Section 14.1

Reading Preview

Objectives

- **Describe** a typical sequence of events in fossilization.
- **Compare** techniques for dating fossils.
- **Identify** and describe major events using the geologic time scale.

Review Vocabulary

extinction: the death of all individuals of a species

New Vocabulary

fossil
paleontologist
relative dating
law of superposition
radiometric dating
half-life
geologic time scale
epoch
era
period
Cambrian explosion
K-T boundary
plate tectonics

Fossil Evidence of Change

MAIN Idea Fossils provide evidence of the change in organisms over time.

Real-World Reading Link Did you know that when you look at the stars at night you are looking into the past? The stars are so far away that the light you see left the stars thousands and sometimes millions of years ago. You also are looking into the past when you look at rocks. The rocks formed thousands or even millions of years ago. Rocks can tell us what Earth was like in the distant past, and sometimes they can tell us what lived during that time.

Earth's Early History

What were the conditions on Earth as it formed, and how did life arise on a lifeless planet? Because there were no people to witness Earth's earliest history, it might seem that this is a mystery. Like any good mystery, however, it left clues behind. Each clue to Earth's history and life's origin is open to investigation by the scientists who study the history of the Earth.

Land environments By studying other planets in the solar system and rocks on Earth, scientists conclude that Earth was a molten body when it formed about 4.6 billion years ago. Gravity pulled the densest elements to the center of the planet. After about 500 million years, a solid crust formed on the surface, much like the crust that forms on the top of lava, as shown in **Figure 14.1.** The surface was rich in lighter elements, such as silicon. From the oldest rocks remaining today, scientists infer that Earth's young surface included a number of volcanic features. In addition, the cooling interior radiated much more heat to the surface than it does today. Meteorites would have caused additional heating as they crashed into Earth's surface. If there had been any life on Earth, it most likely would have been consumed by the intense heat.

Atmosphere Because of its gravitational field, Earth is a planet that is able to maintain an atmosphere. However, no one can be certain about the exact composition of Earth's early atmosphere. The gases that likely made up the atmosphere are those that were expelled by volcanoes. Volcanic gases today include water vapor (H_2O), carbon dioxide (CO_2), sulfur dioxide (SO_2), carbon monoxide (CO), hydrogen sulfide (H_2S), hydrogen cyanide (HCN), nitrogen (N_2), and hydrogen (H_2). Scientists infer that the same gases would have been present in Earth's early atmosphere. The minerals in the oldest known rocks suggest that the early atmosphere, unlike today's atmosphere, had little or no free oxygen.

Clues in Rocks

Earth eventually cooled to the point where liquid water formed on its surface, which became the first oceans. It was a very short time after this—maybe as little as 500 million years—that life first appeared. The earliest clues about life on Earth date to about 3.5 billion years ago.

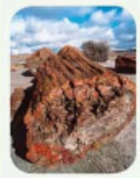
The fossil record A **fossil** is any preserved evidence of an organism. Six categories of fossils are shown in **Table 14.1.** Plants, animals, and even bacteria can form fossils. Although there is a rich diversity of fossils, the fossil record is like a book with many missing pages. Perhaps more than 99 percent of the species that ever have lived are now extinct, but only a tiny percentage of these organisms are preserved as fossils.

Most organisms decompose before they have a chance to become fossilized. Only those organisms that are buried rapidly in sediment are readily preserved. This occurs more frequently with organisms living in water because the sediment in aquatic environments is constantly settling, covering, and preserving the remains of organisms.

Concepts in Motion

Interactive Table To explore more about categories of fossil types, visit biologygmh.com.

Table 14.1 Categories of Fossil Types

Category	Trace fossil	Molds and casts	Replacement	Petrified or permineralized	Amber	Original material
Example						
Formation	A trace fossil is any indirect evidence left by an organism. Footprints, burrows, and fossilized feces are trace fossils.	A mold is an impression of an organism. A cast is a mold filled with sediment.	The original material of an organism is replaced with mineral crystals that can leave detailed replicas of hard or soft parts.	Empty pore spaces are filled in by minerals, such as in petrified wood.	Preserved tree sap traps an entire organism. The sap hardens into amber and preserves the trapped organism.	Mummification or freezing preserves original organisms.

