10 The Record of Life on Earth.

Sufficient for us is the testimony of things produced in the salt waters and now found again in the high mountains, sometimes far from the sea.

—Leonardo da Vinci

These rocks, these bones, these fossil ferns and shells,
Shall yet be touched with beauty, and reveal
The secrets of the book of Earth to man.

—Alfred Noyes

OBJECTIVES

In this chapter you will learn

• what the early Earth was like, and how life may have originated on this planet;

• how the remains of organisms become transformed into fossils;

• how evolution and natural selection work;

• how the history of life is preserved in the fossil record.

1 EARLY EARTH

The history of life is closely intertwined with that of the atmosphere-hydrosphere system. Without a hospitable atmosphere and hydrosphere, life as we know it could not survive. Without life, the atmosphere and the ocean also would not exist in their present forms.

More than 4 billion years ago, in the Hadean eon (see Figure 3.3, page 54), the chemical composition of the atmosphere was very different than it is now. The atmosphere probably consisted of water vapor, carbon dioxide, and nitrogen, with some sulfur compounds and hydrogen chloride. There was no free oxygen (O2), a necessity for most forms of life on Earth today. It was also very hot, even though the Sun's luminosity (brightness) was lower than it is today. The early atmosphere was composed primarily of greenhouse gases, which trapped heat near the surface. It was too hot for water to exist as a liquid, so there were no oceans, lakes, or rivers. Atmospheric pressure was also much greater than it is today. Altogether, the early Earth was inhospitable to life as we know it.

As the Earth cooled, water vapor began to condense. It fell as rain and collected in low-lying areas, forming bodies of water on the surface, probably as early as 4.4 billion years ago. The early rain was highly acidic because the water reacted with gases in the atmosphere to form acids. The acidic rain reacted with the rocks of the crust, causing chemical weathering. Through reactions with minerals, the acidic rainwater was slowly neutralized. Sediments (the products of chemical weathering of the crust) began to form. Thus, the compositions of the atmosphere, the hydrosphere, and the lithosphere all began to change as materials were exchanged among them.

Why was the rain highly acidic early in Earth history?

Answer: Because the water reacted with gases in the atmosphere to form acids.

2 WHERE DID THE ATMOSPHERE COME FROM?

Earth's original envelope of gases—its **primary atmosphere**—was lost early in Earth history, stripped away by strong solar winds. Little by little, the planet generated a **secondary atmosphere** by releasing volcanic gases from its interior. The main constituent of volcanic gas is water vapor, with varying amounts of nitrogen, carbon dioxide, hydrogen, sulfur dioxide, chlorine, hydrogen sulfide, methane, ammonia, carbon monoxide, and other gases. Overall, the volume of volcanic gases released over the past 4 billion years or so is thought to be large enough and in approximately the right proportions to account for the entire volume of the oceans and atmosphere, with one important exception: the atmosphere is approximately 21 percent oxygen. Where did this abundant oxygen come from?

Some oxygen was probably generated in the early atmosphere by the breakdown of water molecules (H2O) into hydrogen and oxygen as a result of interactions with ultraviolet radiation. This is an important process, but it doesn't come close to accounting for the present level of oxygen in the atmosphere. Another oxygen-producing process was required. In **photosynthesis,** light energy is used to make carbon dioxide react with water, producing carbohydrates and releasing oxygen. Most organisms in the biosphere depend upon photosynthesis, either directly or indirectly, to obtain food. Almost all of the free oxygen currently in the atmosphere originated through photosynthesis. (You can learn more about photosynthesis and the other biological processes discussed in this chapter if you read *Biology: A Self-Teaching Guide,* by Steven D. Garber.)

Eventually, enough oxygen was created through photosynthesis by early oxygen-producing organisms to permit oxygen to build up in the atmosphere. Along with the buildup of molecular oxygen (O_2) came an increase in ozone (O_3). When ozone began to function as a screen to filter out harmful ultraviolet radiation, organisms were finally able to survive and flourish in shallow waters and, eventually, on land. This critical stage in the evolution of the atmosphere was reached around 600 million years ago. The fossil record shows that there was an explosion of life forms at that time, the transition from Precambrian time to the Phanerozoic eon.

The biosphere also had a profound impact on the carbon content of the atmosphere and ocean. The shells of marine organisms are composed primarily of calcium carbonate ($CaCO_3$), providing a storage reservoir for carbon dioxide (note that $CaCO_3 = CaO + CO_2$). When these organisms die, their shells are buried by seafloor sediments and are eventually transformed into limestone. Limestone is a long-term reservoir for carbon dioxide, isolating it from the atmosphere and hydrosphere. If all the carbon dioxide currently stored in limestone and other sedimentary rocks were released, there would be as much CO_2 in the Earth's atmosphere as in the atmosphere of Venus, where the greenhouse effect runs rampant and the surface temperature is 480°C (900°F).

Where did the free (molecular) oxygen in the atmosphere come from?

Answer: Some of it came from the breakdown of water molecules in the atmosphere as a result of interactions with ultraviolet radiation, but most of it came from photosynthesis.

3 EARLY LIFE

Life played an important role in the chemical transformation of the Earth's atmosphere and hydrosphere. But where and how did life begin? No one knows the complete answer to this question. The first step may have been **chemosynthesis,** the synthesis from inorganic material of small organic molecules such as amino acids, the basic building blocks of proteins. In 1923, a Russian scientist, Aleksandr Oparin, hypothesized that simple organic compounds may have been synthesized from gases in the primitive atmosphere, with energy supplied by lightning or by ultraviolet radiation from the Sun. Thirty years later an American scientist, Stanley Miller, carried out an experiment to test this hypothesis. He passed electric sparks through a mixture of gases similar to those present in the early atmosphere, and recovered some amino acids and other organic compounds. In later experiments all of the important protein-forming amino acids were synthesized, along with other biologically important compounds.

