CHAPTER 20 History of Life

20.1 The Fossil Record

20.2 Evolutionary Patterns and Processes

20.3 Earth's Early History

Go Online to access your digital course.

- VIDEO
- AUDIO
- INTERACTIVITY
- eTEXT
- ANIMATION
- VIRTUAL LAB
- ASSESSMENT

This artist's rendition of a Devonian landscape shows what parts of the world may have looked like when the first four-legged animals evolved.

HS-LS4-1, HS-LS4-4, HS-LS4-5, HS-ESS1-5, HS-ESS1-6, HS-ESS2-6, HS-ESS2-7

CASE STUDY

How did fossil hunters find *Tiktaalik*?

If social media had existed 375 million years ago, one popular meme could well have been "A small step for fishes … a great leap for animals with backbones!" Why? Because around that time, adaptations that made life on land possible (including legs that could take steps) developed in the ancestors of modern four-limbed animals. But who took that crucial first step?

Life began in the sea, and remained underwater for a long time. By around 430 million years ago, ancestors of land plants and insects had colonized the land. By 100 million years later, land animals with four limbs—called tetrapods—were common. Fossil evidence suggested that the first tetrapods evolved from a group of ancient fishes. The fins of those fishes had some bones that were homologous to the bones of modern animals' arms and legs. But some steps in the evolutionary transformation from fins to limbs were missing.

Could anyone find an ancient four-legged fish that would document this transition? One team, headed by researchers Neil Shubin, Edward Daeschler, and Farish Jenkins, was determined to try. First came intensive studies of geology, geography, and fossils. Then came years of difficult fieldwork in northern Canada, just 600 miles from the North Pole. Finally, in 2004, they announced the discovery of an amazing fossil. They named it *Tiktaalik* (TIK-ta-lik), which means "large, freshwater fish" in the local First Nations language.

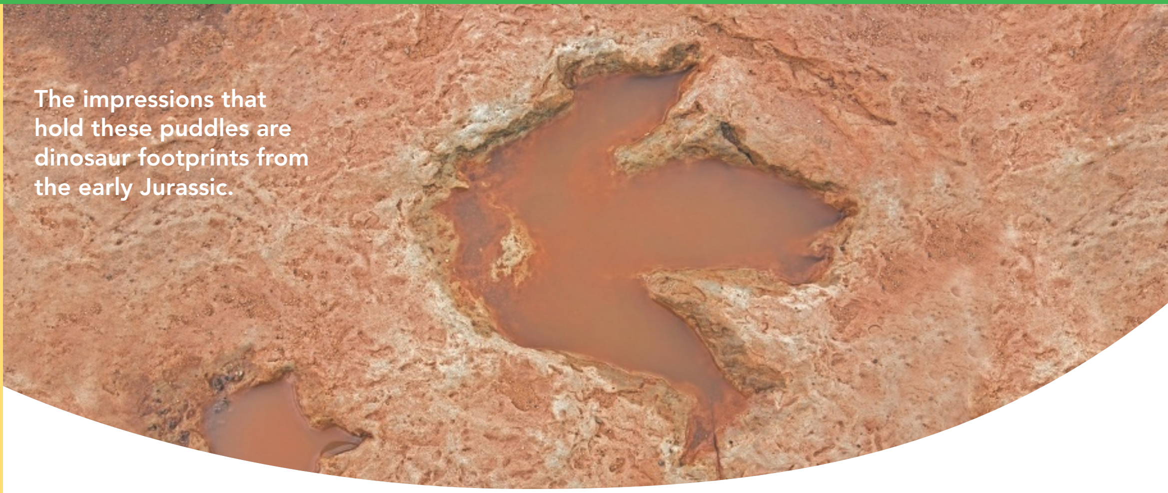
Tiktaalik shared some traits with fishes. It had scales and fins, and it used gills to breathe. But its skeleton differed from those of other fishes in important ways. *Tiktaalik's* fins were connected to its backbone by bony structures that look like a shoulder and pelvis. These structures would have helped those fins to support the animal's weight. *Tiktaalik* also had rib bones that attached to one another, like those of land animals. Taken together, these skeletal features show that *Tiktaalik* could hold its body against the pull of gravity. *Tiktaalik* also had neck bones that allowed it to move its head from side to side. Many land animals today have moveable necks, but fishes don't.

Tiktaalik wasn't the common ancestor of land-dwelling vertebrates, but it gives us a good idea of what that common ancestor might have looked like. Its discoverers dubbed it "fish-a-pod" to emphasize that it represented a stage between fishes and modern tetrapods. They suggest that *Tiktaalik* lived in shallow water, where it propped itself up to snatch prey.

The discovery of *Tiktaalik* was no accident. The research Shubin and his team performed before heading out into the field convinced them that they knew just where to look. Their determination was important, because they searched for four years before finding what they were after! How did they know where to look? What evidence can fossils provide about ancient life and the history of life on Earth? What kinds of patterns do fossils form?

Throughout this chapter, look for connections to the CASE STUDY to help you answer these questions.

LESSON
20.1 The Fossil Record


The impressions that hold these puddles are dinosaur footprints from the early Jurassic.