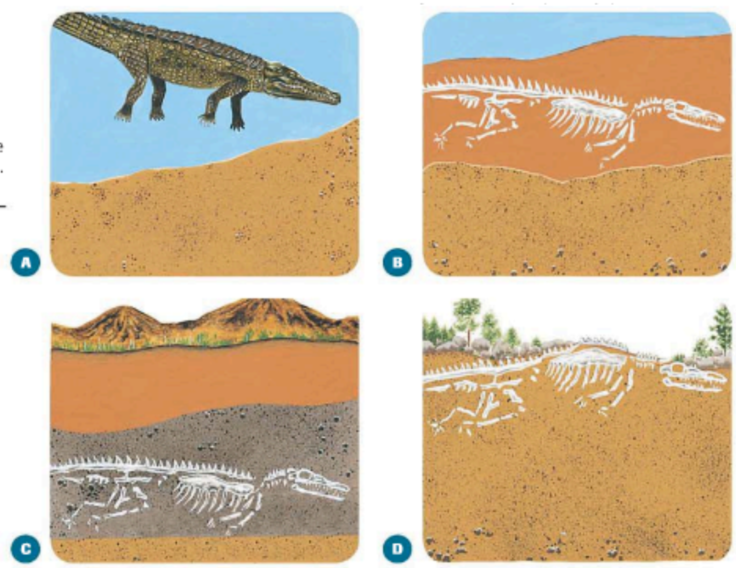


Figure 14.2 (A) Organisms usually become fossilized after they die and are buried by sediment. (B) Sediments build up in layers, eventually encasing the remains in sedimentary rock. (C) Minerals replace, or fill in the pore space of, the bones and hard parts of the organism. (D) Erosion can expose the fossils.

Fossil formation Fossils do not form in igneous (IHG nee us) or metamorphic (meh tuh MOR fihk) rocks. Igneous rocks form when magma from Earth's interior cools. Metamorphic rocks form when rocks are exposed to extreme heat and pressure. Fossils usually do not survive the heat or pressure involved in the formation of either of these kinds of rocks.

Nearly all fossils are formed in sedimentary rock through the process described in **Figure 14.2.** The organism dies and is buried in sediments. The sediments build up until they cover the organism's remains. In some cases, minerals replace the organic matter or fill the empty pore spaces of the organism. In other cases, the organism decays, leaving behind an impression of its body. The sediments eventually harden into rock.

A **paleontologist** (pay lee ahn TAH luh jist) is a scientist who studies fossils. He or she attempts to read the record of life left in rocks. From fossil evidence, paleontologists infer the diet of an organism and the environment in which it lived. In fact, paleontologists often can create images of extinct communities.

Connection to Earth Science When geologists began to study rock layers, or strata, in different areas, they noticed that layers of the same age tended to have the same kinds of fossils no matter where the rocks were found. The geologists inferred that all strata of the same age contained similar collections of fossils. This led to the establishment of a relative age scale for rocks all over the world.

Dating fossils **Relative dating** is a method used to determine the age of rocks by comparing them with those in other layers. Relative dating is based on the **law of superposition,** illustrated in **Figure 14.3,** which states that younger layers of rock are deposited on top of older layers. The process is similar to stacking newspapers in a pile as you read them each day. Unless you disturb the newspapers, the oldest ones will be on the bottom.

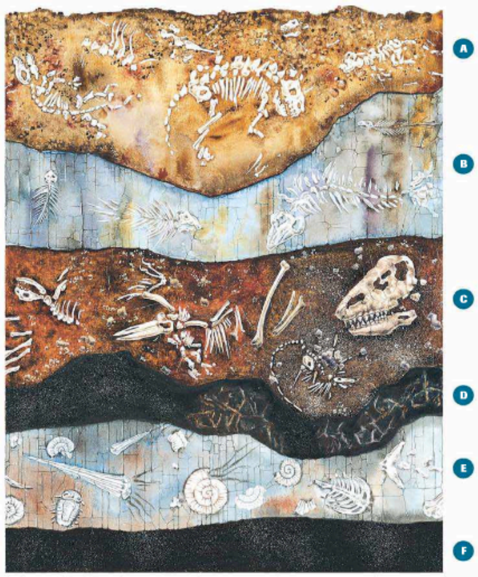
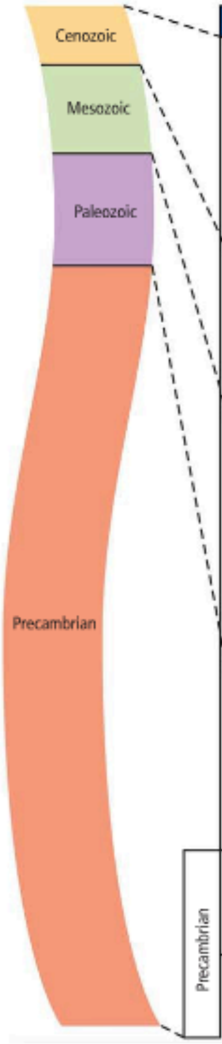


Figure 14.3 According to the law of superposition, rock layers are deposited with the youngest undisturbed layers on top.
Infer *Which layer shows that an aquatic ecosystem replaced a land ecosystem?*

Radiometric dating uses the decay of radioactive isotopes to measure the age of a rock. Recall from Chapter 6 that an isotope is a form of an element that has the same atomic number but a different mass number. The method requires that the **half-life** of the isotope, which is the amount of time it takes for half of the original isotope to decay, is known. The relative amounts of the radioactive isotope and its decay product must also be known.