Oparin believed that the organic molecules from which life originated collected as a "soup" in surface waters. Scientists today have many different ideas about where the organic molecules may have come from originally, but most experts agree with at least some aspects of the "soup" hypothesis. But in what environment was this soup formed? Charles Darwin envisioned life as originating in a "warm little pond" on land. Hydrothermal vents at seafloor spreading centers (called "black smokers") or hot springs like those at Yellowstone Park could have provided the raw materials and the heat needed for chemosynthesis. Even the bubbles in sea foam could have provided a site for the collection of early organic material. In fact, the synthesis of organic molecules may have happened in numerous locations, only to be wiped out by meteorite impacts or harsh environmental conditions, before life finally managed to take hold.

Wherever the first organic molecules came from, the big problem is in the next steps: How did the early molecules link together to become the larger "life" molecules? And how did these molecules develop the capability to grow, metabolize, and reproduce? **Biosynthesis** is the polymerization (linking together, as used in mineralogy; see chapter 2) of small organic molecules to form larger organic molecules, including proteins. When amino acids polymerize to create proteins, water is eliminated. This presents a problem for the soup hypothesis, because it would be difficult—if not impossible—to achieve in an aqueous environment. However, if amino acids are dehydrated and heated, polymerization can occur. Perhaps biopolymers were formed when some organic soup along ancient shorelines dried out and was heated by solar radiation or volcanic heat.

Biosynthesis can make larger molecules out of smaller ones; this provides a foundation for growth, one of the fundamental characteristics of living organisms. But biopolymers have no innate mechanism for replicating themselves or for creating new types of molecules. How did these larger organic molecules develop such a mechanism?

You may recall from biology classes that the plan of a living organism is encoded in its **DNA** (deoxyribonucleic acid), a biopolymer that consists of two twisted, chainlike molecules held together by organic molecules. The information and instructions stored in DNA are decoded and executed by **RNA** (ribonucleic acid). Proteins cannot reproduce without RNA because the RNA contains the information required to construct an exact duplicate of the protein molecule. Both DNA and RNA are crucial for the replication of modern cells, but most experts agree that there must have been an early phase in the development of life in which RNA alone was sufficient. The phrase "RNA world" has been coined to describe this phase. Once RNA became established, its presence became the basis for the synthesis and replication of protein molecules.

Another crucial characteristic of life is **metabolism,** the set of chemical reactions through which an organism derives food energy. Organisms that produce their own organic compounds from inorganic chemical compounds are called **autotrophs.** Most autotrophs produce food in the form of carbohydrates, through the process of photosynthesis. The oxygen that was produced by the first photosynthetic autotrophs was toxic to them—a waste product that had to be removed. These organisms required an **anaerobic,** or oxygen-depleted, environment.

Organisms that derive food energy by feeding on other organisms or on organic compounds produced by other organisms are called **heterotrophs.** When heterotrophs consume another organism, the energy stored in the organic compounds is released by one of two processes. Organisms that cannot tolerate oxygen obtain their energy through the anaerobic process of **fermentation,** in which carbohydrate molecules are partially decomposed to form alcohol, carbon dioxide, and water, releasing energy. Heterotrophs that are not anaerobic obtain their energy through the **aerobic** process of **respiration,** which means that they use oxygen to oxidize carbohydrates, creating carbon dioxide, water, and energy.

Respiration is a more efficient process than fermentation, which does not use all available energy. The end product of fermentation, alcohol, is a high-energy compound that can still be used as a fuel; the products of respiration—carbon dioxide and water—cannot. The advent of organisms that tolerated oxygen therefore meant a huge increase in the efficiency with which organisms obtain food energy. This metabolic efficiency allowed for the development and support of more complex structures. It also meant that organisms could grow larger and join in colonies, because they no longer needed a large, free surface area through which to rid themselves of the waste oxygen they were producing.

What is the difference between a heterotroph and an autotroph?

Answer: Autotrophs produce their own organic compounds from inorganic chemical compounds. Heterotrophs derive food energy by feeding on organic compounds produced by other organisms.

4 CELLS AND CELL PROCESSES

Let's review the essential features that distinguish living from nonliving things. Living organisms can grow, reproduce themselves, and metabolize. Crystals can grow, but they lack the other characteristics of life. Viruses also can grow, but they use the reproductive "machinery" of other organisms in order to replicate themselves, and they lack the ability to metabolize; viruses are "not quite" alive.

All living organisms are composed of one or more cells. The **cell** is the basic structural unit of life, a complex grouping of chemical compounds and structures enclosed in a porous wall, or membrane. The development of the cell membrane was a crucial step in the evolution of life. The membrane separates the materials and chemical reactions that occur inside the cell from the environment outside it. This makes it possible for local organization within the cell to increase. The porous membrane also facilitates the exchange of materials and energy between the cell and its environment. Many bacteria are unicellular (one-called), but most other organisms are multicellular (more than one cell). Cells may be small (0.01 mm, or 0.0004 in) or large (a few cm, or even larger in rare cases), but whatever their size, all cells are either prokaryotic or eukaryotic.

The earliest cells were **prokaryotic cells** (from the Greek *pro,* "before," and *karyote,* "nucleus," hence "before a nucleus"). Prokaryotes are small, simple cells. The main body of the cell, the cytoplasm, lacks distinctly defined areas in which the cell's various functions are carried out. Most important, the nucleus—the portion of the cell that houses the genetic information—is not separated from the cytoplasm by a membrane. Present-day bacteria and related organisms are prokaryotes. Some prokaryotes are heterotrophs and some are autotrophs, but all autotrophs are prokaryotes. The first oxygen-producing organisms were photosynthetic, thermophilic ("heat-loving"), prokaryotic autotrophs, probably similar to modern cyanobacteria (blue-green algae).

Eukaryotic cells (from the Greek *eu,* "good" or "true," hence, "with a true nucleus") are larger and more complex than prokaryotic cells. Their DNA is housed in a well-defined nucleus that is separated from the cytoplasm by a membrane. The cytoplasm contains a variety of well-defined parts, called organelles, each of which has a specific function. Humans, animals, plants, fungi, and many other living things consist of eukaryotic cells.

