.15c). The forces that metamorphose rock generally occur deep underground, at temperatures lower than the rock's melting point, but high enough to change its appearance and physical properties. Metamorphic rock (FIGURE 2.16d) includes rock such as slate, formed when shale is subjected to heat and pressure, and marble, formed when limestone is heated and pressurized.

Geologic processes occur across "deep time"

Geologic processes occur at timescales that are difficult to conceptualize. But it is only by appreciating the long time periods within which our planet's geologic forces operate that we can realize how exceedingly slow processes such as plate tectonics or the formation of sedimentary rock can reshape our planet. This lengthy timescale is referred to as deep time, or geologic time.

The geologic timescale (APPENDIX E) shows the full span of Earth's history—all 4.5 *billion* years of it—and focuses on the most recent 543 million years. Geologists have subdivided Earth's history into 3 eras and 11 periods. The Quaternary period, the most recent, occupies a thin slice of time at the top of the scale because this period began "only" 1.8 million years ago.

Geologists divide this immensely long timescale using evidence from stratigraphy, the study of strata, or layers, of sedimentary rock. Where scientists find fossil evidence for major and sudden changes in the physical, chemical, or biological conditions present on Earth between one set of layers and the next, they assign a boundary between geologic time periods. For instance, fossil evidence for mass extinctions (pp. 58, 278–282) determines several boundaries, such as that between the Permian and Triassic periods.

We live in the Holocene epoch, the most recent slice of the Quaternary period. The Holocene epoch began about 11,500 years ago with a warming trend that melted glaciers and brought Earth out of its most recent ice age. Since then, Earth's climate has been remarkably constant, and this constancy provided our species with the long-term stability we needed to develop agriculture and civilization. However, since the industrial revolution, human activity has had major impacts on Earth's basic processes, including a sharp increase in soil erosion from clearing forests and cultivating land; an alteration in the composition of the atmosphere through emitting greenhouse gases, which elevates Earth's average temperature; and a recent explosion in human population, which has intensified all impacts on Earth. All of these activities have set into motion a new mass extinction event (p. 282). These realizations have led some geologists in 2000 to propose naming a new geologic era, encompassing the past 200 years, after ourselves—the Anthropocene (FIGURE 2.17).

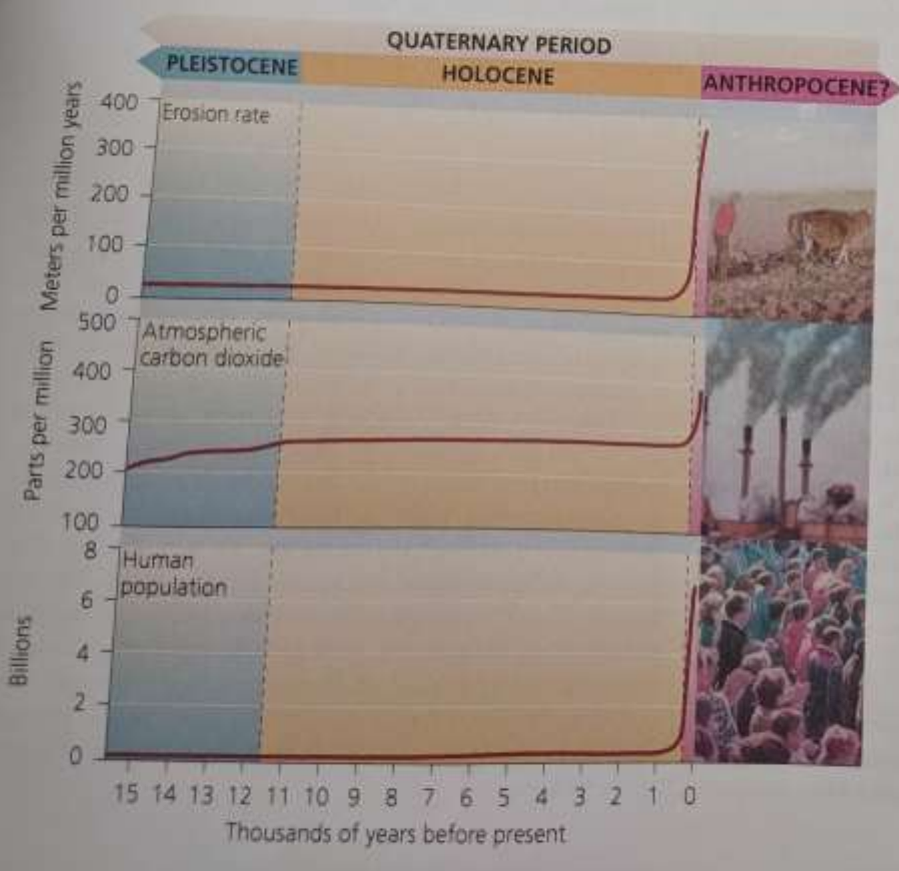


FIGURE 2.17 Global soil erosion rates (top) and atmospheric carbon dioxide concentrations (middle) have increased sharply in just the past few hundred years, along with human population (bottom). These patterns have persuaded some geologists that we should recognize a new epoch in Earth history: the Anthropocene. *Adapted from Zalasiewicz, J., et al., 2008. Are we now living in the Anthropocene? GSA Today 18(2): 4-8, Figure 1.*