One radioactive isotope that is commonly used to determine the age of rocks is Uranium 238. Uranium 238 (U^{238}) decays to Lead 206 (Pb^{206}) with a half life of 4510 million years. When testing a rock sample, scientists calculate the ratio of the parent isotope to the daughter isotope to determine the age of the sample.

Radioactive isotopes that can be used for radiometric dating are found only in igneous or metamorphic rocks, not in sedimentary rocks, so isotopes cannot be used to date rocks that contain fossils. Igneous rocks that are found in layers closely associated with fossil-bearing sedimentary rocks often can be used for assigning relative dates to fossils.



	Era	Period	Epoch	MYA	Biological events
Phanerozoic	Cenozoic	Neogene	Holocene		• Humans form civilizations
			Pleistocene	0.01	• Ice ages occur • Modern humans appear
			Pliocene	1.8	• Hominins appear • Flowering plants are dominant
			Miocene	5.3	• Apes appear • Climate is cooler
		Paleogene	Oligocene	23.0	• Monkeys appear • Climate is mild
			Eocene	33.9	• Flowering plants scattered • Most mammal orders exist
			Paleocene	55.8	• Mammals, birds, and insects scatter • Climate is tropical
				Mass extinction	
	Mesozoic	Cretaceous		65.5	• Flowering plants appear • Dinosaur population peaks
		Jurassic		145.5	• First birds appear • Dinosaurs scatter • Forests are lush
		Triassic		199.6	• Gymnosperms are dominant • Dinosaurs appear • First mammals appear
				Mass extinction	
	Paleozoic	Permian		251.0	• Reptiles scatter
		Carboniferous		299.0	• Ferns and evergreens make up forests • Amphibians appear • Insects scatter
		Devonian	Mass extinction	359.2	• Sharks and bony fishes appear
		Silurian		416.0	• Coral and other invertebrates are dominant • Land plants and insects appear
				Mass extinction	
		Ordovician		443.7	• First vertebrates appear • First plants appear
		Cambrian		488.3	• Cambrian explosion • All body plans arise
Precambrian / Proterozoic	Neoproterozoic	Ediacaran		542	• Soft-bodied organisms appear
		Cryogenian		630	• Invertebrates and algae diversify
		Tonian		850	• Multicellular organisms appear
				1500	• Oldest fossils of eukaryotes
				2500	• Oldest fossils of prokaryotes
				4600	• Earth forms

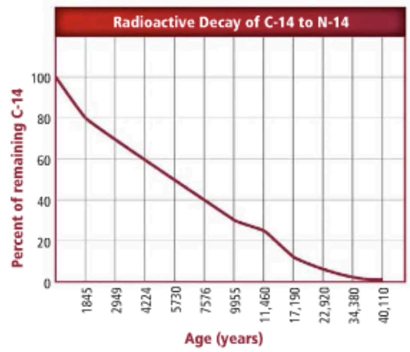


Figure 14.4 The graph shows how the percent of carbon-14 indicates age.

Interpret the graph *What would the age of a rock be if it contained only 10 percent of C-14?*

Materials, such as mummies, bones, and tissues, can be dated directly using carbon-14 (C-14). Given the half-life of carbon-14, shown in **Figure 14.4,** only materials less than 60,000 years old can be dated accurately with this isotope.

The Geologic Time Scale

Think of geologic time as a ribbon that is 4.6 m long. If each meter represents one billion years, each millimeter represents one million years. Earth was formed at one end of the ribbon, and humans appear at the very tip of the other end.

The **geologic time scale,** shown in **Figure 14.5,** is a record of Earth's history. All the major geological and biological events in Earth's history can be identified within the geologic time scale. Because geologic time spans more than 4 billion years, a subdivision of time is usually identified by how many millions of years ago (mya) it occurred. The geologic time scale is divided into two distinct segments—Precambrian time and the Phanerozoic (fan eh roh ZOH ihk) eon. **Epochs** are the smallest unit of geologic time lasting several million years. **Periods** are divisions of geologic time lasting tens of millions of years. An **Era** is a unit of geologic time consisting of two or more periods that lasts hundreds of millions of years.

In 2004, geologists worldwide agreed on a revision of the names and dates in the geologic time scale based on a project coordinated by the International Commission on Stratigraphy. As in all fields of science, continuing research and discoveries might result in future revisions.

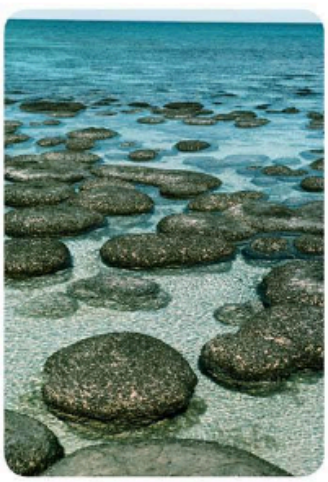


Figure 14.6 Fossils much like these stromatolites are found in rocks almost 3.5 billion years old. Modern day stromatolites are formed by cyanobacteria.