KEY QUESTIONS
- *What do fossils reveal about ancient life?*
- *How do we date events in Earth's history?*
- *How was the geologic time scale established, and what are its major divisions?*
- *How have Earth's physical and biological environments shaped the history of life?*

HS-LS4-1: Communicate scientific information that common ancestry and biological evolution are supported by multiple lines of empirical evidence.
HS-ESS1-5: Evaluate evidence of the past and current movements of continental and oceanic crust and the theory of plate tectonics to explain the ages of crustal rocks.
HS-ESS2-7: Construct an argument based on evidence about the simultaneous coevolution of Earth's systems and life on Earth.

VOCABULARY
extinct
relative dating
index fossil
radiometric dating
half-life
geologic time scale
era
period
plate tectonics

READING TOOL
As you read through this lesson, pay special attention to how fossils form and fill in the graphic organizer in your **Biology Foundations Workbook.**

If you know how to interpret fossils, looking at them can be like watching a documentary about the history of life on Earth. Holding one in your hand can be an emotional experience. As scientist and philosopher Loren Eiseley once wrote, "…every bone that one holds in one's hands is a fallen kingdom, a veritable ruined world, a totally unique object that will never return through time."

Fossils and Ancient Life

Fossils provide vital information about **extinct** species—species that have died out. Fossils form rarely and only under certain conditions. The fossil record is incomplete because for every organism preserved as a fossil, many more die without leaving a trace. Still, the fossil record contains an enormous amount of information for paleontologists (pay lee un TAHL uh jists), researchers who study fossils, to learn about ancient life.

Types of Fossils Fossils can be as large and perfectly preserved as an entire animal, complete with skin, hair, scales, or feathers, and sometimes even internal organs. They can also be as tiny as bacteria, embryos, or pollen grains. Many fossils are mere fragments of an organism—teeth, pieces of a jawbone, or bits of leaf. Sometimes, an organism leaves only trace fossils—casts of footprints, burrows, tracks, or even droppings.

Fossils in Sedimentary Rock Most fossils are preserved in sedimentary rock, as shown **Figure 20-1**. Sedimentary rock usually forms when small particles of sand, silt, clay, or lime settle to the bottom of a body of water. Sedimentary rock can also form from compact desert sand. If sediments build up quickly, they can bury dead organisms before the remains are eaten or scattered by scavengers.

Soft body structures usually decay after death, so most of the time only wood, shells, bones, or teeth remain. These hard structures can be preserved if they are saturated or replaced with mineral compounds. Sometimes, however, organisms are buried so quickly that soft tissues are protected from aerobic decay. When this happens, fossils may preserve detailed imprints of soft-bodied animals and structures like skin or feathers. As layers of sediment build up over time, the remains are buried deeper. Over many years, pressure gradually compresses the lower layers. This pressure, along with chemical activity, can turn the soft sediment into rock.

VIDEO

Learn how scientists construct skeletons from fossilized remains.

INTERACTIVITY

Explore the fossil record and learn how it provides evidence for evolution.

Evaluating Evidence in the Fossil Record

By comparing fossils to each other and to living organisms, paleontologists can propose and test evolutionary hypotheses. ***Fossils reveal information about the structures of ancient organisms, the sequential nature of groups in the fossil record, evolution from common ancestors, and the ecology of ancient environments.***

Comparisons of body structures test hypotheses about the appearance, evolution, and history of groups in the fossil record. Studies of evolutionary change in body structures can also test hypotheses about the evolution of living species from extinct common ancestors and the evolution of diversity. Bone structures and footprints can indicate how animals moved. Fossilized plant leaves and pollen suggest whether an area was a swamp, a lake, a forest, or a desert. Also, when different kinds of fossils are found together, researchers can sometimes reconstruct entire ancient ecosystems.

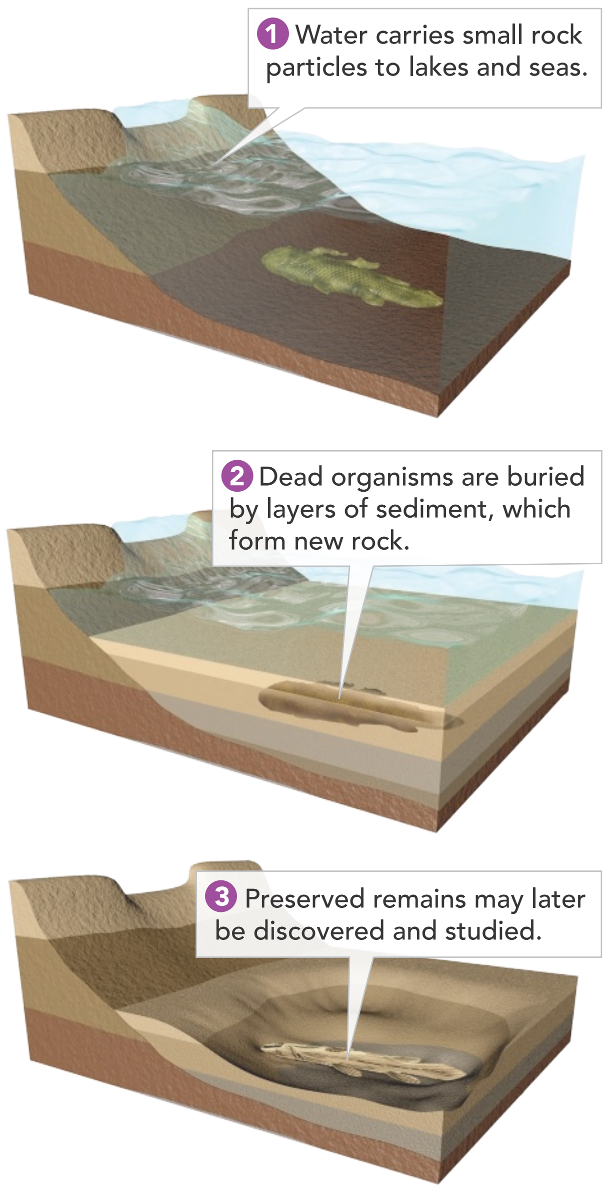
READING CHECK **Explain** Why does a fossil most often form in sediment?

