Earth's Evolution through Geologic Time

CHAPTER

22

Maroon Bells in Autumn, Colorado Rockies. (Photo by Tim Fitzharris/ Minden Pictures)

Earth has a long and complex history. Time and again, the splitting and colliding of continents has resulted in the formation of new ocean basins and the creation of great mountain ranges. Furthermore, the nature of life on our planet has experienced dramatic changes through time.

Many of the changes on planet Earth occur at a "snail's pace," generally too slow for people to perceive. Thus, human awareness of evolutionary change is fairly recent. Evolution is not confined to life forms, for all Earth's "spheres" have evolved together: the atmosphere, hydrosphere, geosphere, and biosphere (Figure 22.1). These changes can be observed in the air we breathe, the composition of the world's oceans, the ponderous movements of crustal plates that give rise to mountains, and the evolution of a vast array of life-forms. As each of Earth's spheres has evolved, it has powerfully influenced the others.

FIGURE 22.1 Earth's spheres have evolved together through the long expanse of geologic time. (Photos by A. Momatiuk Eastcott, B. and C. Michael Collier, D. Carr Clifton/Minden Pictures)

A. Atmosphere

B. Hydrosphere

C. Geosphere

D. Biosphere

Is Earth Unique?

There is only one place in the entire universe, as far as we know, that can support life—a modest-sized planet called Earth that orbits an average-sized star, the Sun. Life on Earth is ubiquitous; it is found in boiling mudpots and hot springs, in the deep abyss of the ocean, and even under the Antarctic ice sheet. However, living space on our planet is greatly limited when we consider the needs of individual organisms, particularly humans. The global ocean covers 71 percent of Earth's surface, but only a few hundred meters below the water's surface pressures are so great that our lungs would begin to collapse. Further, many continental areas are too steep, too high, or too cold for us to inhabit (Figure 22.2). Nevertheless, based on what we know about other bodies in the solar system—and the 80 or so planets recently discovered orbiting around other stars—Earth is still, by far, the most accommodating.

What fortuitous events produced a planet so hospitable to living organisms like us? Earth was not always as we find it today. During its formative years, our planet became hot enough to support a magma ocean. It also went through a several-hundred-million-year period of extreme bombardment, to which the heavily cratered lunar surface testifies. Even the oxygen-rich atmosphere that makes higher life forms possible is a relatively recent event, geologically speaking. Nevertheless, Earth seems to be the right planet, in the right location, at the right time.

The Right Planet

What are some of the characteristics that make Earth unique among the planets? Consider the following:

FIGURE 22.2 Climbers near the top of Mount Everest. At this altitude the level of oxygen is only one-third the amount available at sea level. (Photo courtesy of Woodfin Camp and Associates)

1. If Earth were considerably larger (more massive) the force of gravity would be proportionately greater. Like the giant planets, Earth would have retained a thick, hostile atmosphere consisting of ammonia and methane, and possibly even hydrogen and helium.
2. If Earth were much smaller, oxygen, water vapor and other volatiles would escape into space and be lost forever. Thus, like the Moon and Mercury, which lack an atmosphere, Earth would be void of life.
3. If Earth did not have a rigid lithosphere overlaying a weak asthenosphere, plate tectonics would not operate. Our continental crust (Earth's "highlands") would not have formed without the recycling of plates. Consequently, the entire planet would likely be covered by an ocean a few kilometers deep. As the author Bill Bryson so aptly stated, "There might be life in that lonesome ocean, but there certainly wouldn't be baseball."
4. Most surprisingly, perhaps, is the fact that if our planet did not have a molten metallic core, most of the life forms on Earth would not exist. Although this may seem like a stretch of the imagination, without the flow of iron in the core, Earth could not support a magnetic field. It is the magnetic field which prevents lethal cosmic rays (the solar wind) from showering Earth's surface.

The Right Location

One of the primary factors that determines whether or not a planet is suitable for higher life-forms is its location in the solar system. Earth is in a great location:

1. If Earth were about 10 percent closer to the Sun, like Venus, our atmosphere would consist mainly of the greenhouse gas, carbon dioxide. As a result, Earth's surface temperature would be too hot to support higher life-forms.
2. If Earth were about 10 percent farther from the Sun, the problem would be the opposite—too cold rather than too hot. The oceans would freeze over and Earth's active water cycle would not exist. Without liquid water most life-forms would perish.
3. Earth is located near a star of modest size. Stars like the Sun have a life span of roughly 10 billion years. During most of this time radiant energy is emitted at a fairly constant level. Giant stars on the other hand consume their nuclear fuel at very high rates and thus "burn out" in a few hundred million years. This is simply not enough time for the evolution of humans, which first appeared on this planet only a few million years ago.

The Right Time

The last, but certainly not the least fortuitous factor is timing. The first life-forms to inhabit Earth were extremely primitive and came into existence roughly 3.8 billion years ago. From this point in Earth's history innumerable changes occurred—life-forms came and went along with changes in the physical environment of our planet. Two of many timely, Earth-altering events include:

1. The development of our modern atmosphere. Earth's primitive atmosphere is thought to have been composed mostly of water vapor and carbon dioxide, with small amounts of other gases, but no free oxygen. Fortunately, microorganisms evolved that produced oxygen by the process of *photosynthesis.* By about 2.2 billion years ago an atmosphere with free oxygen came into existence. The result was the evolution of the forbearers of life-forms that occupy Earth today.
2. About 65 million years ago our planet was struck by an asteroid 10 kilometers in diameter. This impact caused a mass extinction during which nearly three-quarters of all plant and animal species died out—including the dinosaurs (Figure 22.3). Although this may not seem like a fortuitous event, the extinction of the dinosaurs opened new habitats for the small mammals that survived the impact. These habitats, along with evolutionary forces, led to the development of the many large mammals that occupy our modern world. Without this event, mammals might still be small rodentlike creatures that live in burrows.

As various observers have noted, Earth developed under "just right" conditions to support higher life-forms. Astronomers like to refer to this as the *Goldilocks scenario.* As in the classic Goldilocks and the Three Bears fable, Venus is too hot (the papa bear's porridge), Mars is too cold (the mama bear's porridge), but Earth is just right (the baby bear's porridge). Did these "just right" conditions come about purely by chance as some researchers suggest, or as others have argued, might Earth's hospitable environment have developed for the evolution and survival of higher life-forms?

The remainder of this chapter will focus on the origin and evolution of planet Earth—the one place in the Universe we know fosters life. As you learned in Chapter 9, researchers utilize many tools to interpret the clues about Earth's past. Using these tools, and clues that are contained in the rock record, scientists have been able to unravel many of the complex events of the geologic past. The goal of this chapter is to provide a brief overview of the history of our planet and its life-forms. The journey takes us back about 4.5 billion years to the formation of Earth and its atmosphere. Next we will consider how our physical world assumed its present form and how Earth's inhabitants changed through time. We suggest that you reacquaint yourself with the *geologic time scale* presented in Figure 22.4 and refer to it as needed throughout the chapter.

FIGURE 22.3 The excavation of a dinosaur fossil from Dry Mesa Quarry, Colorado. (Photo by Michael Collier)

Birth of a Planet

According to the Big Bang theory, the formation of our home planet began about 13.7 billion years ago with a cataclysmic explosion that created all matter and space almost instantaneously (Figure 22.5). Initially atomic particles (protons, neutrons, and electrons) formed, then later as this debris cooled, atoms of hydrogen and helium, the two lightest elements, began to form. Within a few hundred million years, clouds of these gases condensed into stars that compose the galactic systems we now observe fleeing from their birthplace.

As these gases contracted to form the first stars, heating triggered the process of *nuclear fusion.* Within stars' interiors, hydrogen atoms are converted to helium atoms, releasing enormous amounts of energy in the form of radiation (heat, light, cosmic rays). Astronomers have determined that in stars more massive than our Sun, other thermonuclear reactions occur that generate all the elements on the periodic table up to number 26, iron. The heaviest elements (beyond number 26) are only created at extreme temperatures during the explosive death of a star perhaps 10 to 20 times more massive than the Sun. During one of these cataclysmic **supernova** events, an exploding star produces all of the elements heavier than iron and spews them into interstellar space. It is from such debris that our Sun and solar system formed. According to the Big Bang scenario, the atoms in your body were produced billions of years ago in the hot interior of now defunct stars, and the gold in your jewelry was formed during a supernova explosion that occurred trillions of miles away.

From Planetesimals to Protoplanets

Recall that Earth, along with the rest of the solar system, formed about 4.5 billion years ago from the **solar nebula,** a large rotating cloud of interstellar dust and gas (see Chapter 1). As the solar nebula contracted, most of the matter collected in the center to form the hot *protosun,* while the remainder became a flattened spinning disk. Within this spinning disk, matter gradually formed clumps that collided and stuck together to form asteroid-size objects called

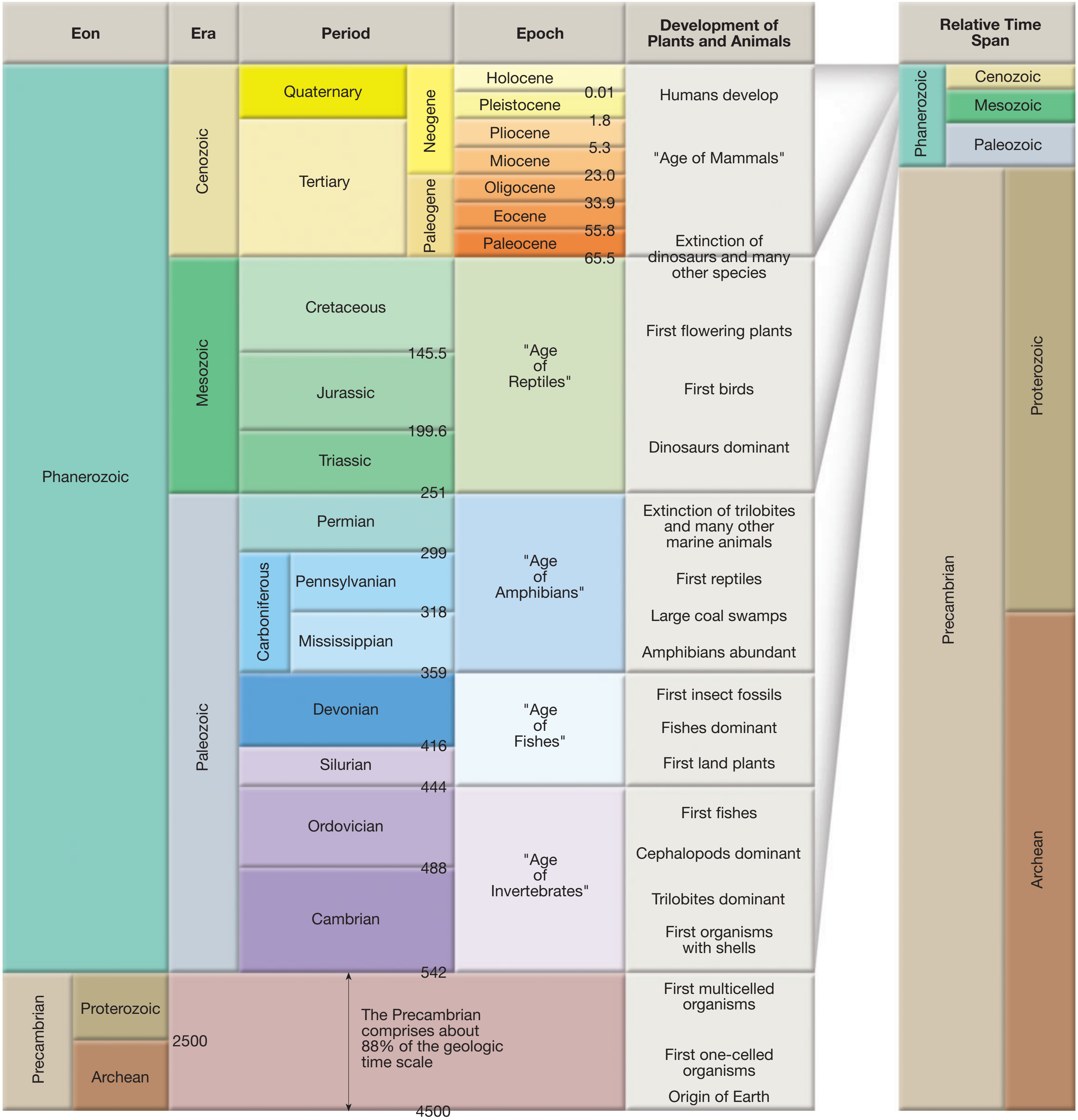


FIGURE 22.4 The geologic time scale. Numbers represent time in millions of years before the present. These dates were added long after the time scale had been established using relative dating techniques. The Precambrian accounts for about 88 percent of geologic time.

planetesimals. The composition of each planetesimal was governed largely by its distance from the hot protosun.

Near the present day orbit of Mercury only metallic grains condensed from the solar nebula. Further out, near Earth's orbit, metallic as well as rocky substances condensed, and beyond Mars, ices of water, carbon dioxide, methane, and ammonia formed. It was from these clumps of matter that the planetesimals formed and through repeated collisions and accretion (sticking together) grew into eight **protoplanets** and their moons (Figure 22.5).

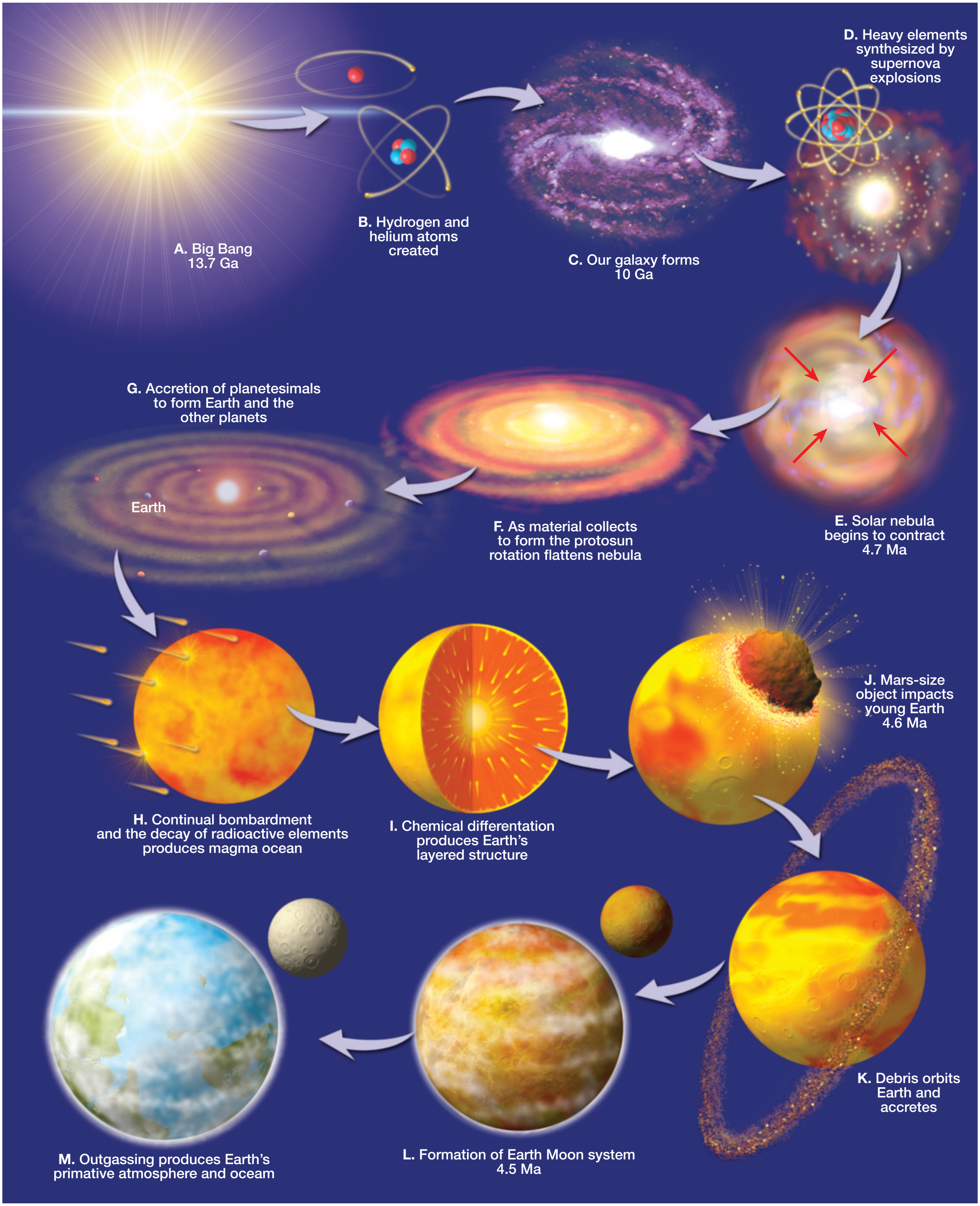


FIGURE 22.5 Major events that led to the formation of early Earth.