All living organisms that are not prokaryotes belong to one of four kingdoms of eukaryotes: Protoctista (single-celled and simple multicellular eukaryotes), Fungi (mushrooms, lichens, and their relatives), Animalia (multicellular organisms that obtain their food by consuming other organisms), and Plantae (multicellular, sexually reproducing eukaryotes that produce their own food; more complicated than algae). The kingdoms are further subdivided, in a hierarchical manner, into successively narrower categories: phylum, class, order, family, genus, and species. A modern human is classified as follows: kingdom: Animalia; phylum: Chordata; class: Mammalia; order: Primates; family: Hominidae; genus: *Homo;* species: *Homo sapiens.*

What is the difference between prokaryotic and eukaryotic cells?

Answer: In prokaryotes, the cytoplasm lacks distinctly defined organelles and the nucleus is not separated from the cytoplasm by a membrane. Eukaryotes are larger and more complex; their nucleus is separated from the cytoplasm by a membrane, and their cytoplasm contains well-defined organelles, each of which has a specific function.

5 SPECIES, EVOLUTION, AND NATURAL SELECTION

What were the mechanisms through which simple single-celled and multicellular organisms eventually diversified into the vast array of organisms that inhabit the Earth today? In the ongoing search for an answer to this question, the most significant early contribution was made by Charles Darwin, whose work revolutionized biology and paleontology. On December 27, 1831, Darwin departed from England aboard HMS *Beagle.* When he set sail, Darwin believed in biblical creation and the fixity of species. By the time he returned, his views had changed considerably.

Darwin kept scrupulous notes and made paintings and sketches of the plants, animals, and fossils he saw on the voyage. He was particularly impressed with the many species of finches he saw on the Galápagos Islands. The South American mainland, just a short distance away, had only one species of finch. Darwin reasoned that long ago finches from the nearby mainland had colonized the islands and had subsequently changed as a result of having to adapt to their new environment. In 1859, many years after his return to England, Darwin published his observations and ideas in a book called *On the Origin of Species by Means of Natural Selection.* He waited a long time to publish his findings because he was concerned about the uproar it might—and did—cause. In his book, Darwin outlined the theory of **evolution,** which basically says that new species evolve from old species. (Recall from chapter 1 that a theory is a hypothesis that has been tested and supported by experimentation and observation. Plate tectonics is a unifying theory in geology. Evolution is a unifying theory in biology and paleontology; it draws together a very large amount of information into a simple, testable model.) All present-day organisms are descendants, through a gradual process of adaption to environmental conditions, of different kinds of organisms that existed in the past. Evolution is an essential characteristic of living things, just like growth, metabolism, and reproduction.

Darwin was not the first to suggest evolution as an explanation for the variety and distribution of species. But he was the first to provide a thorough discussion, supported by clear evidence gathered during his voyage and through subsequent research. Moreover, *On the Origin of Species* was published at a time when scientific thought about the Earth was changing rapidly. The concept of uniformitarianism (see chapter 3) was widely accepted; there was a growing consensus that the Earth was very old. And it had been conclusively shown that some plant and animal species that had once lived were now extinct. Most important, Darwin was the first to propose a reasonable mechanism through which evolution could be achieved.

Darwin (and, almost simultaneously, a young naturalist named Alfred Wallace) proposed that evolution could be achieved through the process of **natural selection,** in which poorly adapted individuals tend to be eliminated from a population. When this happens, there are fewer descendants to inherit the genetic characteristics of the poorly adapted individuals and pass them on to the next generation. All natural populations have individuals with varied characteristics. At any one time and in any given environment, some of these characteristics will be more advantageous than others; they will enable the individual to compete more effectively for scarce resources or to escape predators more easily. These individuals are more likely to survive and to have offspring with similar characteristics. This is informally called "survival of the fittest." Over time the entire population evolves as natural selection favors individuals that are particularly well adapted to their environment.

A population's characteristics may diverge when part of the group is subjected to new environmental conditions. This can happen, for example, if part of a population becomes geographically isolated from the rest (Figure 10.1). A rising mountain chain or an invasion by the sea might provide a physical barrier that separates two groups. Or some individuals might migrate across a large river or to an island and thus become isolated from the main population. In such cases the separated group must adjust to a new and different environment. Natural selection will favor those individuals that are best suited to the new environment. Before the separation occurred, the two groups were part of a single **species,** a population of similar individuals that can interbreed and produce fertile offspring. After the separation they may eventually become so different that they can no longer interbreed successfully. In such a case, a new species develops.

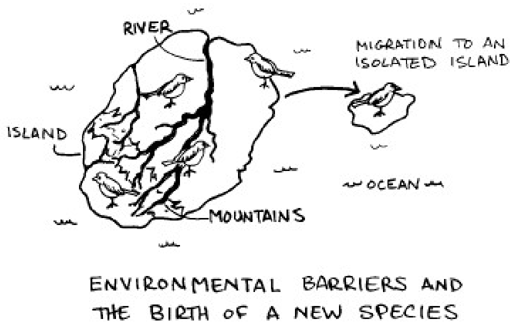


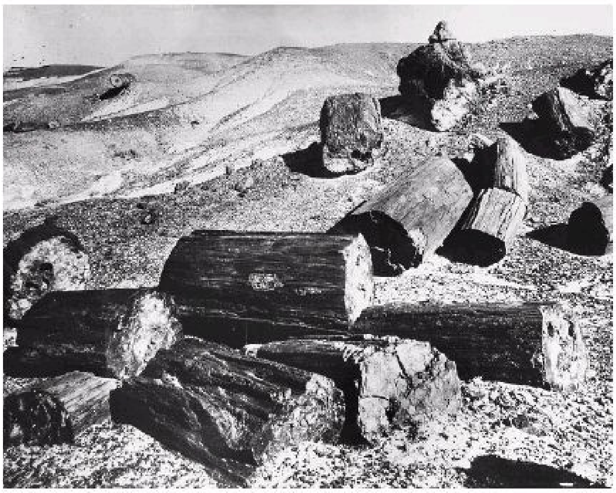
Figure 10.1

What is a species?