Fossil fish *Diplomystus dentatus* (about 50 million years old)

Figure 20-1

Fossil Formation

Most fossils form in sedimentary rock.



Dating Earth's History

The fossil record would not be as useful if we had no way to figure out what happened when. Researchers use several techniques to put fossils in order from oldest to newest and to figure out how old those fossils are.

Relative Dating Because sedimentary rock is formed as layers, lower layers and fossils they contain are generally older than upper layers. **Relative dating** places rock layers and their fossils in a time sequence, as shown in **Figure 20-2**. ***Relative dating helps paleontologists to determine whether a fossil is older or younger than other fossils.***

To help establish the relative age of rock layers and their fossils, scientists use **index fossils**. Index fossils are distinctive fossils used to establish and compare the relative age of rock layers and the fossils they contain. A useful index fossil must be easy to recognize and occur only in a few rock layers (meaning the species existed only for a brief span of geologic time), but layers from that time period must be found in many places (meaning the organism was widely distributed). Trilobites, a large group of distinctive marine organisms, are often used as index fossils. There are more than 15,000 recognized species of trilobite. Together, they can be used to establish the relative dates of rock layers over a time span of nearly 300 million years.

Radiometric Dating Relative dating tells us the order in which fossil organisms first appeared, but provides no information about a fossil's absolute age in years. One way to date rocks and fossils is radiometric dating. **Radiometric dating** relies on radioactive isotopes, which decay or break down into stable isotopes at a steady rate. A **half-life** is the time required for half of the radioactive atoms in a sample to decay. After one half-life, half of the original radioactive atoms have decayed, as shown in **Figure 20-3**. After another half-life, another half of the remaining radioactive atoms will have decayed. ***Radiometric dating uses the proportion of radioactive isotopes to stable isotopes to calculate the age of a sample.***

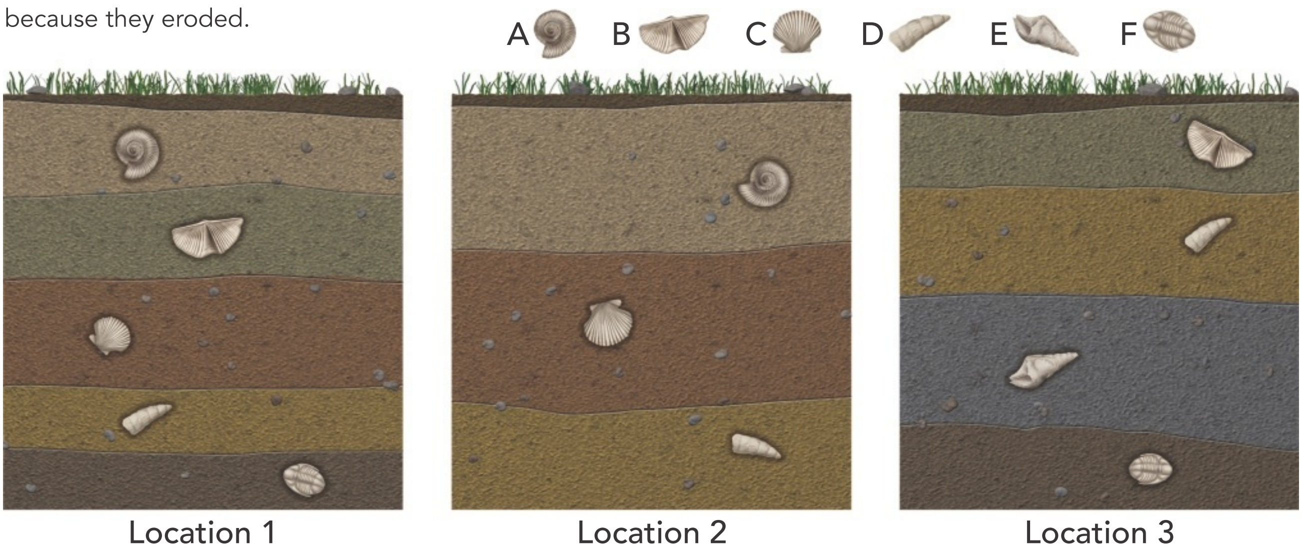
READING TOOL

Draw a sketch that shows index fossils in sedimentary rock near fossils of an unknown age. Write a caption that explains how scientists use index fossils to date other fossils.

Figure 20-2

Index Fossils

If the same index fossil is found in two widely separated rock layers, the rock layers are probably similar in age. **Draw Conclusions** Using the index fossils shown, determine which layers are "missing" from each location. Layers may be missing because they never formed, or because they eroded.