At some point in Earth's evolution a giant impact occurred between a Mars-sized planetesimal and a young, semi-molten Earth. This collision ejected huge amounts of debris into space, some of which coalesced (joined together) to form the Moon (see Figure 24.9, p. 663).

Earth's Early Evolution

As material continued to accumulate, the high-velocity impact of interplanetary debris (planetesimals) and the decay of radioactive elements caused the temperature of our planet to steadily increase. During this period of intense heating, Earth became hot enough that iron and nickel began to melt. Melting produced liquid blobs of heavy metal that sank under their own weight. This process occurred rapidly on the scale of geologic time and produced Earth's dense iron-rich core. The formation of a molten iron core was only the first stage of chemical differentiation, in which Earth was converted from a homogeneous body, with roughly the same stuff at all depths, to a layered planet with material sorted by density (Figure 22.5).

This early period of heating also resulted in a magma ocean, perhaps several hundred kilometers deep. Within the magma ocean buoyant masses of molten rock rose toward the surface, where they eventually solidified to produce a thin, primitive crust. Earth's first crust was probably basaltic in composition, not unlike modern oceanic crust. Whether or not plate tectonics was active at this time is not known. However, vigorous, fluidlike motions in the hot, upper mantle must have continually recycled the crust over and over again.

This period of chemical differentiation established the three major divisions of Earth's interior—the iron-rich *core*, the thin *primitive crust*, and Earth's largest layer, the *mantle*, which is located between the core and the crust. In addition, the lightest material, including water vapor, carbon dioxide, and other gases, escaped to form a primitive atmosphere and, shortly thereafter, the oceans (Figure 22.6).

Origin of the Atmosphere and Oceans

Thank goodness for our atmosphere; without it Earth would be nearly 60 degrees Fahrenheit colder. Although not as cold as the surface of Mars, most water bodies on Earth would be frozen over and the hydrological cycle, where water leaves the ocean as a vapor and returns as a liquid, would be meager at best. Recall that the warming effect of certain gases in the atmosphere, mainly carbon dioxide and water vapor, is called the greenhouse effect.

Today, the air we breathe is a stable mixture of 78 percent nitrogen, 21 percent oxygen, about 1 percent argon (an inert gas), and small amounts of gases such as carbon dioxide and water vapor (see Figure 21.9, p. 573). But our planet's original atmosphere 4.5 billion years ago was very different.

Earth's Primitive Atmosphere

When Earth formed, any atmosphere it might have had would have consisted of the gases most common in the early solar system—hydrogen, helium, methane, ammonia, carbon dioxide, and water vapor (see Chapter 24). The lightest of these gases, hydrogen and helium, would have escaped into space as Earth's gravity is too weak to hold them. Most of the remaining gases were probably blown off by strong *solar winds* (a vast stream of particles) from a young, active Sun. (All stars, including the Sun, apparently experience a highly active stage early in their evolution known as the *T-Tauri phase,* during which their solar winds are very intense.)

Earth's first enduring atmosphere formed by a process called **outgassing,** through which gases trapped in the planet's interior are released. Outgassing continues today from hundreds of active volcanoes worldwide (Figure 22.7). However, early in Earth's history, when massive heating and fluidlike motion occurred in the mantle, the gas output must have been immense. The composition of the gases emitted then were probably roughly equivalent to those released during volcanism today. Depending on the chemical makeup of the magma, the gaseous components of modern

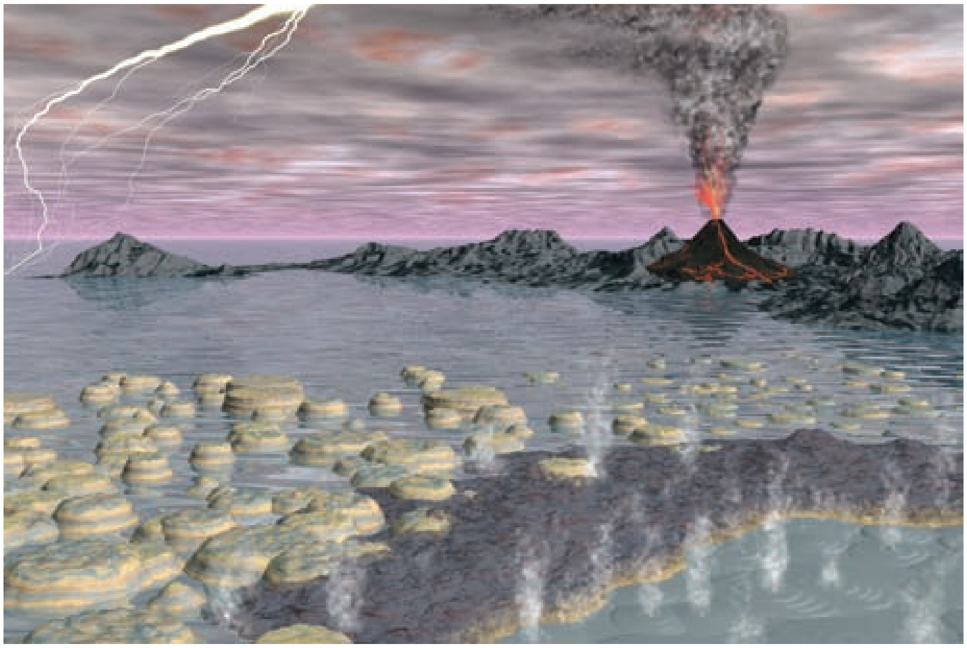


FIGURE 22.6 Artistic depiction of Earth over 4 billion years ago. This was a time of intense volcanic activity that produced Earth's primitive atmosphere and oceans, while early life forms produced mound-like structures called stromatolites.

FIGURE 22.7 Earth's first enduring atmosphere formed by a process called outgassing, which continues today from hundreds of active volcanoes worldwide. (Photo by Marco Fulle/www.stomboli.net)

eruptions consist of between 35–90 percent water vapor, 5–30 percent carbon dioxide, 2–30 percent sulfur dioxide, and lesser amounts of nitrogen, chorine, hydrogen, and argon. Thus, Earth's primitive atmosphere probably consisted of mostly water vapor, carbon dioxide, and sulfur dioxide with minor amounts of other gases, but no free oxygen and little nitrogen.

Oxygen in the Atmosphere

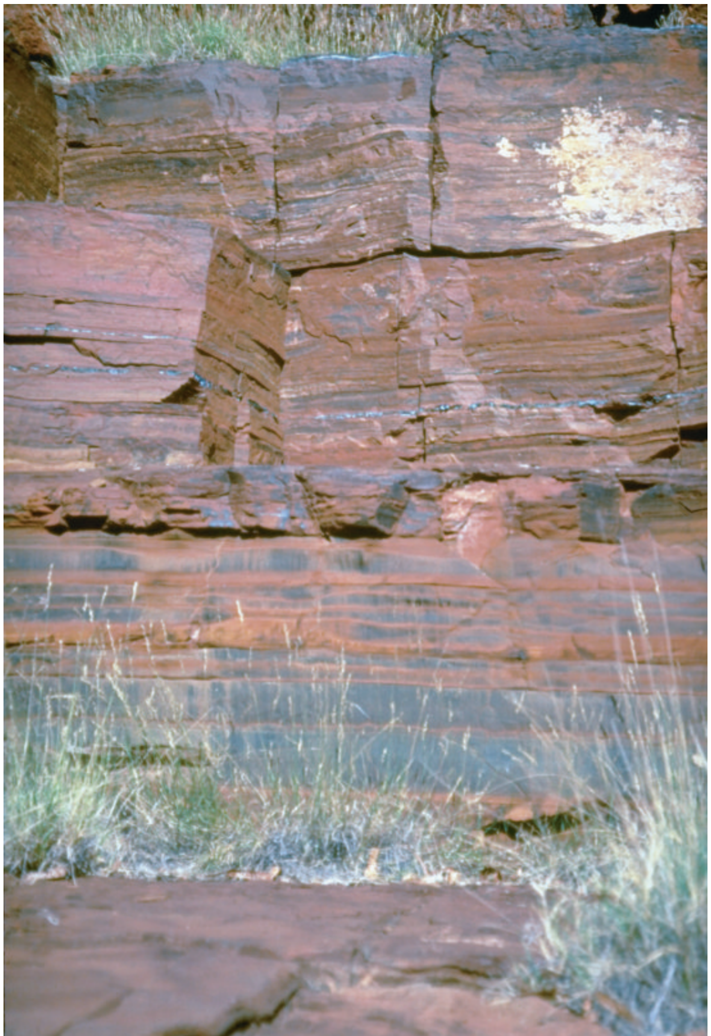
As Earth cooled, water vapor condensed to form clouds, and torrential rains began to fill low-lying areas forming the oceans. It was in the oceans nearly 3.5 billion years ago that photosynthesizing bacteria began to release oxygen into the water. During *photosynthesis,* the Sun's energy is used by organisms to produce organic material (energetic molecules of sugar containing hydrogen and carbon) from carbon dioxide (CO_2) and water (H_2O). The first bacteria probably used hydrogen sulfide (H_2S), rather than water, as the source of hydrogen. Nevertheless, one of the earliest types of bacteria, the *cyanobacteria* began to produce oxygen as a by-product of photosynthesis.

Initially, the newly liberated oxygen was readily consumed by chemical reactions with other atoms and molecules in the ocean, especially iron. The source of most iron appears to be submarine volcanism and associated hydrothermal vents (black smokers). Iron has tremendous affinity for oxygen, and these two elements joined to form iron oxide (also known as rust), which accumulated on the seafloor as sediment. These early iron oxide deposits consist of alternating layers of iron-rich rocks and chert, and are called **banded iron formations** (Figure 22.8). Most banded iron deposits were laid down in the Precambrian between 3.5 and 2 billion years ago, and represent the world's most important reservoir of iron ore.

Once much of the available iron had precipitated and the numbers of oxygen-generating organisms increased, oxygen began to accumulate in the atmosphere. Chemical analysis of rocks suggest that a significant amount of oxygen appeared in the atmosphere as early as 2.2 billion years ago and that the amount increased steadily until it reached a stable level about 1.5 billion years ago. The availability of free oxygen had a major impact on the development of life.

Another significant benefit of the "oxygen explosion" is that when oxygen (O_2) molecules in the atmosphere are bombarded by ultraviolet radiation they rearrange themselves to form *ozone* (O_3). Today ozone is concentrated above the surface in a layer called the *stratosphere* where it absorbs much of the ultraviolet radiation that strikes the atmosphere. For the first time, Earth's surface was protected from this form of solar radiation, which is particularly harmful to DNA. Marine organisms had

FIGURE 22.8 These layered iron-rich rocks, called banded iron formations, were deposited during the Precambrian. Much of the oxygen generated as a by-product of photosynthesis was readily consumed by chemical reactions with iron to produce these rocks. (Courtesy Spencer R. Titley)



always been shielded from ultraviolet radiation by the oceans, but with the development of the protective ozone layer the continents became a more hospitable place for life to develop.

Evolution of the Oceans

About 4 billion years ago, as much as 90 percent of the current volume of seawater was contained in the ocean basins. Because the primitive atmosphere was rich in carbon dioxide as well as sulfur dioxide and hydrogen sulfide, the earliest rain water was highly acidic—even more so than the acid rain that recently damaged lakes and streams in eastern North America. Consequently, weathering of Earth's rocky surface occurred at an accelerated rate. The products released by chemical weathering included atoms and molecules of various substances, including sodium, calcium, potassium, and silica, that were carried into the newly formed oceans. Some of these dissolved substances precipitated to form chemical sediment that mantled the ocean floor. Others gradually built up, increasing the salinity of seawater. Today seawater contains an average of 3.5 percent dissolved salts, most of which is common table salt (sodium chloride). Research suggests that the salinity of the oceans increased rapidly at first, but has not changed dramatically in the last few billion years.

Earth's oceans also served as a depository for tremendous volumes of carbon dioxide, a major constituent in the primitive atmosphere—and they still do today. This is significant because carbon dioxide is a greenhouse gas that strongly influences the heating of the atmosphere. Venus, which was once thought to very similar to Earth, has an atmosphere composed of 97 percent carbon dioxide that produced a "runaway" greenhouse effect. The surface of Venus has a temperature of 475°C (900°F)—hot enough to melt lead.

Carbon dioxide is readily soluble in seawater where it often joins with other atoms or molecules to produce various chemical precipitates. By far the most common compound generated by this process is calcium carbonate ($CaCO_3$), which makes up the most abundant chemical sedimentary rock, *limestone.* Later in Earth's history, marine organisms began to remove calcium carbonate from seawater to make their shells and other hard parts. Included were trillions of tiny marine organisms such as foraminifera, that died and were deposited on the seafloor. Today some of these deposits make up the chalk beds exposed along the White Cliffs of Dover, England shown in Figure 22.9. By locking up carbon dioxide, these limestone deposits prevent this greenhouse gas from easily re-entering the atmosphere.*

Precambrian History: The Formation of Earth's Continents

The first 4 billion years of Earth's history are encompassed in the span of time called the *Precambrian.* Representing nearly 90 percent of Earth's history, the Precambrian is divided into the *Archean eon* ("ancient age") and the succeeding *Proterozoic eon* ("early life"). To get a visual sense of the proportion of time represented by the Precambrian, look at the right side of Figure 22.4, which shows relative time spans for the Precambrian and the eras of the Phanerozoic eon.

Our knowledge of this ancient time is sketchy, for much of the early rock record has been obscured by the very Earth processes you have been studying, especially plate tectonics, erosion, and deposition. Most Precambrian rocks are devoid of fossils, which hinders correlation of rock units. In addition, rocks of this great age are metamorphosed and deformed, extensively eroded, and sometimes obscured by overlying strata of younger age. Indeed, Precambrian history is written in scattered, speculative episodes, like a long book with many missing chapters.