Answer: A population of similar individuals that can interbreed and produce fertile offspring.

6 HOW TO BECOME A FOSSIL.

In chapter 3, a fossil is defined as the remains of an organism that died and became preserved and incorporated into sediments. Although fossilization can occur in many ways, it is much more common for a newly deceased organism to be destroyed. If the organism is exposed to running water, air, scavengers, or bacteria, it will decompose or be eaten or be broken into parts and scattered around. Hard parts such as bones, teeth, and shells are less easily destroyed and hence more likely to be preserved than soft or delicate parts like skin, hair, leaves, flesh, eggshells, or feathers. In any case, for an organism to be preserved as a fossil it must be quickly covered up by a protective layer of sand or mud, or—in rare cases—tree sap, ice, or tar.



"PETRIFIED WOOD." Fossilized tree trunks in Arizona, once buried, have been exposed by erosion. In the fossilization process, the wood is replaced by silica carried in solution by groundwater, a process called permineralization. (Courtesy U.S. Geological Survey)

Sometimes an organism is preserved with little or no alteration. For example, insects millions of years old have been trapped almost intact in tree sap, which recrystallizes to form the mineral amber (hence the premise for the movie *Jurassic Park*). Organisms can also be preserved if they are trapped in ice or tar, like the ancient wooly mammoths found frozen in Siberia, or the unfortunate prehistoric animals that fell into the La Brea Tar Pits in Los Angeles, California. Animals may also be preserved by natural mummification, in which the soft parts dry and harden before the organism is buried by sediment.

Visit a store that sells jewelry or gems and minerals, and ask if they have any amber. Use a small hand lens to examine the amber. See if you can spot any small fragments of plants or insects preserved in the amber.

More often, the remains of organisms are preserved in an altered state. Bones and other hard parts are sometimes replaced by minerals carried in solution by groundwater. Wood that has been preserved in this manner is called "petrified"

TRACE FOSSILS. Dinosaur footprints near Wethersfield, Connecticut, show where a group of dinosaurs, both adults and juveniles, crossed a muddy bank. Footprints are an example of trace fossils. (Courtesy Peabody Museum, Yale University) wood. Infiltrating minerals fill tiny pore spaces in the bones, teeth, wood, or shell, strengthening and hardening them. This is called **permineralization.**

If an organism itself is not preserved, it may still leave behind some evidence of its existence. This may be an imprint or mold in the soft sediment that covered it. Molds can reveal fine details long after the organism itself has been destroyed. The delicate remains of plants are sometimes preserved when volatile material in the plant evaporates, leaving an impression in the form of a thin film of carbon. Organisms can leave behind other types of evidence, called **trace fossils.** Footprints are a common form of trace fossil. Worms often leave burrows or borings. Dinosaurs and birds may leave nests containing the remnants of eggshells. Some prehistoric animals even left behind feces that provide clues about their characteristics, habits, and diets.

In what ways can an organism be preserved with little alteration as a fossil?

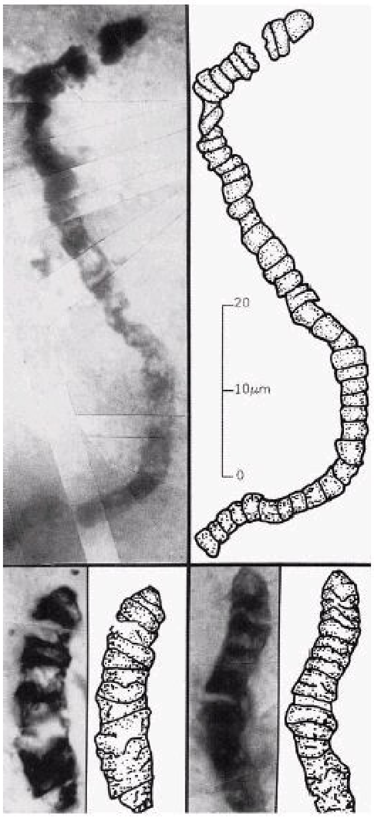
Answer: By natural mummification (drying) or by being encased in tree sap, ice, or tar.

7 THE MOST ANCIENT FOSSILS

Much of the history of life is the history of unicellular and simple multicellular organisms—that is, microbial life. Indeed, the geologic record of life until the end of Precambrian time—a period of almost 3 billion years—is dominated by **microfossils,** fossils so small that they must be studied under a microscope. The study of such fossils is called **micropaleontology.**

The most ancient fossils that have been found are about 3.55 billion years old. The "chemical signatures" of biological processes have been detected in rocks as old as 3.9 billion years. This suggests that life originated soon after the formation of the Earth, even while the planet was still being bombarded by meteorites. Some of the oldest fossils are the remains of microscopic prokaryotes. Others consist of thin layers of calcium carbonate precipitated from seawater as a result of the action of blue-green photosynthetic bacteria (also prokaryotes). The layered structures, called **stromatolites,** are not the remains of actual organisms, but they provide evidence of the presence of organisms. Similar structures are still being formed today.

For at least 2 billion years, through the Hadean and Archean eons and part of the Proterozoic, the only life on the Earth was prokaryotic. A variety of prokaryotic cells developed (although only one type, cyanobacteria, carried out oxygen-producing photosynthesis). How and where the first eukaryotes originated is a subject of much speculation. We can be reasonably sure that eukaryotes arose from prokaryotes. The chemical pathways in the two classes of cells are so similar that



THE MOST ANCIENT FOSSILS. These are examples of the most ancient fossil prokaryotes ever found. They came from a 3.5-billion-year-old rock in Western Australia. Adjacent to each photo is a sketch. The magnification is indicated by the scale: 10 µm (micrometers) = 0.01 mm = 0.0004 in. (Courtesy William Schopf, Department of Earth and Planetary Sciences, UCLA)

they must be related. Most experts believe that eukaryotes originated through a process in which larger prokaryotes enclosed smaller ones.