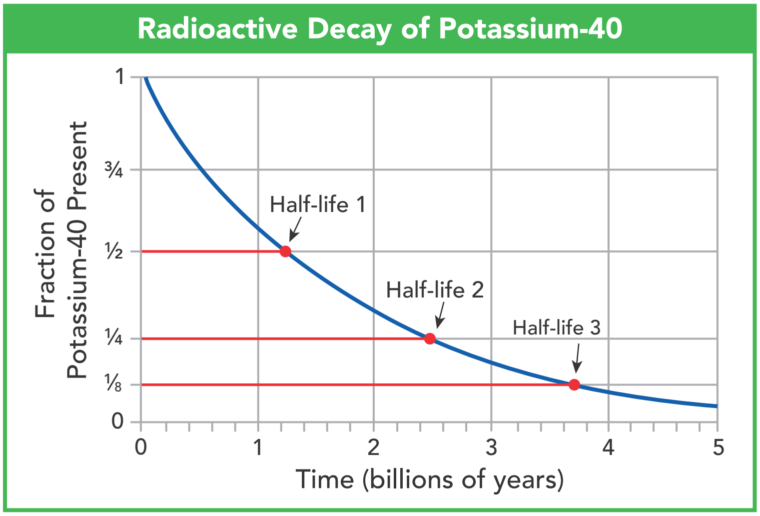


Figure 20-3

Radioactive Decay

The time it takes for half the radioactive atoms in a sample to decay is a half-life. The half-life of potassium-40 is 1.26 billion years.

Different radioactive isotopes decay at different rates. Elements with short half-lives are used to date very recent fossils. Elements with long half-lives are used to date older fossils. Consider how we time sporting events. For a 100-meter dash, a coach depends on the fast-moving second hand of a stopwatch. To time a marathon, the slower-moving hour and minute hands are more useful.

An isotope known as carbon-14, which has a half-life of roughly 5730 years, is useful for directly dating recent fossils. Carbon-14 is produced at a steady rate in the upper atmosphere. Air contains a tiny amount of carbon-14 in addition to the more common, stable, nonradioactive form, carbon-12. Plants take in carbon-14 when they absorb carbon dioxide during photosynthesis, and animals acquire it when they eat plants or other animals. Once an organism dies, it no longer takes in this isotope, so its age can be determined by the amount of carbon-14 remaining in tissues, such as bone or wood. The relatively short half-life of carbon-14 limits its use to organisms that lived during the last 60,000 years. After 10 half-lives have passed, less than one thousandth (1/1000) of the original carbon-14 remains in a sample.

BUILD VOCABULARY

Related Word Forms The word *radiometric* can be broken down into *radio* and *metric*. *Radio* refers to any energy that travels in straight rays, while *metric* can refer to any system of measurement, including measurements that are part of the metric system.

INTERACTIVITY

Use radiometric dating techniques to determine the ages of different objects.

Quick Lab Guided Inquiry

How Can You Model Half-Life?

1. Construct a data table with two columns and five rows. Label the columns “Spill Number” and “Number of Squares Returned.” Enter the numbers 1 to 5 for the spill numbers.
2. Cut out 100 squares with side lengths of about 1 cm. Write an X on one face of each square. Mix the squares thoroughly in a cup.
3. Spill out the squares, and then remove all the squares on which the X faces up. Count and record the number of squares that do not have the X facing up, and return these squares to the cup.
4. Repeat Step 3 four times, or until no squares remain.

ANALYZE AND CONCLUDE

1. **Construct Graphs** Make a line graph to organize the data you recorded. Plot the number of squares returned on the *y*-axis, and the spill numbers 1 to 5 on the *x*-axis.
2. **Interpret Graphs** How does the line graph show a model of half-life for this activity?
3. **Evaluate Models** How well does this model represent the half-life of a radioactive element? What are the limitations of the model?

Older fossils can be dated indirectly, using isotopes with longer half-lives to date the rock layers in which the fossils are found. Isotopes useful for dating include potassium-40 (1.26 billion years), uranium-238 (4.5 billion years), and rubidium-87 (48.8 billion years). These studies provide direct physical evidence for the ages of index fossils that identify periods in Earth's history. They also provide information used to document the rates at which groups appear, evolve, and become extinct.

READING CHECK **Explain** Why can't carbon-14 be used to estimate the age of very old fossils?