Explain *the importance of the organisms that left these stromatolites.*

Precambrian The first 4 billion years, as shown in **Figure 14.5,** make up the Precambrian. This is nearly 90 percent of Earth's entire history, stretching from the formation of Earth to the beginning of the Paleozoic era about 542 million years ago. The Precambrian was an important time. Earth formed and life first appeared. Eventually, autotrophic prokaryotes, much like the cyanobacteria that made the stromatolites in **Figure 14.6,** enriched the atmosphere with oxygen. Eukaryotic cells also emerged, and by the end of the Precambrian, life was flourishing and the first animals had appeared.

Extensive glaciation marked the second half of the Precambrian. This might have delayed the further evolution of life until the ice receded at the beginning of the Ediacaran (ee dee UH kur uhn) period. The Ediacaran period was added to the time scale in 2004. It is the first new period added to the time scale since 1891 and reflects new knowledge of Earth's history. The Ediacaran period lasted from about 630 million years ago to about 542 million years ago, representing about three quarters of a meter on the time ribbon at the end of the Precambrian. Simple organisms, such as the fossil in **Figure 14.7,** inhabited Ediacaran marine ecosystems. Food chains probably were short, and were dominated by animals that consumed tiny particles suspended in the water and by animals that ate debris on the bottom of the sea.

Reading Check **Infer** the process by which early autotrophic prokaryotes produced oxygen.

The Paleozoic era A drastic change in the history of animal life on Earth marked the start of the Paleozoic (pay lee uh ZOH ihk) era. In the space of just a few million years, the ancestors of most major animal groups diversified in what scientists call the **Cambrian explosion.** Not all major groups of organisms evolved rapidly at this time, and paleontologists still do not know when the rapid changes started or ended.

Major changes in ocean life occurred during the Paleozoic. More importantly, it seems the first life on land emerged during this era. Life in the oceans continued to evolve through the Cambrian period. Fish, land plants, and insects appeared during the Ordovician and Silurian periods. Organisms of many kinds, including huge insects, soon flourished in swampy forests that dominated the land, as shown in **Figure 14.8.** Tetrapods, the first land vertebrates (animals with backbones), emerged in the Devonian period. By the end of the Carboniferous period, the first reptiles were roaming the forests.

Figure 14.7 Paleontologists disagree about scarce Ediacaran fossils such as this one. Some paleontologists suggest that they are relatives of today's living invertebrates such as segmented worms, while others think they represent an evolutionary dead end of giant protists or simple metazoans.

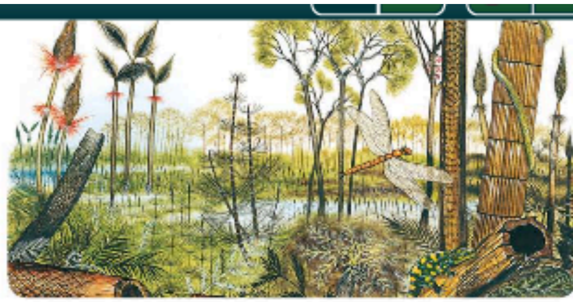


Figure 14.8 During the Carboniferous period, swamp forests covered much of Earth's land surface. Insects dominated the air, and tetrapods flourished in freshwater pools.

Infer ***How were the plants of the Paleozoic era different from those of today?***

A mass extinction ended the Paleozoic era at the end of the Permian period. Recall from Chapter 5 that a mass extinction is an event in which many species become extinct in a short time. Mass extinctions have occurred every 26 to 30 million years on average. Between 60 and 75 percent of the species alive went extinct in each of these events. During the Permian mass extinction, 90 percent of marine organisms disappeared. Geologists disagree about the cause of the Permian extinction, but most agree that geological forces, including increased volcanic activity, would have disrupted ecosystems or changed the climate.

The Mesozoic era At the beginning of the Triassic period, the ancestors of early mammals were the dominant land animals. Mammals and dinosaurs first appeared late in the Triassic period, and flowering plants evolved from nonflowering plants. Birds evolved from a group of predatory dinosaurs in the middle Jurassic period. For the rest of the Mesozoic, reptiles, such as the dinosaurs illustrated in **Figure 14.9,** were the dominant organisms on the planet. Then, about 65 million years ago, a meteorite struck Earth.

The primary evidence for this meteorite impact is found in a layer of material between the rocks of the Cretaceous (krih TAY shus) period and the rocks of the Paleogene period, the first period of the Cenozoic era. Paleontologists call this layer the **K-T boundary.** Within this layer, scientists find unusually high levels of an element called iridium. Iridium is rare on Earth, but relatively common in meteorites. Therefore, the presence of iridium on Earth indicates a meteorite impact.

Many scientists think that this impact is related to the mass extinction at the end of the Mesozoic era, which eliminated all dinosaurs except birds, most marine reptiles, many marine invertebrates, and numerous plant species. The meteorite itself did not wipe out all of these species, but the debris from the impact probably stayed in the atmosphere for months or even years, affecting global climate. Those species that could not adjust to the changing climate disappeared.