Once the atmosphere was oxygenated, the emergence of eukaryotes became more likely, for a number of reasons. Prokaryotes need free space around them; crowding interferes with the movement of nutrients and water into and out of the cell. Aerobic eukaryotes are not bothered by crowding, so they can form three-dimensional colonies of cells. Eukaryotes (with the possible exception of the very earliest forms) use oxygen for respiration. As discussed above, this is more efficient than the anaerobic process of fermentation, so eukaryotes do not require as large a surface area as prokaryotes to facilitate the movement of food and waste. This is why eukaryotic cells can be larger (that is, have a greater volume-to-surface ratio) than prokaryotic cells. Because of their greater efficiency in metabolism, eukaryotes can maintain a more complex cell structure.

Eukaryotes appeared at least 1.4 billion years ago, in the middle of the Proterozoic eon. The exact date is not known with certainty, but the fossil evidence clearly shows that by 1 billion years ago they were well established (Figure 10.2). With the appearance of eukaryotes and the transition to an oxygenated atmosphere, more habitats became available, and many new life-forms emerged.

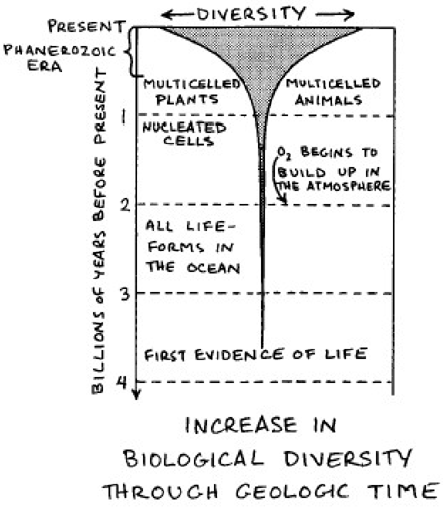


Figure 10.2

The earliest fossils of larger multicellular organisms appear just at the end of the Proterozoic eon in rocks that are about 600 million years old. These fossils, which are now known from a number of localities worldwide, were first found in the Ediacara Hills of South Australia and are called the Ediacara fauna. The Ediacara fauna lived in quiet marine bays. They were jellylike animals with no hard parts. The Ediacara animals represent a huge jump in complexity from the first unicellular eukaryotes, which appeared 800 million years earlier. Scientists still do not know much about what happened during those 800 million years.

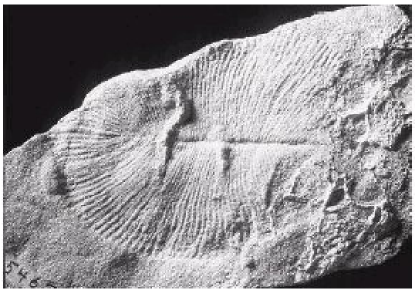
What are the oldest known fossils?

Answer: Remains of microscopic prokaryotes (about 3.55 billion years old) and stromatolites.

8 BIOLOGICAL DIVERSITY IN THE CAMBRIAN PERIOD

About 600 million years ago, with the appearance of larger multicellular animals like the Ediacara fauna, life-forms began to diversify very rapidly (Figure 10.2). The Phanerozoic eon, starting with the Cambrian period, was a time of increasing **biodiversity,** that is, increasing number and variety of species. Why was this so? One hypothesis is that sexual reproduction, which developed with the eukaryotes, caused the Cambrian explosion of biological diversity. Another hypothesis is that before that time there was too little oxygen in the atmosphere to support the metabolism of larger organisms. As noted earlier, the increase of ozone (O3) in the atmosphere shielded Cambrian life-forms from harmful ultraviolet radiation. The rising oxygen content of the atmosphere may also have affected the biochemistry of calcium phosphate and calcium carbonate, the two main skeleton- and shell-building components.

Whatever the reasons, a great many changes occurred about 550 million years ago in the early Cambrian. Compact animals were evolving to replace the soft-bodied, jellylike organisms of Ediacara times: trilobites, mollusks (clams and sea snails), and echinoderms (sea urchins). All of these (except trilobites) are types that have persisted up to the present. These animals were equipped with gills, filters, efficient guts, a circulatory system, and other characteristics of more advanced life-forms. The Cambrian also saw the development of skeletons, internal and external. These gave organisms a selective advantage, protecting them against predators, against drying out, against being injured in turbulent water, and so on. Many soft-bodied creatures also persisted in the Cambrian. They can be seen in the fossils of the Burgess Shale, a beautiful collection of soft-bodied animals and plants that were covered by black muds in Cambrian times and eventually preserved as fossils in



ANCIENT FOSSIL. *Dickinsonia costata,* the remains of a creature that lived about 600 million years ago. Like a jellyfish, *Dickinsonia* lacked hard parts, so the fossil is an impression made on sand when the creature died. The specimen is 3 inches in length and came from the Flinders Range, South Australia. Photograph by William Sacco.

shale in British Columbia. The rich diversity and extraordinary life-forms of the Cambrian marine environment are almost unparalleled in the history of the Earth.

Why do you think early geologists chose the beginning of the Cambrian period as the dividing line between Proterozoic time and Phanerozoic time?

Answer: There was an enormous explosion of biological diversity at the beginning of the Cambrian; this is preserved in the fossil record as a distinctive transition.

The great proliferation of life in the Cambrian was confined to the sea. Successful organisms diversified and flourished; unsuccessful ones disappeared. By 500 million years ago the main kinds of structural organization for animal life had been established. The big step that remained was to leave the sea and occupy the land. Eventually all kingdoms of life took that step.