Geologic Time Scale

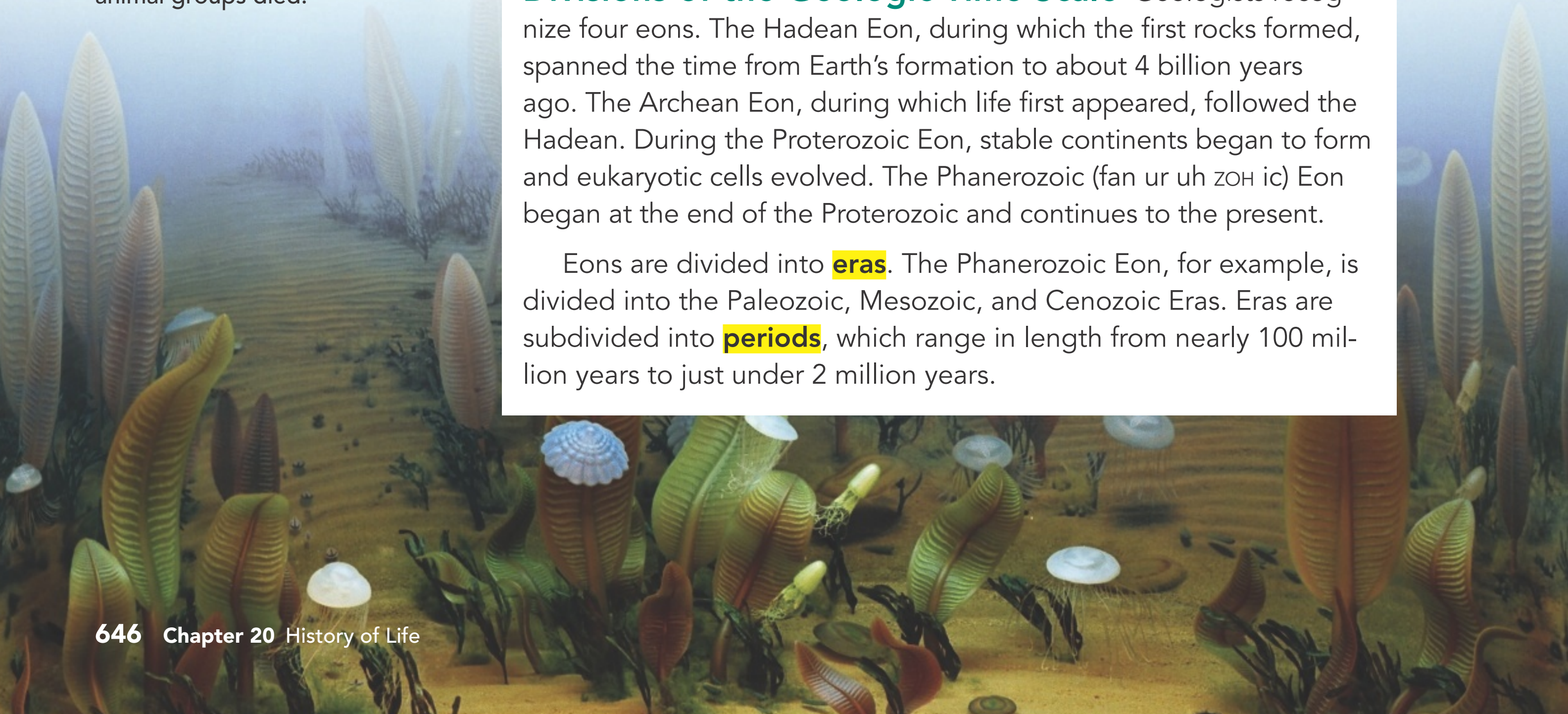
Geologists and paleontologists have built a timeline of Earth's history called the **geologic time scale**. The most recent version is shown in **Figure 20-4**. ***The geologic time scale is based on both relative and absolute dating. The major divisions of the geologic time scale are eons, eras, and periods.***

Establishing the Time Scale By studying rock layers and index fossils, early paleontologists placed Earth's rocks and fossils in order by relative age. As they worked, they noticed major changes in the fossil record at boundaries between certain rock layers. Geologists used rock-layer boundaries to determine where one division of geologic time ended and the next began. Because these divisions of geologic time were described in this way, the lengths of ages are not consistent. The Cambrian Period, for example, began 542 million years ago and continued until 488 million years ago, which makes it 54 million years long. The Cretaceous Period was 80 million years long.

Years after the time scale was established, radiometric dating was used to assign specific ages to the various rock layers. The time scale is constantly being tested, verified, and adjusted.

Divisions of the Geologic Time Scale Geologists recognize four eons. The Hadean Eon, during which the first rocks formed, spanned the time from Earth's formation to about 4 billion years ago. The Archean Eon, during which life first appeared, followed the Hadean. During the Proterozoic Eon, stable continents began to form and eukaryotic cells evolved. The Phanerozoic (fan ur uh ZOH ic) Eon began at the end of the Proterozoic and continues to the present.

Eons are divided into **eras**. The Phanerozoic Eon, for example, is divided into the Paleozoic, Mesozoic, and Cenozoic Eras. Eras are subdivided into **periods**, which range in length from nearly 100 million years to just under 2 million years.



During the Cambrian Period, multicellular life experienced its greatest adaptive radiation in what is called the Cambrian explosion. The Cambrian ended with a large mass extinction in which nearly 30 percent of all animal groups died.

Geologic Time Scale				
	Eon	Era	Period	Time (millions of years ago)
	Phanerozoic	Cenozoic	Quaternary	1.8–present
			Neogene	23–1.8
			Paleogene	65.5–23
		Mesozoic	Cretaceous	146–65.5
			Jurassic	200–146
			Triassic	251–200
		Paleozoic	Permian	299–251
			Carboniferous	359–299
			Devonian	416–359
			Silurian	444–416
			Ordovician	488–444
			Cambrian	542–488
Precambrian Time	Proterozoic			2500–542
	Archean			4000–2500
	Hadean			About 4600–4000

◀ *Tiktaalik* (Devonian)