Figure 14.9 The dominant organisms during the Mesozoic era were dinosaurs. A mass extinction occurred at the end of the Mesozoic era that eliminated all dinosaurs, with the exception of their avian and reptilian descendants.

Figure 14.10 These illustrations show the movement of Earth's major tectonic plates from about 225 million years ago to 65 million years ago, when all of the continents were joined into one landmass called Pangaea.

Concepts In Motion

Interactive Figure To see an animation of continental drift, visit biologygmh.com.

Scientists also think that the course of evolution in the Cenozoic era was shaped by the massive geological changes shown in **Figure 14.10** that characterized the Mesozoic era. While it might appear to us that continents are immobile, they have been moving since they formed. Alfred Wegener, a German scientist, presented the first evidence for continental drift in the 1920s. Continental drift has since become part of the theory of plate tectonics. **Plate tectonics** describes the movement of several large plates that make up the surface of Earth. These plates, some of which contain continents, move atop a partially molten layer of rock underneath them.

The Cenozoic era The most recent era is the one in which mammals became the dominant land animals. At the beginning of the Cenozoic (sen uh ZOH ihk) era, which means "recent life," most mammals were small and resembled shrews. After the mass extinction at the end of the Mesozoic era, mammals began to diversify into distinct groups, including primates—the group to which you belong. Humans appeared very recently, near the end of the geologic time scale, in the current Neogene period. Humans survived the last ice age, but many species of mammals did not. To get an idea of how recently modern humans have appeared, you need to remove about two threads at the end of your geologic time ribbon. These threads represent the time that humans have existed on Earth.

Section 14.1 Assessment

Section Summary

- Early Earth was lifeless for several hundred million years.
- Fossils provide evidence of past life.
- Relative dating and radiometric dating are two methods used to determine the age of fossils.
- The geologic time scale is divided into eras and periods.
- Major events in the geological time scale include both biological and geological changes.

Understand Main Ideas

1. MAIN Idea **Discuss** how fossils provide evidence of change from the earliest life-forms to those alive today.
2. **Diagram** a typical sequence of events in fossilization.
3. **Discuss** two ways that radiometric dating can be used to establish the age of a fossil.
4. **Explain** major events in three periods of the geologic time scale.

Think Critically

5. **Infer** what changes you might observe in the fossil record that would indicate the occurrence of a mass extinction.

MATH in Biology

6. Out of the total of Earth's history (approximately 4.6 billion years), modern humans have existed for only 100,000 years. To put this in perspective, calculate the percentage of Earth's history that modern humans have existed.

Section 14.2

Reading Preview

Objectives

- **Differentiate** between spontaneous generation and biogenesis.
- **Sequence** the events that might have led to cellular life.
- **Describe** the endosymbiont theory.

Review Vocabulary

amino acid: building blocks for proteins

New Vocabulary

spontaneous generation
theory of biogenesis
endosymbiont theory

The Origin of Life

MAIN Idea **Evidence indicates that a sequence of chemical events preceded the origin of life on Earth and that life has evolved continuously since that time.**

Real-World Reading Link In a recipe, some steps can be out of order, but some steps have to occur earlier than others or the end result will be different from what was intended. In the same way, to arrive at the pattern of life that is seen today, events leading to the emergence of life had to occur in specific ways.

Origins: Early Ideas

Perhaps one of the oldest ideas about the origin of life is spontaneous generation. **Spontaneous generation** is the idea that life arises from nonlife. For example, at one time people thought that mice could be created by placing damp hay and corn in a dark corner, or that mud could give rise to worms, insects, and fish. These ideas might seem humorous to us today, but before much was known about reproduction, it is easy to see how someone might form these conclusions.

One of the first recorded investigations of spontaneous generation came in 1668. Francesco Redi, an Italian scientist, tested the idea that flies arose spontaneously from rotting meat. He hypothesized that flies—not meat—produced other flies. In his experiment, illustrated using present-day equipment in **Figure 14.11,** Redi observed that maggots, the larvae of flies, appeared only in flasks that were open to flies. Closed flasks had no flies and no maggots. The results of his experiments failed to convince everyone, however. Although people were beginning to use the microscope during Redi's time and knew that organisms invisible to the naked eye could be found almost everywhere, some thought that these tiny organisms must arise spontaneously, even if flies did not.