We are, however, relatively certain that during the early Archean, Earth was covered by a magma ocean. It is from this material that Earth's atmosphere, oceans and first continents arose.

Earth's First Continents

More than 95 percent of Earth's population lives on the continents—not included are people living on volcanic islands such as the Hawaiian Islands and Iceland. These islanders

FIGURE 22.9 This prominent chalk deposit, the White Cliffs of Dover, is found in southern England. Similar deposits are also found in northern France. (Photo by Jon Arnold/Getty Images/Taxi)

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*For more on this, see Box 7.1, "The Carbon Cycle and Sedimentary Rocks," on p. 200.

inhabit unusually thick pieces of oceanic crust, thick enough to rise above sea level.

What differentiates continental crust from oceanic crust? Recall that oceanic crust is a comparatively dense (3.0g/cm^3), homogeneous layer of basaltic rocks derived from partial melting of the rocky, upper mantle. Furthermore, oceanic crust is thin, averaging only 7 kilometers in thickness. Unusually thick blocks of oceanic crust, such as ocean plateaus, tend to form over mantle plumes (hot spot volcanism). Continental crust, on the other hand, is composed of a variety of rock types, has an average thickness of nearly 40 kilometers, and contains a large percentage of low-density (2.7 g/cm^3) silica-rich rocks such as granite.

These are very important differences. Oceanic crust, because it is relatively thin and dense, occurs several kilometers below sea level—unless, of course it has been shoved up onto a landmass by tectonic forces. Continental crust, because of its great thickness and lower density, extends well above sea level. Also, recall that oceanic crust of normal thickness will readily subduct, whereas thick, buoyant blocks of continental crust resist being recycled into the mantle.

Making Continental Crust Earth's first crust was probably basalt, like that generated at modern oceanic ridges. But we do not know for sure because none has ever been found. The hot turbulent mantle that existed during the Archean eon probably recycled most of this material back into the mantle. In fact, it may have been recycled over and over again, much like the "crust" that forms on a lava lake is continually being replaced with fresh lava from below (Figure 22.10).

The oldest preserved continental rocks (greater than 3.5 billion years old) occur as small, highly deformed terranes, which are incorporated within somewhat younger blocks of continental crust (Figure 22.11). The oldest of these is the 4 billion-year-old Acasta gneiss located in the Slave Province of Canada's Northwest Territories. (A few tiny crystals of zircon, found in the Jack Hills area of Australia have radiometric dates between 3.8 and 4.4 billion years.)

The formation of continental crust is simply a continuation of the gravitational segregation of Earth materials that began during the final stage in the accretion of our planet. After the metallic core and rocky mantle formed, low density, silica-rich minerals were gradually extracted from the mantle to form continental crust. This occurs through a multi-stage process during which partial melting of ultramafic mantle rocks (peridotite) generates basaltic rocks and remelting of basalts produces magmas that crystallize to form felsic, quartz-bearing rocks (see Chapter 4). However, little is known about the details of the mechanisms that operated during the Archean to generate these silica-rich rocks.

Many geologists, but certainly not all, conclude that some type of plate-like motion that included subduction operated early in Earth's history. In addition, hot spot volcanism likely played a role as well. However, because the mantle was hotter in the Archean than it is today, both of these phenomena would have progressed at higher rates than their modern counterparts. Hot spot volcanism is thought to have created immense shield volcanoes as well as oceanic plateaus. At the same time, subduction of oceanic crust generated volcanic island arcs. These relatively small, thin crustal fragments represent the first phase in creating stable, continental-size landmasses.

From Continental Crust to Continents According to one model, the growth of large continental masses was accomplished through the collision and accretion of various types of terranes as illustrated in Figure 22.12. This type of collision tectonics deformed and metamorphosed the sediments caught between the converging crustal fragments, shortening and thickening the developing crust. Within the deepest regions of these collision zones, partial melting of the thickened crust generated silica-rich magmas that ascended and intruded the rocks above. The result was the formation of large crustal provinces that, in turn, accreted with others to form even larger crustal blocks called **cratons.** (That portion of a modern craton that is exposed at the surface is referred to as a *shield*.) The assembly of a large craton involved several major mountain building episodes such as occurred when the Indian subcontinent collided with Asia. Figure 22.13 shows the extent of crustal material that was produced during the Archean and Proterozoic eons. This was accomplished by the collision and accretion of many thin and highly mobile terranes into nearly recognizable continental masses.

The Precambrian was a time when much of Earth's continental crust was generated. However, a substantial amount of crustal ma-

FIGURE 22.10 Rift pattern on lava lake. The crust covering this lava lake is continually being replaced with fresh lava from below, much like Earth's crust was recycled early in its history. (Photo by Juerg Alean/www.stromboli.net)

FIGURE 22.11 These rocks at Isua, Greenland, some of the world's oldest, have been dated at 3.8 billion years. (Photo courtesy of Corbis/Bettmann)

terial was destroyed as well. Crust can be lost in two ways, by weathering and erosion or by direct reincorporation into the mantle through subduction. Evidence suggests that during much of the Archean, thin slabs of continental crust were destroyed mainly by subduction into the mantle. However, by about 3 billion years ago, cratons grew sufficiently large and thick to resist direct reincorporation into the mantle. From this point onward, weathering and erosion took over as the primary processes of crustal destruction. By the end of the Precambrian most of the modern continental crust had formed—perhaps 85 percent.

In summary, terranes are the basic building blocks of continents and terrane collisions are the major means by which continents grow.

The Making of North America

North America provides an excellent example of the development of continental crust and its piecemeal assembly into a continent. Notice in Figure 22.14 that very little continental crust older that 3.5 billion years still remains. In the late Archean, between 3–2.5 billion years ago, there was a period of major crustal growth. During this time span, the accretion of numerous island arcs and other crustal fragments generated several large crustal provinces. North America contains some of these crustal units, including the Superior and Hearne/Rae cratons shown in Figure 22.14. The locations of these ancient continental blocks during their formation are not known.

About 1.9 billion years ago these crustal provinces collided to produce the Trans-Hudson mountain belt (Figure 22.14). (This mountain-building episode was not restricted to North America, because ancient deformed strata of similar age are also found on other continents.) This event built the North America craton, around which several large and numerous small crustal fragments were later added. Examples of these late arrivals include the Blue Ridge and Piedmont

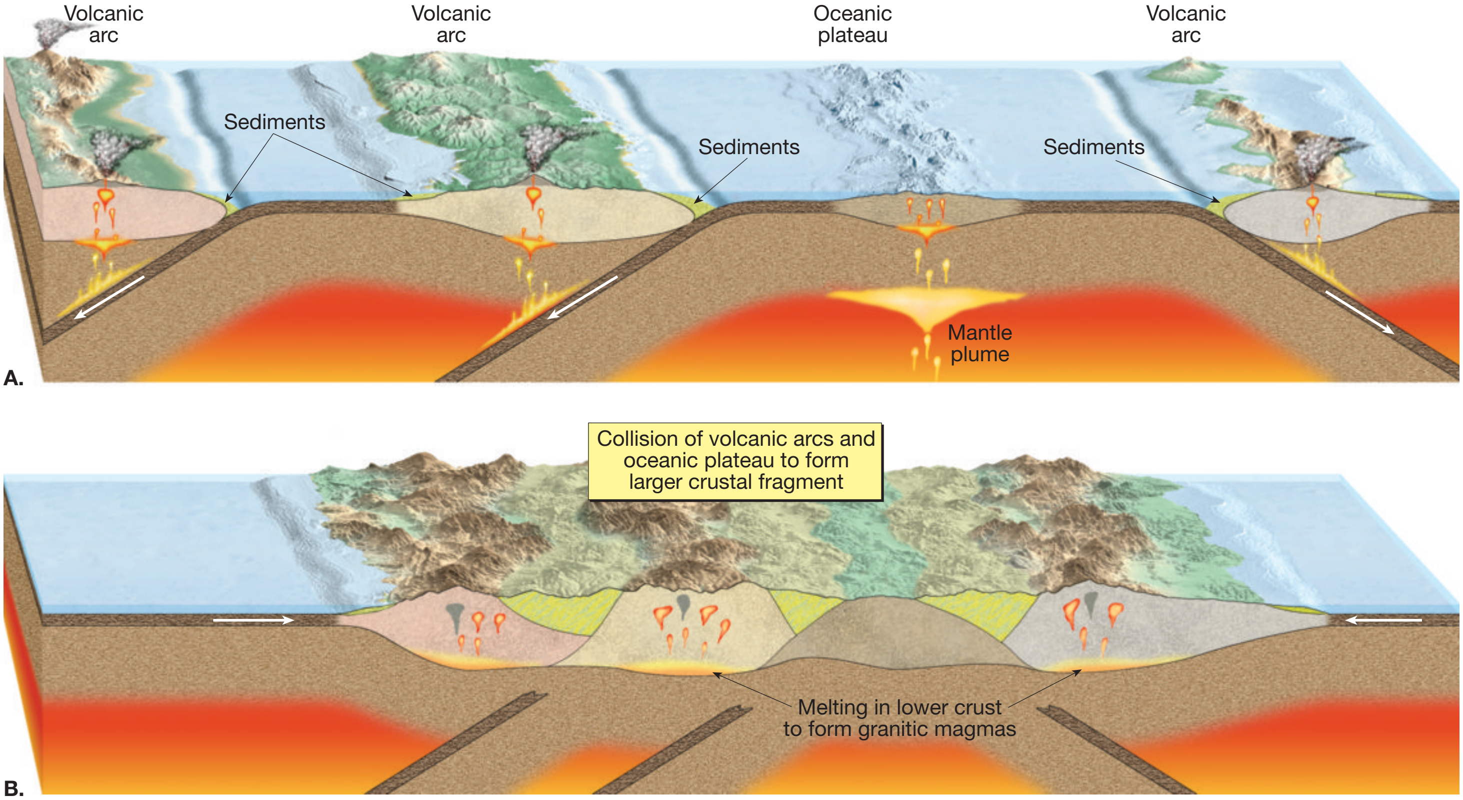


FIGURE 22.12 According to one model, the growth of large continental masses was accomplished through the collision and accretion of various types of terranes.

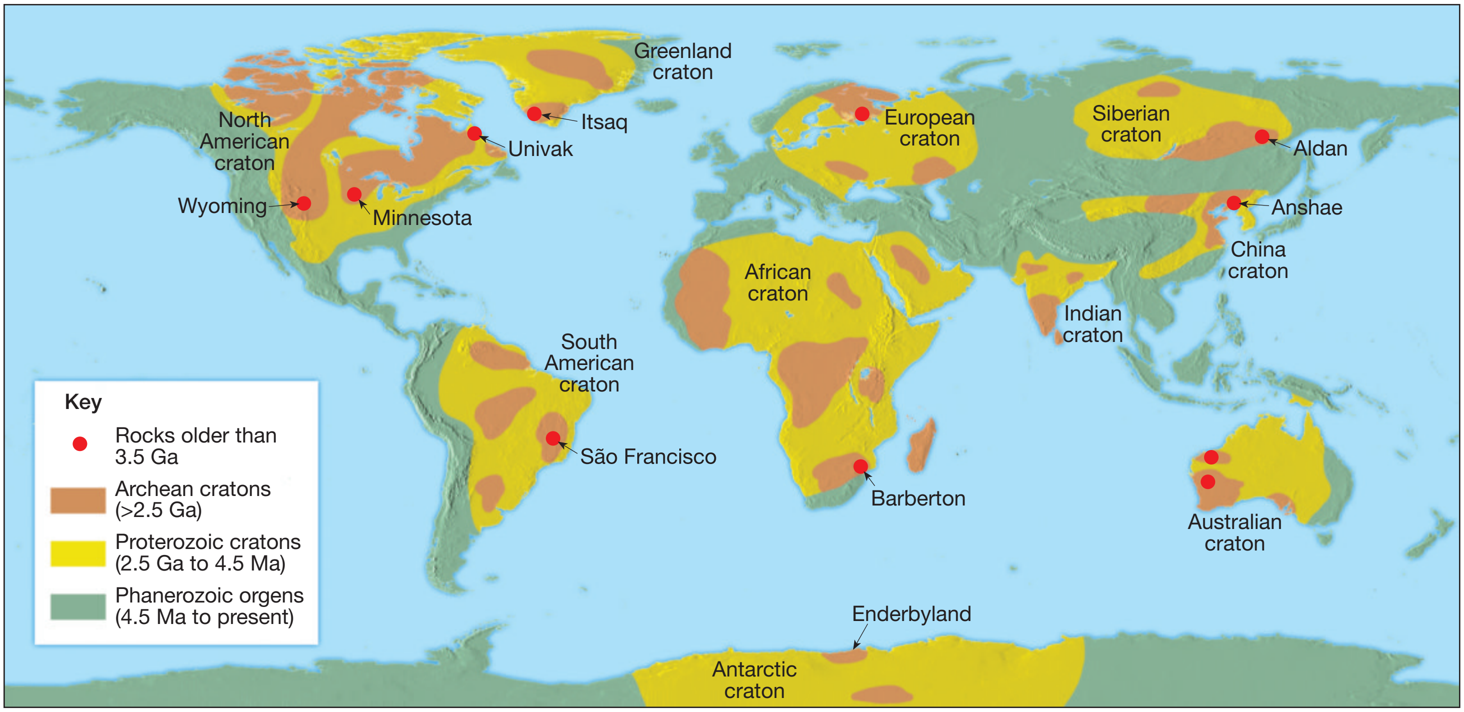


FIGURE 22.13 Illustration showing the extent of crustal material remaining from the Archean and Proterozoic eons.

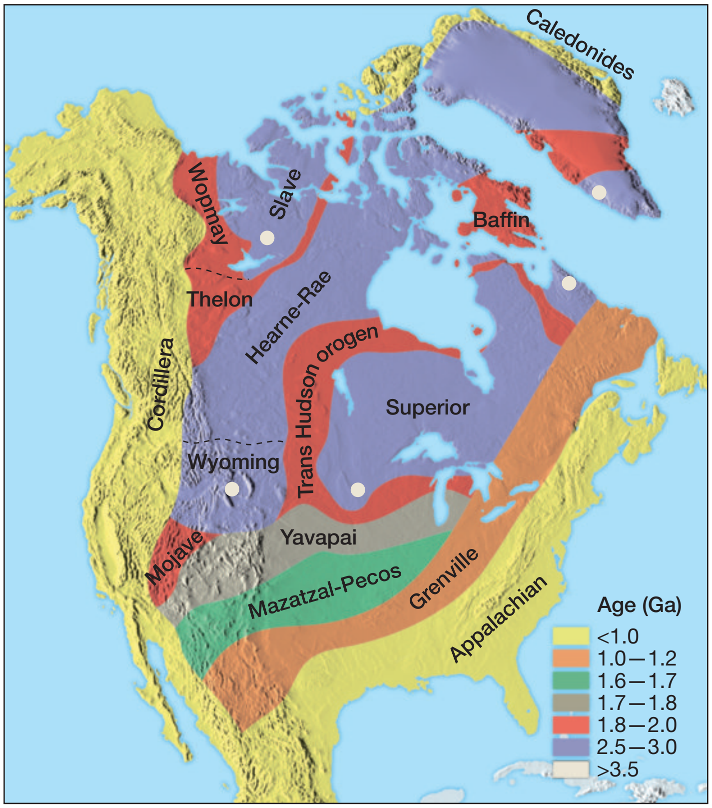


FIGURE 22.14 Map showing the major geological provinces of North America and their ages in billions of years (Ga). It appears that North America was assembled from crustal blocks that were joined by processes very similar to modern plate tectonics. These ancient collisions produced mountainous belts that include remnant volcanic island arcs trapped by the colliding continental fragments.

provinces of the Appalachians and several terranes that were added to the western margin of North America during the Mesozoic and Cenozoic eras to generate the mountainous North American Cordillera.