The requirements for life on land are the same for all organisms. The most important are:

1. Structural support, needed because aquatic organisms are buoyed up by water, whereas land organisms must contend with gravity

2. An internal aquatic environment, with a plumbing system and methods of conserving water against loss to the surrounding atmosphere

3. A method of exchanging gases with air instead of with water

4. A moist environment for the reproductive system, essential for all sexually reproducing organisms

9 PLANTS

The earliest land plants evolved from green algae. Eventually, vascular plants evolved, with structural support from stems and limbs (requirement 1), and a set of channels through which water and dissolved elements are transferred from roots to leaves (requirement 2). Gas exchange with the air (requirement 3) is controlled by adjustable openings (stomata) in the leaves.

The earliest land plants were seedless. Ferns and club mosses are modern seedless plants. Many of the adult forms of seedless plants can tolerate some drought, but all plants rely on moisture for the sexual phase of their reproductive cycles. Without moisture, the reproductive cells have no medium in which to reach each other and fuse, so fertilization does not occur. Consequently, seedless plants have never been able to survive in places that lack a dependable supply of moisture for at least part of the growing season. Seedless plants reached their peak in the Mississippian and Pennsylvanian periods, when they dominated the vast forests on the tropical floodplains and deltas of North America, Europe, and Asia. The remains of these plants produced huge deposits of coal.

By the middle Devonian a few plants were on the way to meeting requirement 4, providing their own moist environment to facilitate sexual reproduction. These plants were the **gymnosperms** ("naked-seed plants"). The female cell of a gymnosperm is attached to the vascular system and therefore has a supply of moisture. The male cell is carried in a pollen grain with a waxy coating. When the two fuse, a seed results. The seed provides moisture and nutrients that sustain the growth of the young plant until it can support itself through photosynthesis. This important change allowed plants to survive in other habitats besides swampy lowlands. Naked-seed plants survive today; ginkgoes and conifers are examples. Freed from their original swampy habitat, the gymnosperms did not have to compete with the great seedless trees of the coal forests. By the end of the Pennsylvanian period, they had spread over most of the world.

Gymnosperms have one drawback. The male cell carrier, the pollen, is spread through the air. What chance does a pollen grain in the air have of finding a female cell? The odds are against it. To ensure success, gymnosperms have to make huge amounts of pollen. Flowering plants (**angiosperms,** or enclosed-seed plants) solved this problem. For a small incentive (nectar or a share of the pollen), insects deliver the pollen from one flower to another, or from one part of the plant to another. Birds and other animals also help the angiosperms by eating their seed-bearing fruits. The seeds are distributed throughout the animal's territory in its feces. Angiosperms evolved after gymnosperms, but by the end of the Cretaceous period angiosperms had become the dominant land plants. Angiosperms have developed close relationships with animals: insects for pollination, and birds and quadrupeds (four-footed animals) for seed dispersal. Many flowering plants, such as grasses and birches, also rely on the wind to help disperse their seeds and pollen.

What is the difference between angiosperms and gymnosperms? Which developed first?

Answer: Angiosperms are flowering, enclosed-seed plants. Gymnosperms are naked-seed plants; they developed first.

10 ANIMALS

The first major expansion of multicellular marine animals occurred in the last few million years of Precambrian time, at the end of the Proterozoic eon. Among the creatures in the Cambrian seas were many that belong to the phylum Arthropoda, so called because of their jointed legs. Modern arthropods include crabs, spiders, centipedes, and insects, members of the most diverse phylum on the Earth. Arthropods were the first animals to make the change from sea to land.

With a few exceptions, arthropods were quite small and light. They were covered with a hard shell of chitin (a fingernail-like material). Thus, they were well adapted for life on land in regard to structural support and water conservation. The first to go on land were probably Silurian centipedes and millipedes. Insects were abundant by the Mississippian period, and included dragonflies with a wingspan of up to 60 cm (24 in). For all their success as land creatures, however, the arthropods have very primitive respiratory and vascular systems. For example, insects breathe through tiny tubes that penetrate the outer coating. This mode of respiration severely limits the size of an organism and is the reason why most insects are small. Their "blood" is simply body fluid bathing the internal organs; it does not circulate in closed vessels. The fluid is kept in motion by a sluggish "heart" that is little more than a contracting tube. At first it seems odd that these primitive animals could have diversified into more than a million terrestrial species. Yet the arthropods' simple vascular system is obviously effective.

Among the fossils of the Burgess Shale is a small, inconspicuous fossil called *Pikaia. Pikaia* is a **chordate** because it has a notochord, a cartilaginous rod running along the back of the body. (Humans are also chordates. We have a notochord as embryos; later it is replaced by the backbone.) *Pikaia* and other Cambrian fish were jawless, probably feeding on organic matter dredged from the seafloor. In these jawless fish we see the first important stage in the development of **vertebrates,** animals that possess backbones. Jawed fish came next. With the development of jaws came a great burst of diversification. The original jawless fish, only a few centimeters long, were quickly joined by larger fish. These included 9-meter (29.5-ft) armored sharks and other cartilaginous fish, and the huge order of ray-finned fish that are familiar to us as game and food fish. The possession of jaws allowed fish to move into a wide range of ecological niches.

The first fish to venture onto land, in the Devonian period, may have been one of the Crossopterygii, or lobefinned fish. (Interestingly, crossopterygians were thought to be extinct until a living example called *Coelacanthus* was found in the Indian Ocean in 1938.) Crossopterygians had several features that could have enabled them to make the transition to land. Their lobelike fins, for example, contained all the elements of a quadruped limb. They had internal nostrils, a characteristic of air-breathing animals. As fish, they already had developed a vascular system that was adequate for life on land. However, recent DNA studies of modern coelacanths, amphibians, and lungfish suggest that lungfish, rather than lobefinned fish, may have been the ancestors of the first land-dwelling amphibians. The lungs used by modern lungfish to take occasional gulps of air during periods of drought were developed long before the first amphibians appeared. Presumably, it would have been a relatively simple adaptation for these lungs to become full-time suppliers of air for amphibians in a terrestrial environment.