Figure 14.11 Francesco Redi showed that flies and maggots did not arise spontaneously from rotting meat.
Infer *the purpose of the covered flask in Redi's experiment.*

Control group **Experimental group**

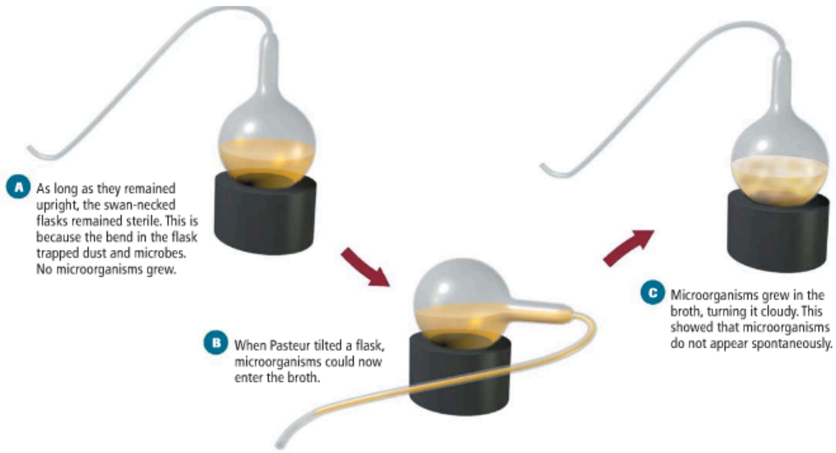


Figure 14.12 Pasteur's experiment showed that sterile broth remained free of microorganisms until exposed to air.

The idea of spontaneous generation was not completely rejected

The idea of spontaneous generation was not completely rejected until the mid-1800s. It was replaced by the **theory of biogenesis** (bi oh JEN uh sus), which states that only living organisms can produce other living organisms. Louis Pasteur designed an experiment to show that biogenesis was true even for microorganisms. Pasteur's experiment is illustrated in **Figure 14.12.** In one flask, only air was allowed to contact a sterile nutrient broth. Nutrient broth supports the growth of microorganisms. In another flask, both air and microorganisms were allowed to contact the broth. No microorganisms grew in the first container. They did, however, grow in the second container.

Origins: Modern Ideas

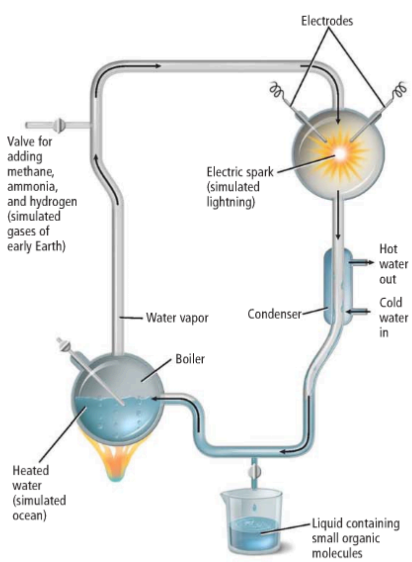
If life can arise only from pre-existing life, then how did the first life-form appear? Most biologists agree that life originated through a series of chemical events early in Earth's history. During these events, complex organic molecules were generated from simpler ones. Eventually, simple metabolic pathways developed. Such pathways allowed molecules to be synthesized or broken down more efficiently. These pathways might have led to the emergence of life as we know it. How this happened is a topic of ongoing research among scientists today.

Simple organic molecule formation The primordial soup hypothesis was an early hypothesis about the origin of life. Scientists Alexander Oparin and John Haldane suggested this hypothesis in the 1920s. They thought that if Earth's early atmosphere had a mix of certain gases, organic molecules could have been synthesized from simple reactions involving those gases in the early oceans. UV light from the Sun and electric discharge in lightning might have been the primary energy sources. They thought that these organic molecules would have eventually supplied the precursors to life.

Connection to Chemistry In 1953, American scientists Stanley Miller and Harold Urey were the first to show that simple organic molecules could be made from inorganic compounds, as proposed by Oparin and Haldane. Miller and Urey built a glass apparatus, illustrated in **Figure 14.13,** to simulate the early Earth conditions hypothesized by Oparin. They filled the apparatus with water and the gases that they thought had made up the early atmosphere. The water was boiled and electric discharges were used to simulate lightning as an energy source. Upon examination, the resulting mixture contained a variety of organic compounds including amino acids. Because amino acids are the building blocks of proteins, this discovery supported the primordial soup hypothesis.

Later, other scientists found that hydrogen cyanide could be formed from even simpler molecules in simulated early Earth environments. Hydrogen cyanide can react with itself to eventually form adenine, one of the nucleotide bases in the genetic code. Many other experiments have since been carried out under conditions that probably reflect the atmosphere of early Earth more accurately. The final reaction products in these experiments were amino acids and sugars as well as nucleotides.

Some scientists suggest that the organic reactions that preceded life's emergence began in the hydrothermal volcanic vents of the deep sea, where sulfur forms the base of a unique food chain. Still others think that meteorites brought the first organic molecules to Earth.



Concepts In Motion

Interactive Figure To see an animation of the Miller-Urey experiment, visit biologygmh.com.

Figure 14.13 The Miller-Urey experiment showed for the first time that organic molecules could be produced from gases proposed to have made up the atmosphere of early Earth.