Supercontinents of the Precambrian

Supercontinents are large landmasses that contain all, or nearly all, of the existing continents. Pangaea was the most recent but certainly not the only supercontinent to exist in the geologic past. The earliest well-documented supercontinent, Rodinia, formed during the Proterozoic eon about 1.1 billion years ago. Although its reconstruction is still being researched, it is clear that Rodinia had a much different configuration than Pangaea (Figure 22.15). One obvious difference is that North America was located near the center of this ancient landmass.

Between 800 and 600 million years ago, Rodinia gradually split apart and the pieces dispersed. By the close of the Precambrian, many of the fragments had reassembled to produce a large landmass located in the Southern Hemisphere called *Gondwana*. Sometimes considered a supercontinent in its own right, Gondwana was comprised mainly of present-day South America, Africa, India, Australia, and Antarctica (Figure 22.16). Other continental fragments also formed—North America, Siberia, and northern Europe. We will consider the fate of these Precambrian landmasses later in the chapter.

Supercontinent Cycle The idea that rifting and dispersal of one supercontinent is followed by a long period during

FIGURE 22.15 Simplified drawing showing one of several possible configurations of the supercontinent Rodinia. For clarity, the continents are drawn with somewhat modern shapes, which was not the case 1 billion years ago. (After P. Hoffman, J. Rogers, and others)

which the fragments are gradually reassembled into a new supercontinent having a different configuration is called the **supercontinent cycle.** As indicated earlier the assembly and dispersal of supercontinents had a profound impact on the evolution of Earth's continents. In addition, this phenomenon has greatly influenced global climates as well as contributing to periodic episodes of rising and falling sea level.

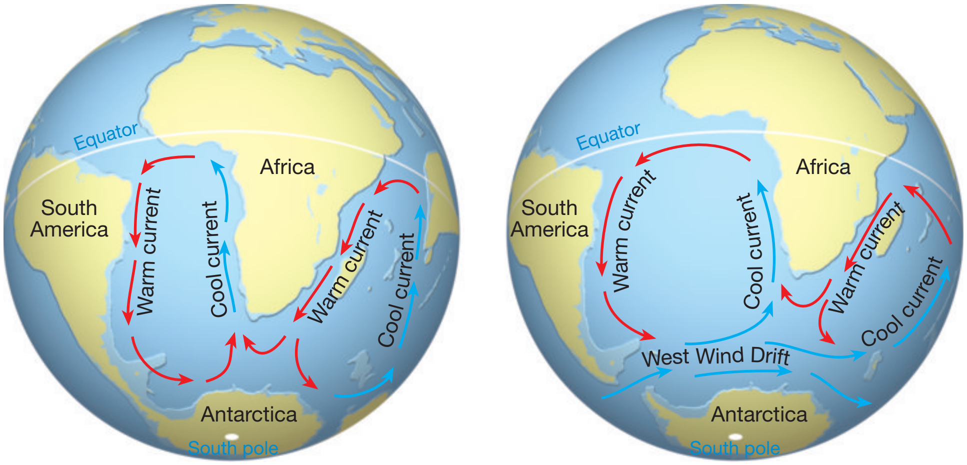
Climate and Supercontinents Moving continents change the patterns of ocean currents and affect global wind patterns, resulting in a change in the distribution of temperature and precipitation. One relatively recent example of how the dispersal of a supercontinent influenced climate relates to the formation of the Antarctic ice sheet. Although eastern Antarctica remained over the South Pole for more than 100 million years, it was not glaciated until about 25 million years ago. Prior to this time South America was connected to the Antarctic Peninsula. This arrangement of landmasses helped maintain a circulation pattern in which warm ocean currents reached the coast of Antarctica as shown in Figure 22.17A. This is similar to how the modern Gulf Stream keeps Iceland mostly ice free—despite its name. However, as South America separated from Antarctica, it moved northward, permitting ocean circulation to flow from west to east around the entire continent of Antarctica (Figure 22.17B). This current, called the West Wind Drift, effectively cut off the entire Antarctic coast from the warm, poleward-directed currents in the southern oceans. This led to eventual covering of almost the entire Antarctic landmass with glacial ice.

A. Continent of Gondwana

B. Continents not a part of Gondwana

FIGURE 22.16 Reconstruction of Earth as it may have appeared in late Precambrian time. The southern continents were joined into a single landmass called Gondwana. Other landmasses that were not part of Gondwana include North America, northwestern Europe and northern Asia. (After P. Hoffman, J. Rogers, and others)

Local and regional climates have also been impacted by large mountain systems that formed through the collision of large cratons. Because of their high elevations, mountains exhibit markedly lower average temperatures than the surrounding lowlands. In addition, when air is forced to rise



A. 50 million years ago **B.** Present

FIGURE 22.17 Comparison of the oceanic circulation pattern 50 million years ago with that of the present. When South America separated from Antarctica the West Wind Drift developed, which effectively isolated the entire Antarctic coast from the warm, poleward-directed currents in the southern oceans. This led to the eventual covering of much of Antarctica with glacial ice.

over these lofty structures, lifting "squeezes" moisture from the air, leaving the region downwind relatively dry. A modern analogy is the wet, heavily forested western slopes of the Sierra Nevada and the dry climate of the Great Basin desert that lies directly to the east (see Figure 19.4, p. 519). Furthermore, large mountain systems, depending on their elevation and latitude, may support extensive valley glaciation, as the Himalayas do today.

Because early Precambrian life was very primitive (mostly bacteria) and left few remains, little is known about Earth's climate during this period. However, evidence from the rock record indicates that continental glaciation occurred several times in the geologic past, including the late Precambrian.

Sea Level Changes and Supercontinents Significant sea level changes have been documented numerous times in geologic history and many appear related to the assembly and dispersal of supercontinents. If sea level rises, or the average elevation of a landmass is lowered by erosional or tectonic forces, shallow seas advance onto the continents. The result is the deposition of widespread marine sediments, often a few hundred meters thick. Evidence for such periods when the seas advanced onto the continents include thick sequences of ancient sedimentary rocks that blanket large areas of modern landmasses.

Sea level tends to rise during a period of "global warming" that results in melting of glacial ice. (This appears to be happening today, see chapter 21.) Naturally, during periods of cooling, glacial ice will accumulate, sea level will drop, and shallow inland seas will retreat, thereby exposing large areas of the continental margins.

The supercontinent cycle and sea level changes are directly related to the rates of *seafloor spreading*. When the rate of spreading is rapid, as it is along the East Pacific Rise today, the production of warm oceanic crust is also high. Because warm oceanic crust is less dense (takes up more space) than cold crust, fast spreading ridges occupy more

A. **B.**

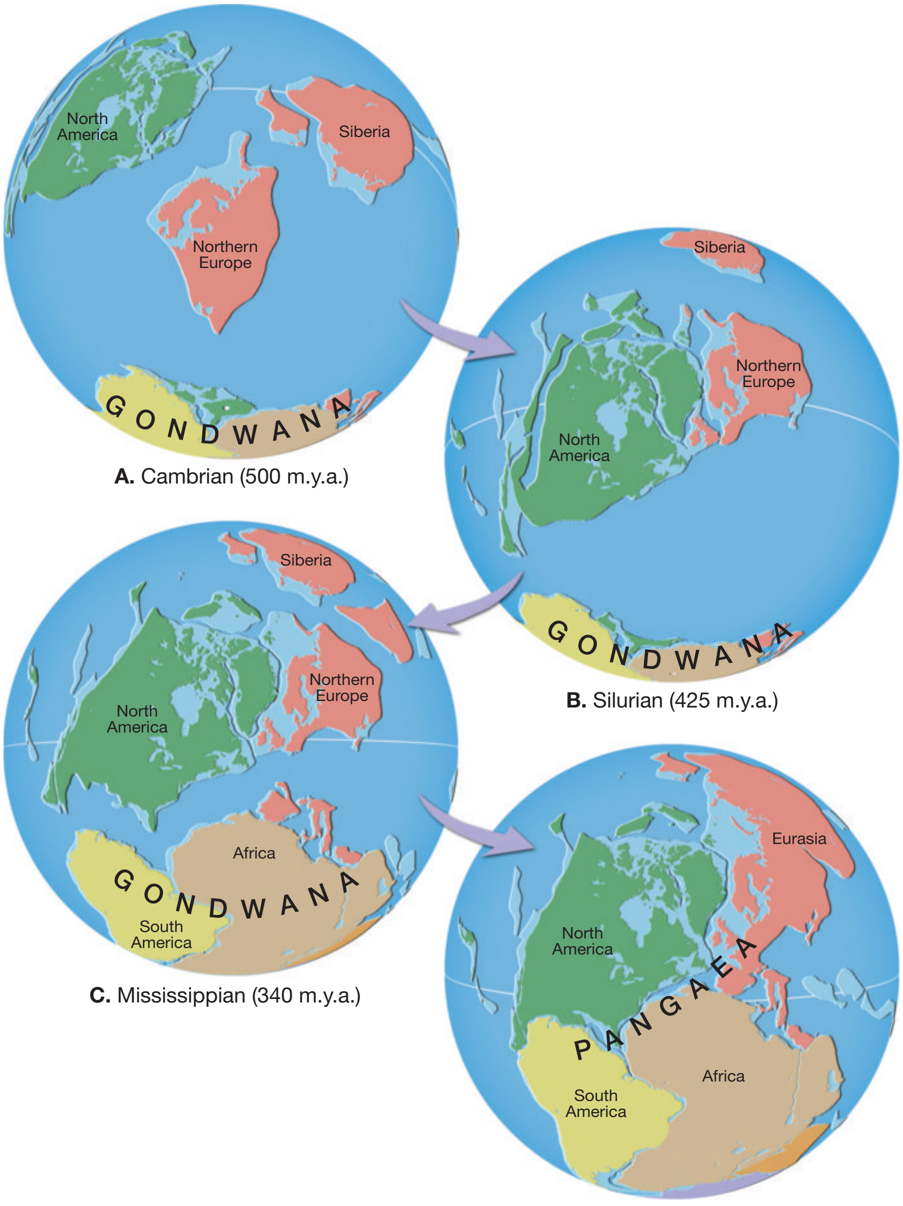
FIGURE 22.18 Fossils of common Paleozoic life forms. **A.** Natural cast of a trilobite. Trilobites dominated the early Paleozoic ocean, scavenging food from the bottom. **B.** Extinct coiled cephalopods. Like their modern descendants, these were highly developed marine organisms. (Photos courtesy of E.J. Tarbuck) volume in the ocean basins than slow spreading centers. (Think of getting into a bathtub full of water.) As a result, when the rates of seafloor spreading increase, sea level rises. This, in turn, causes shallow seas to advance onto the low-lying portions of the continents.

Phanerozoic History: The Formation of Earth's Modern Continents

The time span since the close of the Precambrian, called the *Phanerozoic eon,* encompasses 542 million years and is divided into three eras: Paleozoic, Mesozoic, and Cenozoic. The beginning of the Phanerozoic is marked by the appearance of the first life forms with hard parts such as shells, scales, bones, or teeth that greatly enhance the chance of an organism being preserved in the fossil record (Figure 22.18).* Consequently, the study of Phanerozoic crustal history was aided by the availability of fossils, which facilitated much more refined methods for dating geologic events. Moreover, because every organism is associated with its own particular niche, the greatly improved fossil record provided invaluable information for deciphering ancient environments.

Paleozoic History

As the Paleozoic era opened, North America was a land with no living things, either plant or animal. There were no Appalachian or Rocky Mountains; the continent was a largely barren lowland. Several times during the early Paleozoic, shallow seas moved inland and then receded from the interior of the continent. Deposits of clean sandstones mark the shorelines of these shallow seas in the mid-continent. One deposit, the St. Peter sandstone, is mined extensively in Missouri and Illinois for the manufacture of glass, filters, abrasives, and for "tract sand" used in oil and natural gas drilling.



A. Cambrian (500 m.y.a.)

B. Silurian (425 m.y.a.)

C. Mississippian (340 m.y.a.)

D. Triassic (250 m.y.a.)

FIGURE 22.19 During the late Paleozoic, plate movements were joining together the major landmasses to produce the supercontinent of Pangaea. (After P. Hoffman, J. Rogers, and others)

Formation of Pangaea One of the major events of the Paleozoic was the formation of the supercontinent of Pangaea. It began with a series of collisions that gradually joined North America, Europe, Siberia, and other smaller crustal fragments (Figure 22.19). These events eventually generated a large northern continent called *Laurasia.* This landmass was located in the tropics where warm wet conditions led to the formation of vast swamps that ultimately became the coal which fueled the Industrial Revolution of the 1800s and that we still use in large quantities today. During the early Paleozoic, the vast southern continent of Gondwana encompassed five continents—South America, Africa, Australia, Antarctica, India, and perhaps portions of China. Evidence of an extensive continental glaciation places this landmass near the South Pole! By the end of the Paleozoic, Gondwana had migrated northward to collide with Laurasia, culminating in the formation of the supercontinent of Pangaea.

The accretion of Pangaea spans more than 200 million years and resulted in the formation of several mountain belts. This time period saw the collision of northern Europe

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*For more about this see the discussion on "Conditions Favoring Preservation" in Chapter 9, p. 256.

(mainly Norway) with Greenland to produce the Caledonian Mountains. At roughly the same time at least two microcontinents collided with and deformed the sediments that had accumulated along the eastern margin of North America. This event was an early phase in the formation of the Appalachian Mountains.

By the late Paleozoic, the joining of northern Asia (Siberia) and Europe created the Ural Mountains. Northern China is also thought to have accreted to Asia by the end of the Paleozoic, whereas southern China may not have become part of Asia until after Pangaea had begun to rift apart. (Recall that India did not accrete to Asia until about 45 million years ago.)

Pangaea reached its maximum size about 250 million years ago as Africa collided with North America (Figure 22.19D). This event marked the final episode of growth in the long history of the Appalachian Mountains (see Chapter 14).

Mesozoic History

Spanning about 186 million years, the Mesozoic era is divided into three periods: the Triassic, Jurassic, and Cretaceous. Major geologic events of the Mesozoic include the breakup of Pangaea and the evolution of our modern ocean basins.

The Mesozoic era began with much of the world's land above sea level. In fact, in North America no period exhibits a more meager sedimentary record than the Triassic period. Of the exposed Triassic strata, most are red sandstones and mudstones that lack marine fossils, features that indicate a terrestrial environment. (The red color in sandstone comes from the oxidation of iron.)

As the Jurassic period opened, the sea invaded western North America. Adjacent to this shallow sea, extensive continental sediments were deposited on what is now the Colorado Plateau. The most prominent is the Navajo Sandstone, windblown, white quartz sandstone that, in places, approaches a thickness of 300 meters (1000 feet). These remnants of massive dunes indicate that a major desert occupied much of the American Southwest during early Jurassic times (Figure 22.20). Another well-known Jurassic deposit is the Morrison Formation—the world's richest storehouse of dinosaur fossils. Included are the fossilized bones of huge dinosaurs such as Apatosaurus (formerly Brontosaurus), Brachiosaurus, and Stegosaurus.