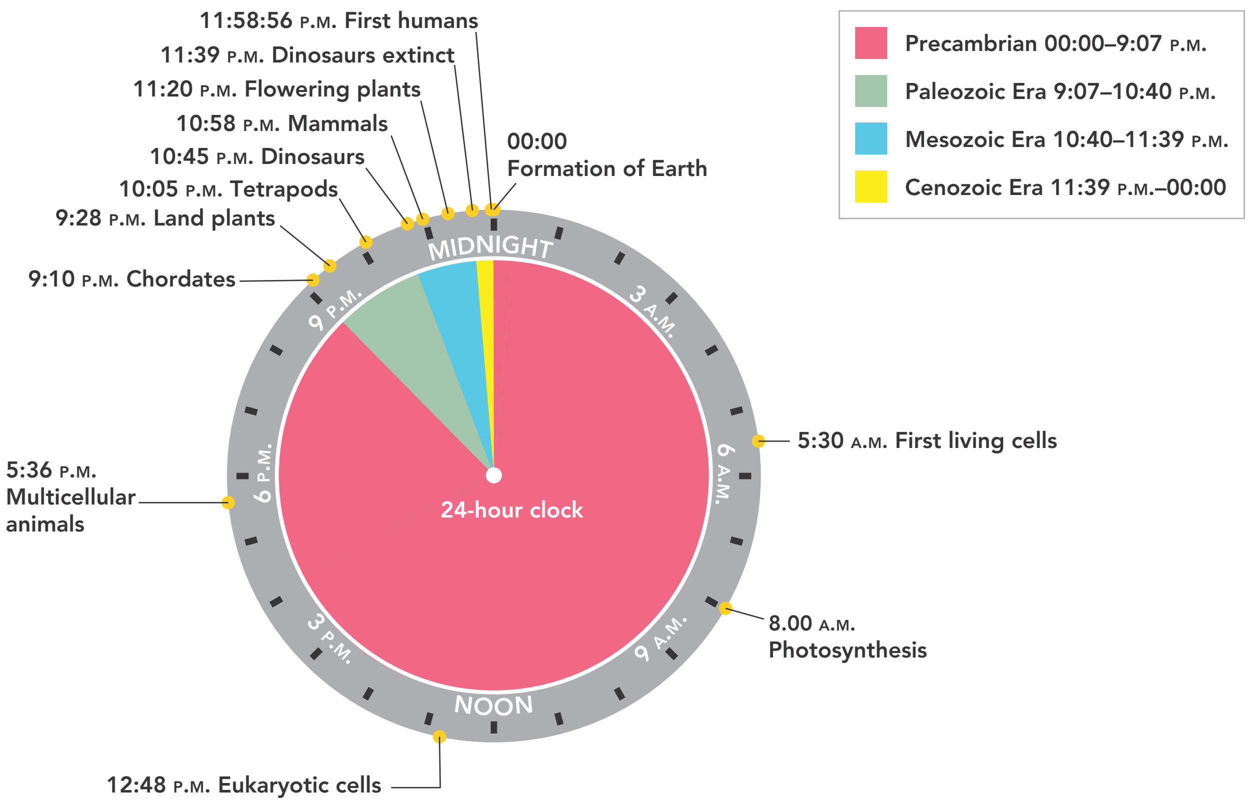
INTERACTIVITY

Figure 20-4

Geologic Time Scale

The basic divisions of the geologic time scale are eons, eras, and periods. Precambrian time was the name originally given to all of Earth's history before the Phanerozoic Eon. Note that the Paleogene and Neogene are sometimes called the Tertiary Period, but this term is considered outdated.

Naming the Divisions The divisions of the geologic time scale were named in different ways. The Cambrian Period was named after Cambria—an old name for Wales, which is where rocks from that time were first identified. The Carboniferous ("carbon-bearing") Period is named for large coal deposits that formed during that time. Geologists started to name divisions of the time scale before any rocks older than the Cambrian Period had been identified. For this reason, all of geologic time before the Cambrian was simply called Precambrian Time. Precambrian Time covers about 90 percent of Earth's history. See Appendix C: Illustrated History of Life for more detailed information about each division.



Visual Analogy

Figure 20-5

Geologic Time as a Clock

To help visualize the enormous span of time since Earth formed, this model compresses the history of Earth into a 24-hour period. Notice the relative length of Precambrian Time—almost 22 hours. **Use Analogies** Using this model, about what time did life appear? The first plants? The first humans?

Comparing Time What do you think is a long period of time? Would you describe a year as a long time, or a decade, or a century? On the geologic time scale, even a thousand years is like a passing moment. The model shown in **Figure 20-5** represents all of Earth's history on the face of a clock. Notice that Precambrian Time, when life was just beginning, covers about 90 percent of the clock face. In contrast, the history of modern humans fits into about a minute.

READING CHECK **Use an Analogy** How does the time span of human history compare to the history of Earth? Use an analogy to compare them.

Life on a Changing Planet

During a human lifetime, environments seem constant. Areas around the Gulf of Mexico are usually hot and humid. Antarctica is usually cold. But Earth's environments and climate changed dramatically over millions of years, and those changes profoundly affected the history of life. Life, in turn, has also had profound effects on Earth.

Changes in Climate Earth's regional climates have changed repeatedly over time because of nonhuman causes of global change. Many dramatic changes in regional environments were triggered by fairly small shifts in global temperature. For example, during a global "heat wave" of the Mesozoic era, average global temperatures were only 6 to 12 degrees Celsius higher than they were in the twentieth century. During the great ice ages, which chilled the globe as recently as 10,000 years ago, temperatures were only about 5 degrees Celsius cooler than they are now.