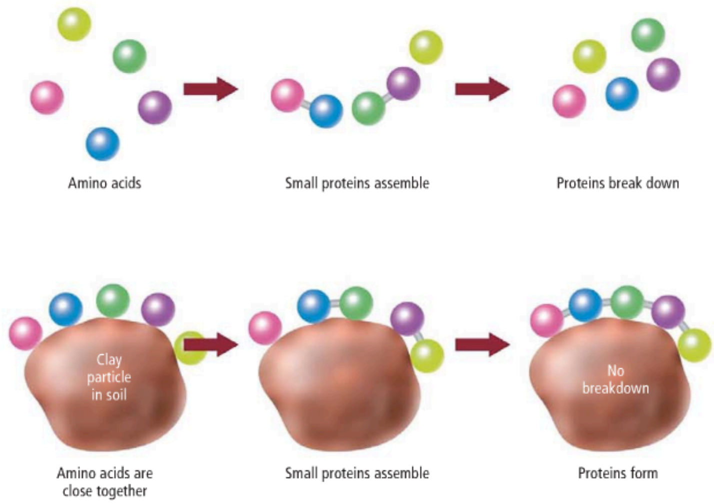


Figure 14.14 Without clay, amino acids could have formed small, unstable proteins. In the presence of clay, amino acids might have come together in a more stable manner.

Making proteins Wherever the first organic molecules originated, it is clear that the next critical step was the formation of proteins. Amino acids alone are not sufficient for life. Life requires proteins, which, as you might recall from Chapter 6, are chains of amino acids. In the Miller-Urey experiment, amino acids could bond to one another, but they could separate just as quickly, as illustrated in **Figure 14.14.** One possible mechanism for the formation of proteins would be if amino acids were bound to a clay particle. Clay would have been a common sediment in early oceans, and it could have provided a framework for protein assembly.

Genetic code Another requirement for life is a coding system for protein production. All modern life has such a system, based on either RNA or DNA. Because all DNA-based life-forms also contain RNA, and because some RNA sequences appear to have changed very little through time, many biologists consider RNA to have been life's first coding system. Researchers have been able to demonstrate that RNA systems are capable of evolution by natural selection. Some RNAs also can behave like enzymes. These RNA molecules, called ribozymes, could have carried out some early life processes. Other researchers have proposed that clay crystals could have provided an initial template for RNA replication, and that eventually the resulting molecules developed their own replication mechanism.

Molecules to cells Another important step in the evolution of life was the formation of membranes. Researchers have tested ways of enclosing molecules in membranes, allowing early metabolic and replication pathways to develop. In this work, as in other origin-of-life research, the connection between the various chemical events and the overall path from molecules to cells remains unresolved.

Cellular Evolution

What were the earliest cells like? Scientists don't know because the first life left no fossils. The earliest fossils are 3.5 billion years old. Chemical markings in rocks as old as 3.8 billion years suggest that life was present at that time even though no fossils remain. In 2004, scientists announced the discovery of what appeared to be fossilized microbes in volcanic rock that is 3.5 billion years old. This suggests that cellular activity had become established very early in Earth's history. It also suggests that early life might have been linked to volcanic environments.

Figure 14.15 Some archaebacteria live near deep-sea hydrothermal vents. They use energy from inorganic molecules to form the base of the vent food web.

The first cells Scientists hypothesize that the first cells were prokaryotes. Recall from Chapter 7 that prokaryotic cells are much smaller than eukaryotic cells, and they lack a defined nucleus and most other organelles. Many scientists think that modern prokaryotes called archaea (ar KEE uh) are the closest relatives of Earth's first cells. These organisms often live in extreme environments, such as the hot springs of Yellowstone Park or the volcanic vents in the deep sea, such as the one shown in **Figure 14.15.** These are environments similar to the environment that might have existed on early Earth.

Photosynthesizing prokaryotes Although archaea are autotrophic, they do not obtain their energy from the Sun. Instead, they extract energy from inorganic compounds such as sulfur. Archaea also do not need or produce oxygen.

Scientists think that oxygen was absent from Earth's earliest atmosphere until about 1.8 billion years ago. Any oxygen that appeared earlier than 1.8 billion years ago likely bonded with free ions of iron as oxygen does today. Evidence that iron oxide was formed by oxygen generated by early life is found in unique sedimentary rock formations, such as those shown in **Figure 14.16,** that are between about 1.8 billion and 2.5 billion years old. Scientists hypothesize that after 1.8 billion years ago, the early Earth's free iron was saturated with oxygen, and oxygen instead began accumulating in the atmosphere.

oxygen instead began accumulating in the atmosphere.

Many scientists think that photosynthesizing prokaryotes evolved not long after the archaea—very early in life's history. Fossil evidence of these primitive prokaryotes, called cyanobacteria, has been found in rocks as old as 3.5 billion years. Cyanobacteria eventually produced enough oxygen to support the formation of an ozone layer. Once an ozone shield was established, conditions would be right for the appearance of eukaryotic cells.

Figure 14.16 These sedimentary rock formations appear as banded layers. Scientists believe that banding is a result of cyclic peaks in oxygen production.