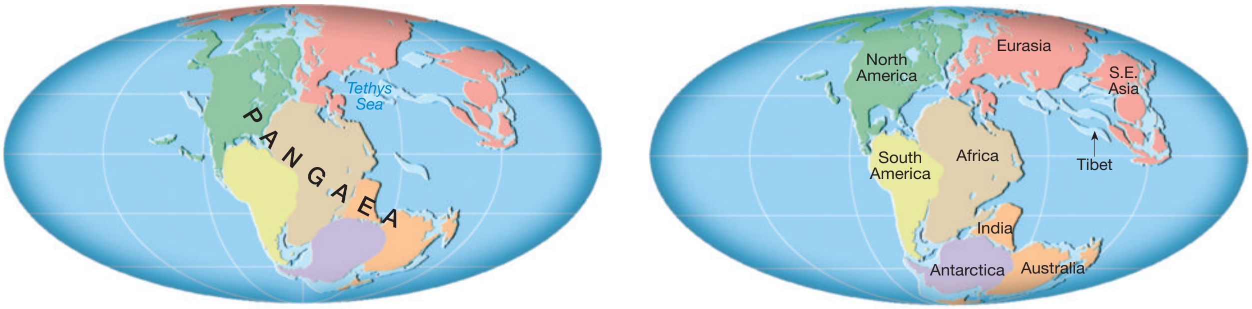
As the Jurassic period gave way to the Cretaceous, shallow seas once again invaded much of western North America, as well as the Atlantic and Gulf coastal regions. This led to the formation of great swamps similar to those of the Paleozoic era. Today the Cretaceous coal deposits in the western United States and Canada are very important economically. For example, on the Crow Native American reservation in Montana, there are nearly 20 billion tons of high-quality coal of Cretaceous age.

Another major event of the Mesozoic era was the breakup of Pangaea (Figure 22.21). About 165 million years ago a rift developed between what is now North America and western Africa, marking the birth of the Atlantic Ocean. As Pangaea gradually broke apart, the westward-moving North American plate began to override the Pacific basin (see Figure 13.26, p. 371). This tectonic event marked the beginning of a continuous wave of deformation that moved inland along the entire western margin of North America. By Jurassic times, subduction of the Farallon plate had begun to produce the chaotic mixture of rocks that exist today in the Coast Ranges of California. Further inland, igneous activity was widespread, and for nearly 60 million years volcanism was rampant as huge masses of magma rose to within a few miles of the surface. The remnants of this activity include the granitic plutons of the Sierra Nevada as well as the Idaho batholith, and British Columbia's Coast Range batholith.

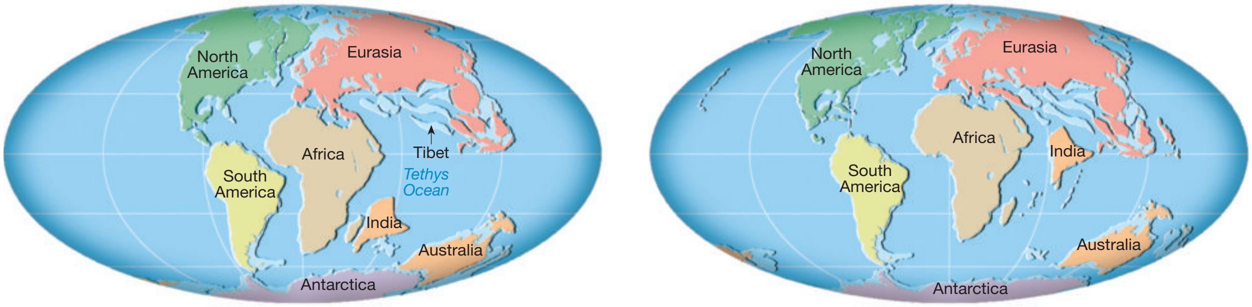
Tectonic activity that began in the Jurassic continued throughout the Cretaceous. Compressional forces moved huge rock units in a shinglelike fashion toward the east. Across much of North America's western margin, older rocks were thrust eastward over younger strata, for distances exceeding 150 kilometers (90 miles). This ultimately formed the vast Northern Rockies that extend from Wyoming to Alaska.

As the Mesozoic came to an end, the southern ranges of the Rocky Mountains formed. This mountain-building event, called the Laramide Orogeny, occurred when large blocks of deeply buried Precambrian rocks were lifted nearly vertically along steeply dipping faults, upwarping the overlying younger sedimentary strata. The mountain ranges produced by the Laramide Orogeny include the Front Range of Colorado, the Sangre de Cristo of New Mexico and Colorado, and the Bighorns of Wyoming (see Box 14.2, p. 392).

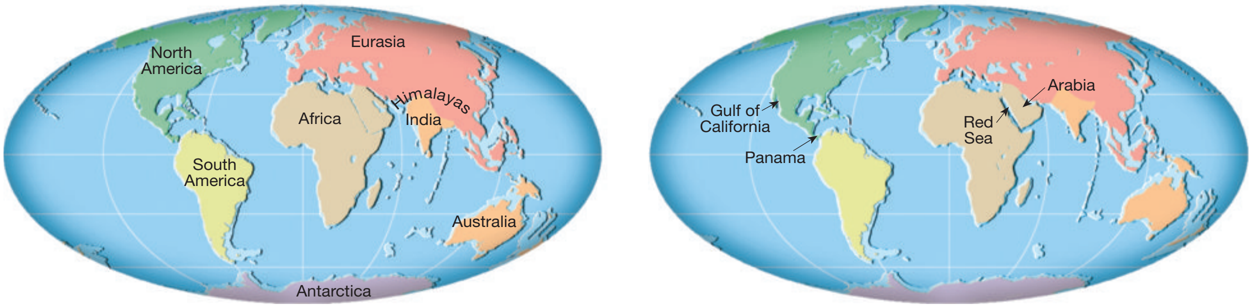
FIGURE 22.20 These massive, cross-bedded sandstone cliffs in Zion National Park are the remnants of ancient sand dunes. (Photo by Michael Collier)



A. 200 Million Years Ago (Late Triassic Period) **B.** 150 Million Years Ago (Late Jurassic Period)



C. 90 Million Years Ago (Cretaceous Period) **D.** 50 Million Years Ago (Early Cenozoic)



E. 20 Million Years Ago (Late Cenozoic) **F.** Present

FIGURE 22.21 Several views of the breakup of Pangaea over a period of 200 million years.

Cenozoic History

The Cenozoic era, or "era of recent life," encompasses the last 65.5 million years of Earth history. It is during this span that the physical landscapes and life-forms of our modern world came into being. The Cenozoic era represents a much smaller fraction of geologic time than either the Paleozoic or the Mesozoic. Although shorter, it nevertheless possesses a rich history because the completeness of the geologic record improves as time approaches the present. The rock formations of this time span are more widespread and less disturbed than those of any preceding time period.

The Cenozoic era is divided into two periods of very unequal duration—the Tertiary and the Quaternary. The Tertiary period includes five epochs and embraces about 63 million years, practically all of the Cenozoic era. The Quaternary period consists of two epochs that represent only the last 2 million years of geologic time.

Most of North America was above sea level throughout the Cenozoic era. However, the eastern and western margins of the continent experienced markedly contrasting events because of their different relationships with plate boundaries. The Atlantic and Gulf coastal regions, far removed from an active plate boundary, were tectonically stable. By contrast, western North America was the leading edge of the North American plate. As a result, plate interactions during the Cenozoic gave rise to many events of mountain building, volcanism, and earthquakes.

Eastern North America The stable continental margin of eastern North America was the site of abundant marine sedimentation. The most extensive deposition surrounded the Gulf of Mexico, from the Yucatán Peninsula to Florida. Here, the great buildup of sediment caused the crust to downwrap and produced numerous faults. In many instances, the faults created structures in which oil and natural gas accumulated. Today, these and other petroleum traps are the most economically important resource of the Gulf Coast, as evidenced by the numerous offshore drilling platforms.

By early Cenozoic time, most of the original Appalachians had been eroded to a low plain. Later, isostatic adjustments raised the region once again, rejuvenating its rivers. Streams eroded with renewed vigor, gradually sculpting the surface into its present-day topography. The sediments from this erosion were deposited along the eastern margin of the continent, where they attained a thickness of many kilometers. Today, portions of the strata deposited during the Cenozoic are exposed as the gently sloping Atlantic and Gulf coastal plains. It is here that much of the population of the eastern and southeastern United States resides.

Western North America In the West, the Laramide Orogeny that built the southern Rocky Mountains was coming to an end (Figure 22.22). As erosion lowered the mountains, the basins between uplifted ranges filled with sediments. Eastward, a great wedge of sediment from the eroding Rockies was creating the Great Plains.

Beginning in the Miocene epoch about 20 million years ago, a broad region from northern Nevada into Mexico experienced crustal extension that created more than 150 fault-block mountain ranges. Today, they rise abruptly above the adjacent basins, creating the Basin and Range Province (see Chapter 14).

As the Basin and Range Province was forming, the entire western interior of the continent was gradually uplifted. This event re-elevated the Rockies and rejuvenated many of the West's major rivers. As the rivers became incised, many spectacular gorges were formed, including the Grand Canyon of the Colorado River, the Grand Canyon of the Snake River, and the Black Canyon of the Gunnison River.

Volcanic activity was also common in the West during much of the Cenozoic. Beginning in the Miocene epoch, great volumes of fluid basaltic lava flowed from fissures in portions of present-day Washington, Oregon, and Idaho. These eruptions built the extensive (1.3 million square miles) Columbia Plateau. Immediately west of the Columbia Plateau, volcanic activity was different in character. Here, more viscous magmas with higher silica contents erupted explosively, creating the Cascades, a chain of stratovolcanoes extending from northern California into Canada. Some of these volcanoes are still classified as active.

A final episode of deformation occurred in the West in late Tertiary time, creating the Coast Ranges that stretch along the Pacific Coast. Meanwhile, the Sierra Nevada were faulted and uplifted along their eastern flank, forming the imposing mountain front we know today.

As the Tertiary period drew to a close, the effect of mountain building, volcanic activity, isostatic adjustments, and extensive erosion and sedimentation had created a physical landscape very similar to the configuration of today. All that remained of Cenozoic time was the final 2 million year episode called the Quaternary period. During this most recent (and current) phase of Earth history, in which humans evolved, the action of the glacial ice, wind, and running water added the finishing touches.

Earth's First Life

The oldest fossils show that life on Earth was established at least 3.5 billion years ago. Microscopic fossils similar to modern cyanobacteria (formerly known as blue-green algae) have been found in silica-rich chert deposits in locations worldwide. Two notable areas are in southern Africa, where the rocks date to more than 3.1 billion years, and in the Gunflint Chert (named for its use in flintlock rifles) of Lake Superior. Chemical traces of organic matter in even older rocks have led paleontologists to conclude that life may have existed 3.8 billion years ago.

How did life begin? A requirement for life, in addition to a hospitable environment, is the chemical raw materials needed to form life's critical molecules, DNA, RNA, and proteins. One of the building blocks of these substances are organic compounds called *amino acids.* The first amino acids may have been synthesized from methane and ammonia which were plentiful in Earth's primitive atmosphere. The question remains whether these gases could have been easily reorganized into useful organic molecules by ultraviolet light. Or lightning may have been the impetus, as the well-known experiments conducted by Stanley Miller and Harold Urey attempted to demonstrate.

Other researchers suggest that amino acids arrived ready-made, delivered by asteroids or comets that collided

FIGURE 22.22 San Juan Mountains near Telluride, Colorado, are one of several ranges that make up the Rocky Mountains. (Photo by Jim Steinberg/Photo Researchers, Inc.)

with a young Earth. A group of meteorites (debris from asteroids and comets that strike Earth) called *carbonaceous chrondrites* are known to contain amino acidlike organic compounds. Maybe early life had an extraterrestrial beginning.

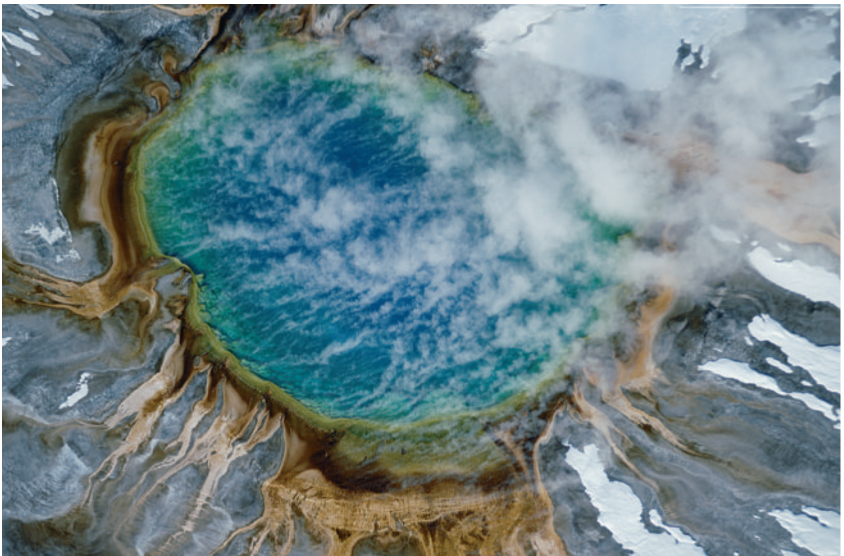
Yet another hypothesis proposes that the organic material needed for life came from the methane and hydrogen sulfide that spews from deep-sea hydrothermal vents. The study of modern bacteria and other "hyperthermophiles" that live around hydrothermal vents (black smokers) suggests that life may have formed in this extreme environment, where temperatures exceed the boiling point of water.

Is it possible that life originated near a hydrothermal vent deep on the ocean floor, or within a hot spring similar to those in Yellowstone National Park (Figure 22.23)? Some origin-of-life researchers think that this scenario is highly improbable as the scalding temperatures would have destroyed any early types of self-replicating molecules. They argue that life's first home would have been along sheltered stretches of ancient beaches, where waves and tides would have brought together various organic materials formed in the Precambrian oceans.

Regardless of where life originated, change was inevitable (Figure 22.24). The first known organisms were single-cell bacteria that belong to the group called **prokaryotes** which means their genetic material (DNA) is not separated from the rest of the cell by a nucleus. Because oxygen was absent from Earth's early atmosphere and oceans, the first organisms employed anaerobic (without oxygen) metabolism to extract energy from "food." Their food source was likely organic molecules in their surroundings, but the supply of this material was limited. Then a type of bacteria evolved that used solar energy to synthesize organic compounds (sugars). This event was an important turning point in evolution—for the first time organisms had the capability of producing food for themselves as well as for other organisms.

Recall that photosynthesis by ancient cyanobacteria, a type of prokaryote, contributed to the gradual rise in the level of oxygen, first in the ocean and then in the atmosphere. Thus, these early organisms radically transformed our planet. Fossil evidence for the existence of these microscopic bacteria includes distinctively layered mounds of calcium carbonate, called **stromatolites** (Figure 22.25A). Stromatolites are not actually the remains of organisms, but limestone mats built up by lime-accreting bacteria. Strong evidence for the origin of these ancient fossils is the close similarity they have to modern stromatolites found in Shark Bay, Australia (Figure 22.25B).