Geologic Forces Regional and global environments are influenced by interactions between wind and ocean currents, as well as by geological features like mountains and plains. Over long periods of time, geological forces built mountains, moved continents, and created volcanic island chains like the Galápagos. The movement of continents produced even more dramatic changes in Earth's landscape, as shown in **Figure 20-6**. The theory of **plate tectonics** explains the movements of continents and oceans. They are the result of solid "plates" moving slowly, about 3 centimeters per year, over Earth's mantle.

In addition, comets and large meteors have crashed into Earth many times in the past. Some of these impacts were so violent that they kicked enough dust and debris into the atmosphere to cause or contribute to climate change that drove major extinctions.

BUILD VOCABULARY

Word Origins The word *tectonic* originates from the Latin word *tectonicus*, which means "of or relating to building or construction."

Figure 20-6

The Changing Face of Earth

Over the last several hundred million years, the face of Earth has changed dramatically due to the movement of tectonic plates. Continents once collided to form "super continents" and then drifted apart again. These actions changed the flow of ocean currents and altered global climate, albeit very gradually. These plates continue to move today.

Ordovician Period 488–444 mya

During the Ordovician, continents were separated and ringed by shallow seas rich in marine life.

Carboniferous Period 359–299 mya

In the Carboniferous, continents began to come together. Eventually, they would fuse into the super continent, Pangaea.

Triassic Period 251–200 mya

During the Triassic, Pangaea started to break apart.

Cretaceous Period 146–65.5 mya

By the end of the Cretaceous, the continents as we know them, began to drift apart from each other.

Present Day

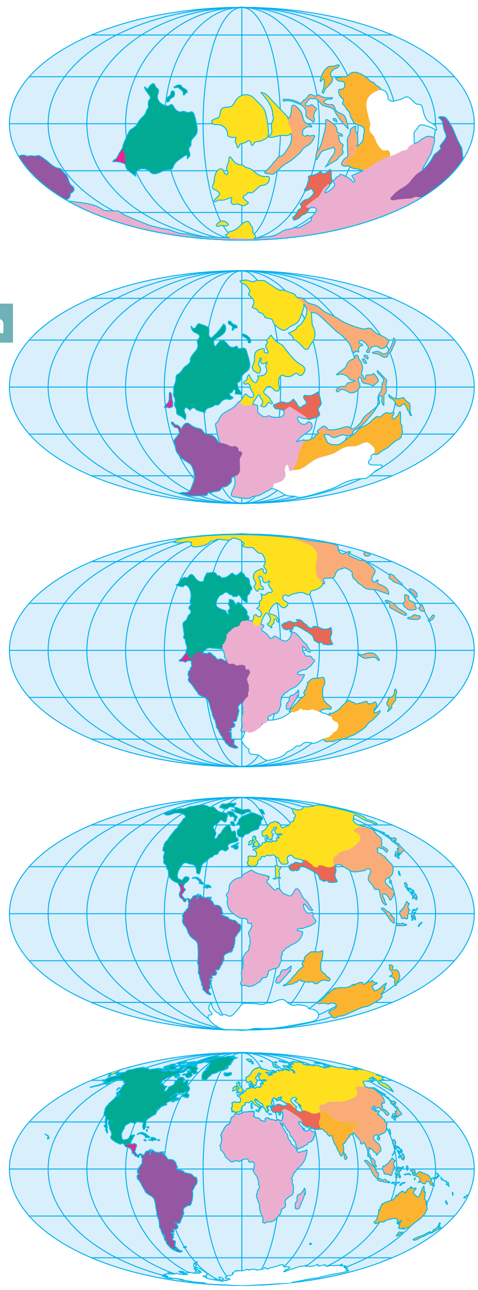


Figure 20-7

Changing Habitats

Mountains in South Africa hold fossils of sea stars and marine mollusks that are about 400 million years old. The fossils are evidence that these rocks were once part of a shallow sea floor teeming with life, such as the modern day ocean floor shown.

Effects on Life As Earth's land changed, the habitats it provided changed as well. ***Global climate change, mountain building, the emergence of islands, continental drift, changes in levels of continents and oceans, and meteor impacts have altered Earth's habitats, with major effects on the history of life.*** These environmental changes altered ecological interactions among organisms and between organisms and their environments. Those altered interactions, in turn, changed the pressures of natural selection, favoring adaptation to new conditions. In addition, both the emergence of new habitats and changes in the environment of existing habitats created new ecological niches. Those new niches offered opportunities for natural selection to increase diversity among species.

The movement of tectonic plates also shaped biogeography, or the distribution of fossils and living organisms. For example, the continents of Africa and South America are now separated by the Atlantic Ocean, but fossils of *Mesosaurus*, an aquatic reptile, have been found in Africa and South America. The presence of the same fossils on both continents indicates that they were joined at the time those organisms lived. **Figure 20-7** shows an example of a current land mass that was once the site of a shallow sea.