The endosymbiont theory Eukaryotic cells appeared in the fossil record about 1.8 billion years ago, around two billion years after life first formed. Eukaryotic cells have complex internal membranes, which enclose various organelles, including mitochondria and, in plant cells, chloroplasts. Mitochondria metabolize food through cellular respiration, and chloroplasts are the site of photosynthesis. Both mitochondria and chloroplasts are about the size of prokaryotic cells and contain similar prokaryote features. This lead some scientists to speculate that prokaryotic cells were involved in the evolution of eukaryotic cells.

In 1966, biologist Lynn Margulis proposed the endosymbiont theory. According to the **endosymbiont theory,** the ancestors of eukaryotic cells lived in association with prokaryotic cells. In some cases, prokaryotes even might have lived inside eukaryotes. Prokaryotes could have entered a host cell as undigested prey, or they could have been internal parasites. Eventually, the relationship between the cells became mutually beneficial, and the prokaryotic symbionts became organelles in eukaryotic cells. This theory explains the origin of chloroplasts and mitochondria, as illustrated in **Figure 14.17.**

Evidence for the endosymbiont theory When Margulis first proposed the endosymbiont theory, many scientists were hesitant to accept it. There is evidence, however, that at least mitochondria and chloroplasts formed by endosymbiosis. For example, mitochondria and chloroplasts contain their own DNA. It is arranged in a circular pattern, just as it is in prokaryotic cells. Mitochondria and chloroplasts also have ribosomes that more closely resemble those in prokaryotic cells than those in eukaryotic cells. Finally, like prokaryotic cells, mitochondria and chloroplasts reproduce by fission, independent from the rest of the cell.

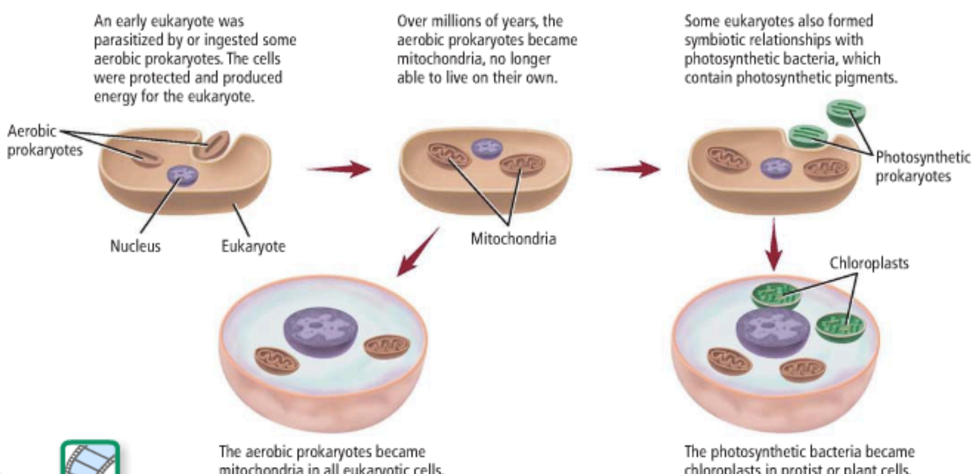


Figure 14.17 This illustration shows how Margulis hypothesized that eukaryotic cells and their organelles evolved.

Concepts In Motion

Interactive Figure To see an animation about the endosymbiont hypothesis, visit biologygmh.com.

Though the endosymbiont theory is widely endorsed, it is important to understand that scientists do not know the early steps that led to the emergence of life or to its early evolution. It is unlikely that any traces of the first life will ever be found. What scientists do know is that the conditions on Earth shortly after it took shape allowed the precursors of life to form.

The evolution of life is better understood than how the first life appeared. Fossil, geologic, and biochemical evidence supports many of the proposed steps in life's subsequent evolution. However, future discoveries might alter any or all of these steps. Scientists will continue to evaluate new evidence and test new theories in years to come.

Section 14.2 Assessment

Section Summary

- Spontaneous generation was disproved in favor of biogenesis.
- The origin of life is hypothesized to be a series of chemical events.
- Organic molecules, such as amino acids, might have been formed from simpler molecules on early Earth.
- The first cells probably were autotrophic and prokaryotic.
- The endosymbiont theory explains how eukaryotic cells might have evolved from prokaryotic cells.

Understand Main Ideas

1. MAIN Idea **Infer** why scientists hypothesize that chemical events preceded the origin of life on Earth.
2. **Compare and contrast** spontaneous generation and biogenesis.
3. **Discuss** why prokaryotic cells probably appeared before eukaryotic cells.
4. **Hypothesize** whether prokaryotic cells might have been symbiotic before the evolution of eukaryotic cells.

Think Critically

5. **Sequence** Describe the hypothesized sequence of chemical and biological events that preceded the origin of eukaryotic cells.

WRITING in **Biology**

6. Write a persuasive paragraph that explains why many scientists accept the endosymbiont theory.