FIGURE 22.23 The Grand Prismatic Pool, Yellowstone National Park, Wyoming. This hot-water pool gets its blue color from several species of heat-tolerant cynobacteria. (Photo by Jim Brandenburg/Minden Pictures)



The oldest fossils of more advanced organisms, called **eukaryotes,** are about 2.1 billion years old. Like prokaryotes, the first eukaryotes were microscopic, water-dwelling organisms. Their cellular structure did, however, contain nuclei. It is these primitive organisms that gave rise to essentially all of the multicelled organisms that now inhabit our planet—trees, birds, fishes, reptiles, and even humans.

During much of the Precambrian, life consisted exclusively of single-celled organisms. It wasn't until perhaps 1.5 billion years ago that multicelled eukaryotes evolved. Green algae, one of the first multicelled organisms, contained chloroplasts (used in photosynthesis) and were the forbears of modern plants. The first primitive marine animals did not appear until somewhat later, perhaps 600 million years ago; we just do not know for sure.

Fossil evidence suggests that organic evolution progressed at an excruciatingly slow pace until the end of the Precambrian. At this time, Earth's continents were barren, and the oceans were populated primarily by organisms too small to be seen with the naked eye. Nevertheless, the stage was set for the evolution of larger and more complex plants and animals at the dawn of the Paleozoic.

Paleozoic Era: Life Explodes

The Cambrian period marks the beginning of the Paleozoic era, about 542 million years ago. This time span saw the emergence of new animal forms, the likes of which have never been seen, before or since. All major invertebrate (animals lacking backbones) groups made their appearance, including jellyfish, sponges, worms, mollusks (clams), and arthropods (insects, crabs). This huge expansion in biodiversity is often referred to as the *Cambrian explosion* (see Box 22.1).

But did it happen? Evidence suggests that these life forms may have gradually diversified late in the Precambrian, but were not preserved in the rock record. After all, the Cambrian period marks the first time organisms developed hard parts. Is it possible that the Cambrian event was an explosion of animal forms that grew in size and became "hard" enough to be fossilized?

Paleontologists may never definitively answer that question. They know, however, that hard parts clearly served many useful purposes and aided adaptations to new lifestyles. Sponges, for example, developed a network of fine interwoven silica spicules that allowed them to grow larger and more erect, and thus capable of extending above the seafloor in search of food. Mollusks (clams and snails)

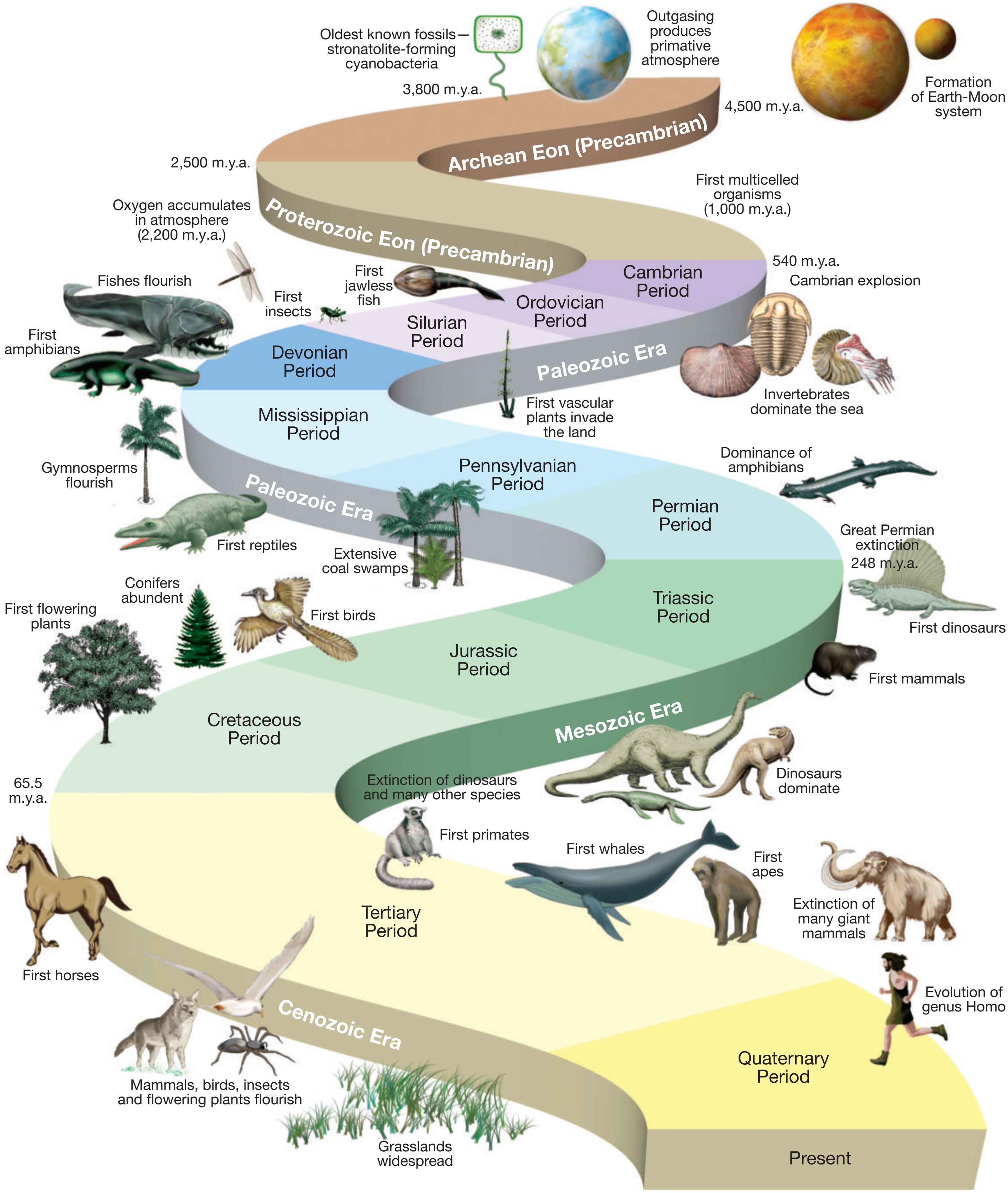


FIGURE 22.24 The evolution of life through geologic time.

FIGURE 22.25 Stromatolites are among the most common Precambrian fossils. **A.** Precambrian fossil stromatolites composed of calcium carbonate deposited by algae in the Helena Formation, Glacier National Park. (Photo by Ken M. Johns/Photo Researchers, Inc.) **B.** Modern stromatolites growing in shallow saline seas, western Australia. (Photo by Bill Bachman/Photo Researchers, Inc.)

BOX 22.1 ▶ UNDERSTANDING EARTH

The Burgess Shale

The possession of hard parts greatly enhances the likelihood of organisms being preserved in the fossil record. Nevertheless, there have been rare occasions in geologic history when large numbers of soft-bodied organisms have been preserved. The Burgess Shale is one well-known example. Located in the Canadian Rockies near the town of Field in southeastern British Columbia, the site was discovered in 1909 by Charles D. Walcott of the Smithsonian Institution.

The Burgess Shale is a site of exceptional fossil preservation and records a diversity of animals found nowhere else (Figure 22.A). The animals of the Burgess Shale lived shortly after the *Cambrian explosion,* a time when there had been a huge expansion of marine biodiversity. Its beautifully preserved fossils represent our most complete and authoritative snapshot of Cambrian life, far better than deposits containing only fossils of organisms with hard parts. To date, more than 100,000 unique fossils have been found.

The animals preserved in the Burgess Shale inhabited a warm, shallow sea adjacent to a large reef that was part of the continental margin of North America. During the Cambrian, the North American continent was in the tropics astride the equator. Life was restricted to the ocean, and the land was barren and uninhabited.

What were the circumstances that led to the preservation of the many life forms found in the Burgess Shale? The animals lived in and on underwater mudbanks that formed as sediment accumulated on the outer margins of a reef adjacent to a steep escarpment (cliff). Periodically the accumulation of muds became unstable and the slumping and sliding sediments moved down the escarpment as turbidity currents. These flows transported the animals in a turbulent cloud of sediment to the base of the reef where they were buried. Here, in an environment lacking oxygen, the buried carcasses were protected from scavengers and decomposing bacteria. This process occurred again and again, building a thick sequence of fossil-rich sedimentary layers. Beginning about 175 million years ago, mountain-building forces elevated these strata from the seafloor and moved them many kilometers eastward along huge faults to their present location in the Canadian Rockies.

The Burgess Shale is one of the most important fossil discoveries of the 20th century. Its layers preserve for us an intriguing glimpse of early animal life that is more than a half billion years old.

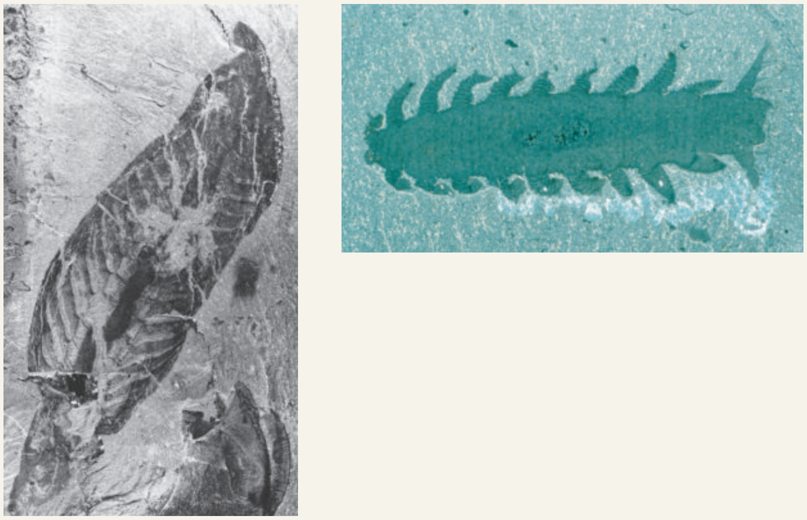


FIGURE 22.A Two examples of Burgess Shale fossils. *Thumatilon walcotti* (left) was a relatively large (up to 20 centimeters, or 8 inches, long) leaflike animal. (Photo by National Museum of Natural History) *Aysheaia pedunculata* (right) was an ancient relative of modern velvet worms and may have clung to soft sponges with tiny hooks on its feet. (Photo by Royal Tyrrell Museum)

secreted external shells of calcium carbonate that provided protection and allowed body organs to function in a more controlled environment. The successful trilobites developed an exoskeleton of a protein called chitin (similar to a human fingernail), which permitted them to search for food by burrowing through soft sediment (Figure 22.18A).

Early Paleozoic Life-Forms

The Cambrian period was the golden age of *trilobites.* More than 600 genera of these mud-burrowing scavengers flourished worldwide. The Ordovician marked the appearance of abundant cephalopods—mobile, highly developed mollusks that became the major predators of their time (Figure 22.26). The descendants of these cephalopods include the squid, octopus, and chambered nautilus that inhabit our modern oceans. Cephalopods were the first truly large organisms on Earth, one species reaching a length of nearly 10 meters (30 feet).

The early diversification of animals was partly driven by the emergence of predatory lifestyles. The larger mobile cephalopods preyed on trilobites that were mostly smaller than a child's hand. The evolution of efficient movement was often associated with the evolution of greater sensory capabilities and more complex nervous systems. These animals developed sensory devices for detecting light, smells, and touch.

Approximately 400 million years ago, green algae that had adapted to survive at the water's edge, gave rise to the first multicellular land plants. The primary difficulty of sustaining plant life on land was obtaining water and staying upright despite gravity and winds. These earliest land plants were leafless, vertical spikes about the size of your index finger. However, by the end of the Devonian period, 40 million years later, the fossil record indicates the existence of forests with trees tens of meters tall.

In the oceans, fishes perfected a new form of support for the body, an internal skeleton, and were the first creatures to have jaws. Armor-plated fishes that had evolved during the Ordovician continued to adapt (Figure 22.27). Their armor plates thinned to lightweight scales that permitted increased speed and mobility. Other fishes evolved during the Devonian, including primitive sharks that had skeletons made of cartilage and bony fishes, the groups to which many modern fishes belong. Fishes, the first large vertebrates, proved to be faster swimmers than invertebrates and possessed more acute senses and larger brains. Hence, they became the dominant predators of the sea. Because of this, the Devonian period is often referred to as the "Age of the Fishes."

Vertebrates Move to Land

During the Devonian, a group of fishes called the *lobe-finned fish* began to adapt to terrestrial environments (Figure 22.28). Like their modern relative, these fishes had sacks that could be filled with air to supplement their "breathing" through gills. The first lobe-finned fish probably occupied freshwater tidal flats or small ponds near the ocean. Some began to use their fins to move from one pond to another in search of food, or to evacuate a pond that was drying up. This favored the evolution of a group of animals that could stay out of water longer and move about on land more efficiently. By the late Devonian, lobe-finned fish had evolved into air-breathing amphibians. Although they had developed strong legs, they retained a fishlike head and tail.

FIGURE 22.26 During the Ordovician period (490–443 million years ago), the shallow waters of an inland sea over central North America contained an abundance of marine invertebrates. Shown in this reconstruction are straight-shelled cephalopods, trilobites, brachiopods, snails, and corals. (© The Field Museum, Neg. # GEO80820c, Chicago)

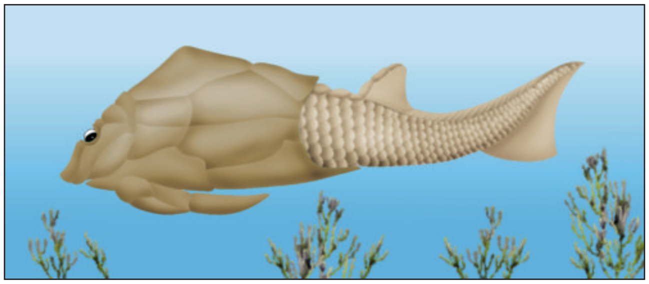


FIGURE 22.27 These placoderms, or "plate-skinned" fish were abundant during the Devonian (417–354 million years ago). (Drawing after A.S. Romer)

Modern amphibians, such as frogs, toads, and salamanders, are small and occupy limited biological niches. But conditions during the late Paleozoic were ideal for these newcomers to the land. Large tropical swamps extended across North America, Europe and Siberia that were teeming with large insects and millipedes (Figure 22.29). With no predators to speak of, amphibians diversified rapidly. Some groups took on lifestyles and forms similar to modern reptiles, such as crocodiles.

Despite their success, the early amphibians were not fully adapted to life out of the water. In fact, amphibian means "double life," because these creatures need both the watery world from which they came and the land onto which they moved. Amphibians are born in the water, as exemplified by tadpoles, complete with gills and tails. In time, these features disappear and an air breathing adult with legs emerges.

Near the end of the Paleozoic, Earth's major landmasses were joined to form the supercontinent of Pangaea (see Figure 22.19, p. 609). This redistribution of land and water along with changes in the elevations of landmasses brought pronounced changes in world climates. Broad areas of the northern continents became elevated above sea level, and the climate grew drier. These changes apparently resulted in the decline of the amphibians (see Box 22.2).