Amphibians never developed an effective method for conserving water. To this day they have permeable skins, which is one reason they have never become wholly independent of aquatic environments. Although amphibians have been successful for many millions of years, they have one difficulty that limits their ability to expand: they have never met the reproductive requirement for life on land. In most amphibian species, the female lays her eggs in water, the male fertilizes them there after a courtship ritual, and the young are fishlike when first hatched (like tadpoles). Amphibians, with one foot on the land, have remained tied to the water for breeding. Although some became quite large (2 to 3 m, about 3 yd), they never diversified much after the Devonian period. One branch went on to become reptiles. Of the rest, those that survive are frogs, toads, newts, salamanders, and limbless water "snakes," which have returned to life in the water.

Reptiles freed themselves from the water by evolving an egg that could be incubated outside of the adult, and by developing a watertight skin. These two modifications enabled them to occupy terrestrial niches that the amphibians had missed because of their need to live near water. Originating in the Mississippian and Pennsylvanian coal swamps, by the Jurassic period the reptiles had moved over the land, up into the air, and back to the water. They had also produced two orders of dinosaurs (the largest quadrupeds ever to walk the Earth) and given rise to two new vertebrate classes, mammals and birds.

Vertebrate animals made the transition into the air in the form of pterosaurs, flying reptiles with long wings and tails. Birds first appeared near the end of the Jurassic period. An early example of a bird, *Archaeopteryx* ("ancient wing"), would have been classified as a dinosaur were it not for the discovery that it had feathers.

In many ways, mammals are better equipped to live on the land than were the great reptiles. Mammals, mostly quadrupeds, are adapted to a faster and more versatile life than the reptiles. By comparing brain-to-body-weight ratios in archaic and modern reptiles and mammals, it can be shown that increase in mammalian brain size is a continuing process, whereas in reptiles brain size has not increased; the ratios in modern reptiles do not differ significantly from those in archaic ones. Still, it took the extinction of the dinosaurs to allow for the great expansion of mammals at the beginning of the Cenozoic era.

What was the first type of animal to make the transition from sea to land?

Answer: Arthropods.

EARLY BIRD. *Archaeopteryx macroura* is an ancient bird preserved as a fossil in the Solenhofen Limestone of Bavaria, Germany. *Archaeopteryx* lived about 120 million years ago, and was one of the first animals to develop feathers. (Smithsonian Institution)

11 THE HUMAN FAMILY

The family of humans, Hominidae, did not descend from the modern ape family, Pongidae. Both families probably diverged from an earlier apelike family. The fossil record for both humans (**hominids**) and apes is poor; many transitional forms are missing, but new and important finds are made by paleontologists every year. These finds are helping scientists to fill in the history of our human family.

At this writing, the oldest known definitive example of a hominid fossil, dated at 4.4 million years, is *Ardipithecus ramidus.* The genus *Ardipithecus* was succeeded by *Australopithecus,* with six known species (so far), the earliest of which (*Australopithecus anamensis*) dates from about 4.2 million years ago. The australopithecines are probably best represented by *Australopithecus afarensis,* of which the famous "Lucy" fossil is an example. The australopithecines were generally small, standing only about 1.0 to 1.5 m (3.5 to 5.0 ft) in height, but they were physically strong and their brain capacity was larger than that of chimpanzees. From the shape of the pelvis and from footprints left in soft volcanic mud more than 3.0 million years ago, we know that these individuals walked upright, though their skulls still looked more apelike than human. Successive australopithecine species inhabited Africa, each overlapping in time with the preceding species, as shown in Table 10.1; they disappeared altogether about 1.1 million years ago.

Homo erectus was probably the first species of our own genus (*Homo*). Fossils of *H. erectus* dating back about 1.8 million years have been found in Africa, Europe, China, and Java. An even earlier species called *Homo habilis,* "handy man," is thought to have used stone tools. Since toolmaking is the distinguishing feature of the genus *Homo,* some experts include *H. habilis* in this genus; others argue that the skull of *H. habilis* is more like that of the australopithecines.

Homo erectus disappeared around 300,000 years ago. By about 230,000 years ago, *Homo neanderthalensis*—"Neanderthal man"—had appeared. The fossil record between 400,000 and 100,000 years ago is poor, so the transition from *H. erectus* to *H. neanderthalensis* is not well understood. From the study of burial sites as much as 100,000 years old, paleontologists and anthropologists have deduced that the Neanderthal people practiced some form of religion. On the basis of similar-

Table 10.1 Approximate Time Line of Hominid Species

	Millions of Years Ago (MYA)					
Species	**5.0**	**4.0**	**3.0**	**2.0**	**1.0**	**0.0**
Ardipithecus ramidus (4.4 mya)						
Australopithecus anamensis (4.2–3.9 mya)						
Australopithecus afarensis (3.9–3.0 mya)						
Australopithecus africanus (3.0–2.0 mya)						
Austraolopithecus aethiopicus (2.6–2.3 mya)						
Australopithecus robustus (2.0–1.5 mya)						
Australopithecus boisei (2.1–1.1 mya)						
Homo habilis (2.4–1.5 mya)						
Homo erectus (1.8 mya–300,000 ya)						
Homo neanderthalensis (230,000–30,000 ya)						
Homo sapiens (120,000 ya–present)						

ities in teeth and brain size (slightly larger than our own), some experts argue that Neanderthal was part of the modern human species; thus, they label it *Homo sapiens neanderthalensis*. However, recent studies suggest that the DNA of Neanderthal is different from our own, which suggests that *Homo sapiens* is not a direct descendant of the Neanderthal. Neanderthals disappeared about 30,000 years ago; they were replaced by the biologically modern Cro-Magnon people, the first indisputable example of our own species, *H. sapiens*.

Did the Cro-Magnon evolve from the Neanderthal, or were they a distinct species? Both peoples lived in Europe for a period of up to 10,000 years before the disappearance of the Neanderthal. Did they meet? Did they interbreed? Were the Neanderthal wiped out by the Cro-Magnon? These and many other questions await answers, as paleontologists continue to search for clues in the fossil record.