Mesozoic Era: Age of the Dinosaurs

As the Mesozoic era dawned, its life forms were the survivors of the great Permian extinction. These organisms diversified in many ways to fill the biological voids created at the close of the Paleozoic. On land, conditions favored those that could adapt to drier climates. Among plants, the gymnosperms were one such group. Unlike the first plants to invade the land, the seed-bearing gymnosperms did not depend on freestanding water for fertilization. Consequently, these plants were not restricted to a life near water's edge.

The gymnosperms quickly became the dominant trees of the Mesozoic. They included the following: cycads that

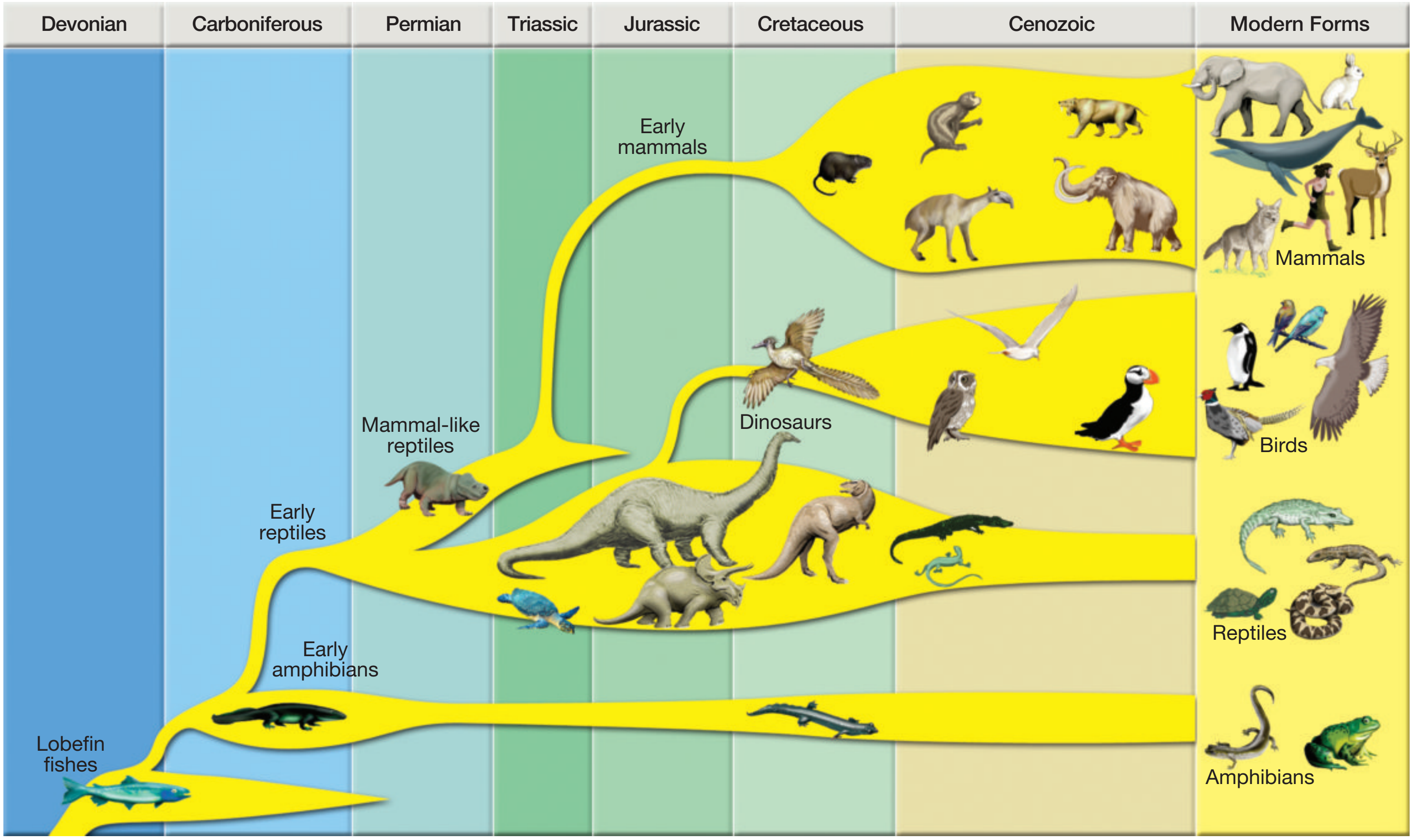


FIGURE 22.28 Relationships of various vertebrates and their evolution from a fish-like ancestor.

FIGURE 22.29 Restoration of a Pennsylvanian-age coal swamp (323 million to 290 million years ago). Shown are scale trees (left), seed ferns (lower left), and scouring rushes (right). Also note the large dragonfly. (© The Field Museum, Neg. # GEO85637c, Chicago. Photographer John Weinstein.)

resembled a large pineapple plant; ginkgoes that had fan-shaped leaves, much like their modern relatives; and the largest plants, the conifers, whose modern descendants include the pines, firs, and junipers. The best-known fossil occurrence of these ancient trees is in northern Arizona's Petrified Forest National Park. Here, huge petrified logs lie exposed at the surface, having been weathered from rocks of the Triassic Chinle Formation (Figure 22.30).

Among the animals, reptiles readily adapted to the drier Mesozoic environment, thereby relegating amphibians to the wetlands where most remain today. Reptiles were the first true terrestrial animals with improved lungs for an active lifestyle and "waterproof" skin that helped prevent the loss of body fluids. Most importantly, reptiles developed shell-covered eggs that can be laid on land. The elimination of a water-dwelling stage (like the tadpole stage in frogs) was an important evolutionary step.

Of interest is the fact that the watery fluid within the reptilian egg closely resembles seawater in chemical composition. Because the reptile embryo develops in this watery environment, the shelled egg has been characterized as a "private aquarium" in which the embryos of these land vertebrates spend their water-dwelling stage of life. With this "sturdy egg," the remaining ties to the oceans were broken, and reptiles moved inland.

The first reptiles were small, but larger forms evolved rapidly, particularly the dinosaurs. One of the largest was *Apatosaurus,* which weighed more than 30 tons and measured over 25 meters (80 feet) from head to tail. For nearly 160 million years, dinosaurs reigned supreme.

Some of the largest dinosaurs were carnivorous (*Tyrannosaurus*), whereas others were herbivorous (like ponderous *Apatosaurus*). The extremely long neck of *Apatosaurus* may have been an adaptation for feeding on tall conifer trees. However, not all dinosaurs were large. Some small forms closely resembled modern, fleet-footed lizards.

The reptiles made one of the most spectacular adaptive radiations in all of Earth history. One group, the pterosaurs, took to the air. These "dragons of the sky" possessed huge membranous wings that allowed them rudimentary flight (Figure 22.31). Another group of reptiles, exemplified by the fossil *Archaeopteryx,* led to more successful flyers: the birds. Whereas some reptiles took to the skies, others returned to the sea, including the fish-eating plesiosaurs and ichthyosaurs (Figure 22.32). These reptiles became proficient swimmers, but they retained their reptilian teeth and breathed by means of lungs.

At the close of the Mesozoic, many reptile groups became extinct. Only a few types survived to recent times, including the turtles, snakes, crocodiles, and lizards (Figure 22.33). The huge, land-dwelling dinosaurs, the marine plesiosaurs, and the flying pterosaurs are known only through the fossil record. What caused this great extinction? (See Box 22.3.)

Cenozoic Era: Age of Mammals

During the Cenozoic, mammals replaced reptiles as the dominant land animals. At nearly the same time, angiosperms (flowering plants with covered seeds) replaced

BOX 22.2 ▸ EARTH AS A SYSTEM

The Great Permian Extinction

By the close of the Permian period, a mass extinction destroyed 70 percent of all vertebrate species on land, and perhaps as much as 90 percent of all marine organisms. The late Permian extinction was the greatest of at least five mass extinctions to occur over the past 500 million years. Each extinction wreaked havoc with the existing biosphere, wiping out large numbers of species. In each case, however, the survivors formed new biological communities that were eventually more diverse than their predecessors. Thus, mass extinctions actually invigorated life on Earth, as the few hardy survivors eventually filled more niches than the ones left behind by the victims.

Several mechanisms have been proposed to explain these ancient mass extinctions. Initially, paleontologists believed they were gradual events caused by a combination of climate change and biological forces, such as predation and competition. Then, in the 1980s, a research team proposed that the mass extinction that happened 65 million years ago occurred swiftly as a result of an explosive impact by an asteroid about 10 kilometers in diameter. This event, which caused the extinction of the dinosaurs, is described in Box 22.3.

Was the Permian extinction also caused by a giant impact, like the now-famous dinosaur extinction? For many years, researchers thought so. However, scant evidence could be found of debris that would have been generated by an impact large enough to destroy many of Earth's lifeforms.

Another possible mechanism for the Permian extinction was the voluminous eruptions of basaltic lavas which began about 251 million years ago and are known to have covered thousands of square kilometers of the land. (This period of volcanism produced the Siberian Traps located in northern Russia.) The release of carbon dioxide would certainly have enhanced greenhouse warming, and the emissions of sulfur dioxide probably resulted in copious amounts of acid rain.

A recent hypothesis begins with this period of volcanism and the ensuing period of global warming but adds a new twist. These researchers agree that the additional carbon dioxide released into the atmosphere would cause rapid greenhouse warming. This alone, however, would not destroy most plants because they tend to be heat tolerant and consume CO_2 in photosynthesis. They contend, instead, that the trouble begins in the ocean rather than on land.

Most organisms on Earth use oxygen to metabolize food, as do humans. However, some forms of bacteria employ *anaerobic* (without oxygen) metabolism. Under normal conditions, oxygen from the atmosphere is readily dissolved in seawater, and is then evenly distributed to all depths by deep-water currents. This oxygen "rich" water relegates "oxygen-hating" anaerobic bacteria to anoxic (oxygen free) environments found in deep-water sediments.

The greenhouse warming associated with the vast outpouring of volcanic debris, however, would have warmed the ocean surface, thereby significantly reducing the amount of oxygen that seawater would absorb (Figure 22.B). This condition favors deep-sea anaerobic bacteria, which generate toxic hydrogen sulfide as a waste gas. As these organisms proliferated, the amount of hydrogen sulfide dissolved in seawater would have steadily increased. Eventually, the concentration of hydrogen sulfide reached a threshold and great bubbles of this toxin exploded into the atmosphere (Figure 22.B). On land, hydrogen sulfide was lethal to both plants and animals, but oxygen-breathing marine life would have been hit hardest.

How plausible is this scenario? Remember that the ideas that were just described represent a hypothesis, a tentative explanation regarding a set of observations. Additional research about this and other hypotheses that relate to the Permian extinction continues.

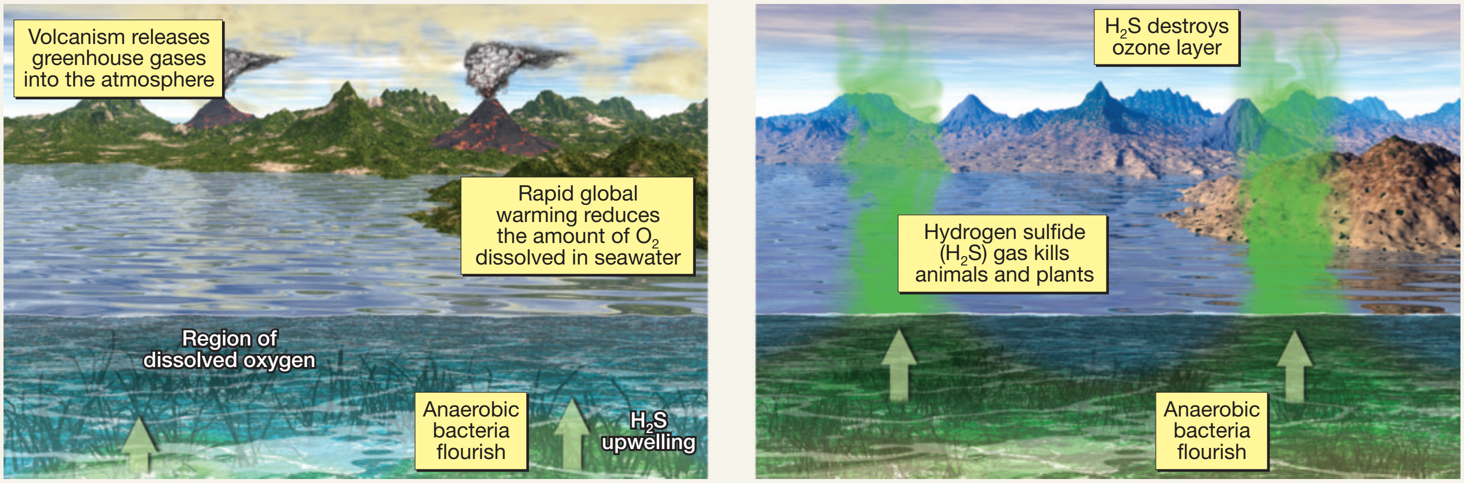


FIGURE 22.B Model for the "Great Permian Extinction". Extensive volcanism released greenhouse gases which resulted in extreme global warming. This condition reduced the amount of oxygen dissolved by seawater. This, in turn, favored "oxygen-hating" anaerobic bacteria, which generated toxic hydrogen sulfide as a waste gas. Eventually, the concentration of hydrogen sulfide reached a threshold and great bubbles of this toxin exploded into the atmosphere, wreaking havoc on organisms on land, but oxygen-breathing marine life was hit the hardest.

BOX 22.3 ▶ UNDERSTANDING EARTH

Demise of the Dinosaurs

The boundaries between divisions on the geologic time scale represent times of significant geological and/or biological charge. Of special interest is the boundary between the Mesozoic era ("middle life") and Cenozoic era ("recent life"), about 65 million years ago. Around this time, about three-quarters of all plant and animal species died out in a *mass extinction.* This boundary marks the end of the era in which dinosaurs and other reptiles dominated the landscape and the beginning of the era when mammals become very important (Figure 22.C). Because the last period of the Mesozoic is the Cretaceous (abbreviated K to avoid confusion with other "C" periods), and the first period of the Cenozoic is the Tertiary (abbreviated T), the time of this mass extinction is called the *Cretaceous–Tertiary* or *KT boundary.*

The extinction of the dinosaurs is generally attributed to this group's inability to adapt to some radical change in environmental conditions. What event could have triggered the rapid extinction of the dinosaurs—one of the most successful groups of land animals ever to have lived?

The most strongly supported hypothesis proposes that about 65 million years ago our planet was struck by a large carbonaceous meteorite, a relic from the formation of the solar system. The errant mass of rock was approximately 10 kilometers in diameter and was traveling at about 90,000 kilometers per hour at impact. It collided with the southern portion of North America in what is now Mexico's Yucatán Peninsula but at the time was a shallow tropical sea (Figure 22.D). The energy released by the impact is estimated to have been equivalent to 100 million megatons (*mega* = million) of high explosives.

For a year or two after the impact, suspended dust greatly reduced the sunlight reaching Earth's surface. This caused global cooling ("impact winter") and inhibited photosynthesis, greatly disrupting food production. Long after the dust settled, carbon dioxide, water vapor, and sulfur oxides that had been added to the atmosphere by the blast remained. If significant quantities of sulfate aerosols formed, their high reflectivity would have helped to perpetuate the cooler surface temperatures for a few more years. Eventually sulfate aerosols leave the atmosphere as acid precipitation. By contrast, carbon dioxide has a much longer residence time in the atmosphere. Carbon dioxide is a *greenhouse gas,* a gas that traps a portion of the radiation emitted by Earth's surface. With the aerosols gone, the enhanced greenhouse effect caused by the carbon dioxide would have led to a long-term rise in average global temperatures. The likely result was that some of the plant and animal life that had survived the initial environmental assault finally fell victim to stresses associated with global cooling, followed by acid precipitation and global warming.

The extinction of the dinosaurs opened up habitats for the small mammals that survived. These new habitats, along with evolutionary forces, led to the development of the large mammals that occupy our modern world.

What evidence points to such a catastrophic collision 65 million years ago? First, a thin layer of sediment nearly 1 centimeter thick has been discovered at the KT boundary, worldwide. This sediment contains a high level of the element *iridium,* rare in Earth's crust but found in high proportions in stony meteorites. Could this layer be the scattered remains of the meteorite that was responsible for the environmental changes that led to the demise of many reptile groups?

Despite growing support, some scientists disagree with the impact hypothesis. They suggest instead that huge volcanic eruptions may have led to a breakdown in the food chain. To support this hypothesis, they cite enormous outpourings of lavas in the Deccan Plateau of northern India about 65 million years ago.

Whatever caused the KT extinction, we now have a greater appreciation of the role of catastrophic events in shaping the history of our planet and the life that occupies it. Could a catastrophic event having similar results occur today? This possibility may explain why an event that occurred 65 million years ago has captured the interest of so many.

FIGURE 22.C Dinosaurs dominated the Mesozoic landscape until their extinction at the close of the Cretaceous period. This skeleton of *Tyrannosaurus* stands on display in New York's Museum of Natural History. (Photo by Gail Mooney/CORBIS Photo)

FIGURE 22.D Chicxulub crater is a giant impact crater that formed about 65 million years ago and has since been filled with sediments. About 180 kilometers (110 miles) in diameter, Chicxulub crater is regarded by some researchers to be the impact site that resulted in the demise of the dinosaurs.

FIGURE 22.30 Petrified logs of Triassic age in Arizona's Petrified Forest National Park. (Photo by David Muench)

gymnosperms as the dominant plants. The Cenozoic is often called the "Age of the Mammals," but could also appropriately be called the "Age of Flowering Plants," for the angiosperms enjoy a similar status in the plant world.

The development of the flowering plants strongly influenced the evolution of both birds and mammals that feed on seeds and fruits. During the middle Tertiary, grasses (angiosperms) developed rapidly and spread over the plains. This fostered the emergence of herbivorous (plant-eating) mammals which, in turn, established the setting for the evolution of the large, predatory mammals.

During the Cenozoic the ocean was teeming with modern fish such as tuna, swordfish and barracuda. In addition, some mammals, including seals, whales, and walruses returned to the sea.

FIGURE 22.31 Fossils of the great flying *Pteranodon* have been recovered from Cretaceous chalk deposits located in Kansas. *Pteranodon* had a wingspan of 7 meters (22 feet), but flying reptiles with twice this wingspan have been discovered in west Texas.

FIGURE 22.32 Marine reptiles such as this *Ichthyosaur* were the most spectacular of sea animals. (Photo by Chip Clark)

From Reptiles to Mammals

The earliest mammals coexisted with dinosaurs for nearly 100 million years but were small rodentlike creatures that gathered food at night when the dinosaurs were less active. Then, about 65 million years ago, fate intervened when a large asteroid collided with Earth and dealt a crashing blow to the reign of the dinosaurs. This transition, during which one dominant group is replaced by another, is clearly visible in the fossil record.

Mammals are distinct from reptiles in that they give birth to live young (which they suckle on milk) and they are warm-blooded. This latter adaptation allowed mammals to

FIGURE 22.33 Fossil skull of a huge crocodile of Mesozoic age. (Photo courtesy of Project Exploration)

FIGURE 22.34 After the breakup of Pangaea, the Australian marsupials evolved differently than their relatives in the Americas. (Photo by Martin Harvey)

lead more active lives and to occupy more diverse habitats than reptiles because they could survive in cold regions. (Most modern reptiles are dormant during cold weather.) Other mammalian adaptations included the development of insulating body hair and more efficient heart and lungs.

With the demise of the large Mesozoic reptiles, Cenozoic mammals diversified rapidly. The many forms that exist today evolved from small primitive mammals that were characterized by short legs, flat five-toed feet, and small brains. Their development and specialization took four principal directions: (1) increase in size, (2) increase in brain capacity, (3) specialization of teeth to better accommodate their diet, and (4) specialization of limbs to better equip the animal for a particular lifestyle or environment.

Marsupial and Placental Mammals Two groups of mammals, the marsupials and the placentals, evolved and diversified during the Cenozoic. The groups differ principally in their modes of reproduction. Young marsupials are born live but at a very early stage of development. At birth, the tiny and immature young enter the mother's pouch to suckle and complete their development. Today, marsupials are found primarily in Australia, where they underwent a separate evolutionary expansion largely isolated from placental mammals. Modern marsupials include kangaroos, opossums, and koalas (Figure 22.34).

Placental mammals, conversely, develop within the mother's body for a much longer period, so that birth occurs after the young are comparatively mature. Most modern mammals are placental, including humans.

In South America, primitive marsupials and placentals coexisted in isolation for about 40 million years after the breakup of Pangaea. Evolution and specialization of both groups continued undisturbed until about 3 million years ago when the Panamanian land-bridge connected the two American continents. This event permitted the exchange of fauna between the two continents. Monkeys, armadillos, sloths, and opossums arrived in North America, while various types of horses, bears, rhinos, camels, and wolves migrated southward. Many animals that had been unique to South America disappeared completely after this event, including hoofed mammals, rhino-sized rodents, and a number of carnivorous marsupials. Because this period of extinction coincided with the formation of the Panamanian land-bridge, it was thought that the advanced carnivores from North America were responsible. Recent research, however, suggests that other factors, including climatic changes, may have played a significant role.

Large Mammals and Extinction

As you have seen, mammals diversified rapidly during the Cenozoic era. One tendency was for some groups to become very large. For example, by the Oligocene epoch, a hornless rhinoceros that stood nearly 5 meters (16 feet) high had evolved. It is the largest land mammal known to have existed. As time passed, many other mammals evolved to larger sizes—more, in fact, than now exist. Many of these large forms were common as recently as 11,000 years ago. However, a wave of late Pleistocene extinctions rapidly eliminated these animals from the landscape.

In North America, the mastodon and mammoth, both huge relatives of the elephant, became extinct. In addition, saber-toothed cats, giant beavers, large ground sloths, horses, camels, giant bison, and others died out (Figure 22.35). In Europe, late Pleistocene extinctions included woolly rhinos,

FIGURE 22.35 Artist's depiction of extinct Cenozoic mammals. (Photo by Chase Studio/Photo Researchers, Inc.)

large cave bears, and the Irish elk. The reason for this recent wave of extinctions that targeted large animals puzzles scientists. These animals had survived several major glacial advances and interglacial periods, so it is difficult to ascribe these extinctions to climate change. Some scientists hypothesize that early humans hastened the decline of these mammals by selectively hunting large forms.

Summary

- The history of Earth began about 13.7 billion years ago when the first elements were created during the *Big Bang.* It was from this material, plus other elements ejected into interstellar space by now defunct stars, that Earth along with the rest of the solar system formed. As material collected, high velocity impacts of chunks of matter called *planetesimals* and the decay of radioactive elements caused the temperature of our planet to steadily increase. Iron and nickel melted and sank to form the metallic core, while rocky material rose to form the mantle and Earth's initial crust.
- Earth's primitive atmosphere, which consisted mostly of water vapor and carbon dioxide, formed by a process called *outgassing,* which resembles the steam eruptions of modern volcanoes. About 3.5 billions years ago, photosynthesizing bacteria began to release oxygen, first into the oceans and then into the atmosphere. This began the evolution of our modern atmosphere. The oceans, formed early in Earth's history, as water vapor condensed to form clouds, and torrential rains filled low-lying areas. The salinity in seawater came from volcanic outgassing and from elements weathered and eroded from Earth's primitive crust.
- The Precambrian, which is divided into the Archean and Proterozoic eons, spans nearly 90 percent of Earth's history, beginning with the formation of Earth about 4.5 billion years ago and ending approximately 542 million years ago. During this time, much of Earth's stable continental crust was created through a multi-stage process. First, partial melting of the mantle generated magma that rose to form volcanic island arcs and oceanic plateaus. These thin crustal fragments collided and accreted to form larger crustal provinces, which, in turn assembled into larger blocks called *cratons.* Cratons, which form the core of modern continents, were created mainly during the Precambrian.
- Supercontinents are large landmasses that consist of all, or nearly all, existing continents. *Pangaea* was the most recent supercontinent, but a massive southern continent called *Gondwana,* and perhaps an even larger one, *Rodinia,* preceded it. The splitting and reassembling of supercontinents have generated most of Earth's major mountain belts. In addition, the movement of these crustal blocks have profoundly affected Earth's climate, and have caused sea level to rise and fall.
- The time span following the close of the Precambrian, called the *Phanerozoic eon,* encompasses 542 million years and is divided into three eras: *Paleozoic, Mesozoic,* and *Cenozoic.* The Paleozoic era was dominated by continental collisions as the supercontinent of Pangaea assembled—forming the Caledonian, Appalachian, and Ural Mountains. Early in the Mesozoic, much of the land was above sea level. However, by the middle Mesozoic, seas invaded western North America. As Pangaea began to break up, the westward-moving North American plate began to override the Pacific plate, causing crustal deformation along the entire western margin of North America. Most of North America was above sea level throughout the Cenozoic. Owing to their different relations with plate boundaries, the eastern and western margins of the continent experienced contrasting events. The stable eastern margin was the site of abundant sedimentation as isostatic adjustment raised the Appalachians, causing streams to erode with renewed vigor and deposit their sediment along the continental margin. In the West, building of the Rocky Mountains (the *Laramide Orogeny*) was coming to an end, the Basin and Range Province was forming, and volcanic activity was extensive.
- The first known organisms were single-celled bacteria, *prokaryotes,* which lack a nucleus. One group of these organisms, called cyanobacteria, that used solar energy to synthesize organic compounds (sugars) evolved. For the first time, organisms had the ability to produce their own food. Fossil evidence for the existence of these bacteria includes layered mounds of calcium carbonate called *stromatolites.*
- The beginning of the Paleozoic is marked by the *appearance of the first life-forms with hard parts* such as shells. Therefore, abundant Paleozoic fossils occur, and a far more detailed record of Paleozoic events can be constructed. Life in the early Paleozoic was restricted to the seas and consisted of several invertebrate groups, including trilobites, cephalopods, sponges and corals. During the Paleozoic, organisms diversified dramatically. Insects and plants moved onto land, and lobe-finned fishes that adapted to land became the first amphibians. By the Pennsylvanian period, large tropical swamps, which became the major coal deposits of today, extended across North America, Europe, and Siberia. At the close of the Paleozoic, a mass extinction destroyed 70 percent of all vertebrate species on land and 90 percent of all marine organisms.
- The Mesozoic era, literally the era of middle life, is often called the "*Age of Reptiles.*" Organisms that survived the extinction at the end of the Paleozoic began to diversify

in spectacular ways. *Gymnosperms* (cycads, conifers, and ginkgoes) became the dominant trees of the Mesozoic because they could adapt to the drier climates. Reptiles became the dominant land animals. The most awesome of the Mesozoic reptiles were the *dinosaurs.* At the close of the Mesozoic, many large reptiles, including the dinosaurs, became extinct.

- The Cenozoic is often called the "*Age of Mammals*" because these animals replaced the reptiles as the dominant vertebrate life forms on land. Two groups of mammals, the marsupials and the placentals, evolved and expanded during this era. One tendency was for some mammal groups to become very large. However, a wave of late *Pleistocene* extinctions rapidly eliminated these animals from the landscape. Some scientists suggest that early humans hastened their decline by selectively hunting the larger animals. The Cenozoic could also be called the "*Age of Flowering Plants.*" As a source of food, flowering plants (angiosperms) strongly influenced the evolution of both birds and herbivorous (plant-eating) mammals throughout the Cenozoic era.

Review Questions

1. Why is Earth's molten, metallic core important to humans living today?
2. What two elements made up most of the very early universe?
3. What is the cataclysmic event called in which an exploding star produces all of the elements heavier than iron?
4. Briefly describe the formation of the planets from the solar nebula.
5. What is meant by outgassing and what modern phenomenon serves that role today?
6. Outgassing produced Earth's early atmosphere, which was rich in what two gases?
7. Why is the evolution of a type of bacteria that employed photosynthesis to produce food important to most modern organisms?
8. What was the source of water for the first oceans?
9. How does the ocean remove carbon dioxide from the atmosphere? What role do tiny marine organisms, such as foraminifera, play?
10. Explain why Precambrian history is more difficult to decipher than more recent geological history.
11. Briefly describe how cratons come into being.
12. What is the supercontinent cycle?
13. How can the movement of continents trigger climate change?
14. Match the following words and phrases to the most appropriate time span. Select from the following: *Precambrian, Paleozoic, Mesozoic, Cenozoic.*
    - **a.** Pangaea came into existence.
    - **b.** First trace fossils.
    - **c.** The era that encompasses the least amount of time.
    - **d.** Earth's major cratons formed.
    - **e.** "Age of Dinosaurs."
    - **f.** Formation of the Rocky Mountains.
    - **g.** Formation of the Appalachian Mountains.
    - **h.** Coal swamps extended across North America, Europe, and Siberia.
    - **i.** Gulf Coast oil deposits formed.
    - **j.** Formation of most of the world's major iron-ore deposits.
    - **k.** Massive sand dunes covered a large portion of the Colorado Plateau region.
    - **l.** The "Age of the Fishes" occurred during this span.
    - **m.** Pangaea began to break apart and disperse.
    - **n.** "Age of Mammals."
    - **o.** Animals with hard parts first appeared in abundance.
    - **p.** Gymnosperms were the dominant trees.
    - **q.** Stromatolites were abundant.
    - **r.** Fault-block mountains formed in the Basin and Range region.
15. Contrast the eastern and western margins of North America during the Cenozoic era in terms of their relationships to plate boundaries.
16. What did plants have to overcome to move onto land?
17. What group of animals is thought to have left the ocean to become the first amphibians?
18. Why are amphibians not considered "true" land animals?
19. What major development allowed reptiles to move inland?
20. What event is thought to have ended the reign of the dinosaurs?

Key Terms

banded iron formations (p. 602)
cratons (p. 604)
eukaryotes (p. 613)
outgassing (p. 601)
planetesimals (p. 598)
prokaryotes (p. 613)
protoplanets (p. 599)
solar nebula (p. 598)
stromatolites (p. 613)
supercontinent (p. 606)
supercontinent cycle (p. 607)
supernova (p. 598)

Web Resources

The *Earth* Website uses the resources and flexibility of the Internet to aid in your study of the topics in this chapter. Written and developed by geology instructors, this site will help improve your understanding of geology. Visit **http://www.prenhall.com/tarbuck** and click on the cover of *Earth 9e* to find:

- Online review quizzes.
- Critical thinking exercises.
- Links to chapter-specific Web resources.
- Internet-wide key-term searches.

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