Has there been a time in Earth history when more than one hominid species was alive?

Answer: Yes.

12 MASS EXTINCTIONS

Embedded in the fossil record is a story of adaptation and recovery following catastrophic episodes in which many species become extinct within a geologically short time. Such episodes are called **mass extinctions.** Most people are aware that the dinosaurs became extinct about 65 million years ago, at the boundary between the Cretaceous (K) and Tertiary (T) periods. But many are not aware that other animal and plant species were also affected. Approximately one-quarter of all known animal families living at the time, including marine and land-dwelling species, became extinct at the end of the Cretaceous period. This mass disappearance of species is clearly evident in the fossil record. It is the reason that early paleontologists selected this particular stratigraphic horizon to represent a major boundary in the geologic timescale.

The great K-T extinction is not unique, nor was it the most dramatic of such occurrences. There have been at least 5 and possibly as many as 12 mass extinctions during the past 250 million years. The most devastating of these occurred 245 million years ago at the end of the Permian period, when as many as 96 percent of all species died out. Another great extinction occurred at the end of the Triassic period, and several earlier extinctions affected marine organisms.

What causes mass extinctions? Some evidence suggests that the K-T extinction may have been caused by a giant meteorite impact. If an extraterrestrial body

METEORITE IMPACT CRATER. Meteor Crater, Arizona, has a raised rim, formed as a result of broken rock being thrown out by a meteorite impact. The crater is 50,000 years old, 1.2 km (0.75 mi) in diameter, and 200 m (656 ft) deep. Many much larger impacts have occurred during the Earth's long history. Note that this particular impact was too small and happened much too recently to have caused the extinction of the dinosaurs. (Courtesy U.S. Geological Survey)

such as a meteorite or a comet 10 km (more than 6 mi) in diameter struck the Earth, it would cause massive environmental devastation. The effects could include earthquakes, tsunamis, widespread fires, acid rain, atmospheric particulates that might cause global darkness, and intense climatic changes. Evidence for these and related effects has been found in the stratigraphic horizon that marks the K-T boundary. Throughout the world the boundary is also marked by a thin layer of clay that is rich in the element iridium (Ir). This is consistent with an influx of extraterrestrial material, because meteorites contain a great deal of iridium compared to the amount contained in terrestrial rocks.

It is possible that a meteorite impact caused the K-T extinction, but the causes of other major extinctions are not as clear. Many scientists feel that some extinctions—particularly the great marine extinctions of the Paleozoic era—were more likely caused by climatic or other environmental changes than by catastrophic events such as meteorite impacts. The study of mass extinctions seems particularly relevant today; the present rate of species extinctions from human causes is rivaled only by the greatest mass extinctions in Earth history.

What was the greatest mass extinction in geologic history?

Answer: The Permian extinction, 245 million years ago.

SELF-TEST

These questions are designed to help you assess how well you have learned the concepts presented in chapter 10. The answers are given at the end.

1. The most ancient fossils that have been found are about __________ billion years old.

a. 1.5

b. 2.5

c. 3.5

d. 4.5

2. "Petrified wood" is wood that has been preserved by the process of __________.

a. natural mummification

b. carbonization

c. molding

d. permineralization

3. Although *Archaeopteryx* had feathers, many scientists feel that it should be classified as a(n) __________ rather than as a bird.

a. dinosaur

b. mammal

c. arthropod

d. amphibian

4. __________ is the idea that poorly adapted individuals tend to be eliminated from a population, with the result that fewer descendants will inherit the genetic characteristics of the poorly adapted individuals.

5. __________ is the study of fossils that are so small they must be studied with a microscope.

6. The mass extinction that was responsible for the extinction of the dinosaurs (as well as other species) occurred __________ million years ago, at the boundary between the __________ and __________ periods.

7. The early Earth was very hot, because the Sun's luminosity was much brighter than it is today. (T or F)

8. Respiration is more efficient than fermentation as a mechanism for organisms to obtain energy. (T or F)

9. The earliest land plants were the gymnosperms; the angiosperms followed closely thereafter. (T or F)

10. What is the role of limestones and shelled organisms in regulating climate and modifying the chemistry of the Earth's atmosphere?

11. What are trace fossils, and what are some types of trace fossils?

12. Did the family of humans (Hominidae) evolve directly from modern apes (Pongidae)?

13. What is a chordate? Are humans chordates?

ANSWERS

1. c

2. d

3. a

4. Natural selection

5. Micropaleontology

6. 65; Cretaceous; Tertiary

7. F

8. T

9. F

10. Limestone is made from the remains of shelled organisms. Limestone ($CaCO_3$) is a huge, long-term storage reservoir for carbon dioxide, removing it from the atmosphere and hydrosphere. If all the carbon dioxide currently stored in limestones were released back into the atmosphere, the Earth would have a runaway greenhouse effect and an atmosphere like that of Venus, where the surface temperature is about 480°C.

11. A trace fossil is fossilized evidence left behind by an organism, without necessarily leaving any part of the organism itself. Examples include footprints, burrows, borings, nests, molds or imprints, and feces.

12. No, the two groups probably diverged from an earlier apelike family.

13. A chordate is an animal with a notochord, a cartilaginous rod running along the back of the body. Humans are chordates; we have a notochord as embryos, later replaced by the backbone.

KEY WORDS.

aerobic
anaerobic
angiosperm
autotroph
biodiversity
biosynthesis
cell
chemosynthesis
chordate
DNA (deoxyribonucleic acid)
eukaryotic cell
evolution
fermentation
gymnosperm
heterotroph
hominid
mass extinction
metabolism
microfossil
micropaleontology
natural selection
permineralization
photosynthesis
primary atmosphere
prokaryotic cell
respiration
RNA (ribonucleic acid)
secondary atmosphere
species
stromatolite
trace fossil
vertebrate