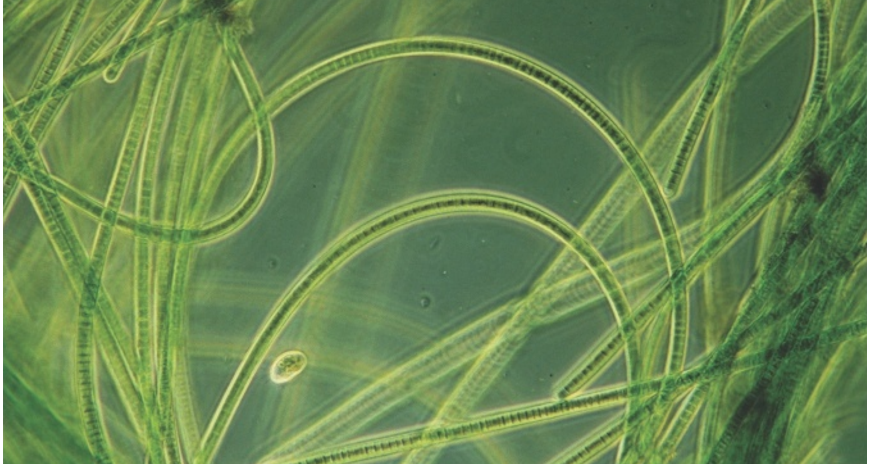


Figure 20-8

Blue-Green Algae

Earth's first atmosphere had very little oxygen. The first photosynthetic organisms, which were like the algae shown here, caused carbon dioxide levels to fall and oxygen levels to rise—and forever changed life on Earth (LM 160×).

Biological Forces Life is definitely affected by changes in Earth's physical environment. But life also plays a major role in shaping that environment. Today, plants, animals, and microorganisms are active players in global cycles of key elements, including carbon, nitrogen, and oxygen. That has been true ever since life evolved. For example, Earth's early atmosphere contained much more carbon dioxide than it does today—and little or no oxygen. Then early photosynthetic organisms began absorbing carbon dioxide and releasing oxygen. Our planet has never been the same since. Earth cooled as carbon dioxide levels dropped. The iron content of the oceans fell, as soluble iron ions reacted with oxygen to form insoluble compounds (rust) that settled to the ocean floor. These changes affected climate and ocean chemistry in many ways.

The actions of living organisms over time have changed conditions in the atmosphere, the oceans, and the land. Those changes altered the pressures of natural selection in ways that favored the evolution of different adaptations in existing species. The changes caused pressures that led to the emergence of new species and new groups of species. The presence of oxygen, for example, led to the evolution of aerobic metabolism, transforming life on Earth.

HS-LS4-1, HS-ESS1-5, HS-ESS2-7

LESSON 20.1 Review

KEY QUESTIONS

1. What can fossils reveal about the ecosystems in which the organisms once existed? Include an example.
2. How is relative dating of fossils different from absolute dating?
3. How does geologic time compare to the time scales we use in everyday life?
4. Explain how life both has been affected by geologic change and has affected geologic change.

CRITICAL THINKING

5. **Evaluate Reasoning** Using radiometric dating, the age of a sedimentary rock in a rock layer is dated to 530 million years ago. A science student concludes that the fossils in the rock layer are also 530 million years old. Explain whether or not this conclusion is reasonable.
6. **Construct an Explanation** Earth's climate has changed many times throughout its long history. How does continental climates change as a result of continental drift?
7. **CASE STUDY** What techniques do you think Shubin and his fellow researchers used to determine how deep they should dig to look for *Tiktaalik*?

LESSON 20.2

Evolutionary Patterns and Processes

Some animals and plants evolve in response to each other.

KEY QUESTIONS

- *What patterns describe the sequential nature of groups in the fossil record?*
- *What does the fossil record show about periods of stasis and rapid change?*
- *What are two patterns of macroevolution?*
- *What evolutionary characteristics are typical of coevolving species?*

HS-LS4-1: Communicate scientific information that common ancestry and biological evolution are supported by multiple lines of empirical evidence.
HS-LS4-4: Construct an explanation based on evidence for how natural selection leads to adaptation of populations.
HS-LS4-5: Evaluate the evidence supporting claims that changes in environmental conditions may result in: (1) increases in the number of individuals of some species, (2) the emergence of new species over time, and (3) the extinction of other species.

VOCABULARY

macroevolutionary pattern
background extinction
mass extinction
gradualism
punctuated equilibrium
adaptive radiation
convergent evolution
coevolution

READING TOOL

Use the section headings to guide you through this lesson. Take notes on the important vocabulary terms in your **Biology Foundations Workbook.**

The fossil record documents that life has changed in a chronological sequence. Species and larger clades evolved, survived for a time, and either continued to evolve or became extinct. The fossil record also documents that more than 99 percent of all species that have ever lived are extinct. How have so many species and larger clades evolved? Why are so many extinct?

Speciation and Extinction

The fossil record provides evidence about the nature and rate of evolutionary change in species and larger clades. Major transformations in anatomy, phylogeny, ecology, and behavior, which usually take place in larger clades, are known as **macroevolutionary patterns**. ***The emergence, growth, and extinction of larger clades, such as dinosaurs, mammals, or flowering plants, are examples of macroevolutionary patterns.***

Macroevolution and Cladistics Fossils are classified using the same cladistic techniques used to classify living species. In some cases, fossils are placed in clades that contain only extinct organisms. In other cases, fossils are placed in clades that include living organisms. Cladograms illustrate hypotheses about how closely related organisms are, by proposing relationships among living species, extinct species, and common ancestors that they share. Note that hypothesizing that an extinct species is *related* to a living species is *not* the same thing as claiming that the extinct organism is a direct *ancestor* of that living species. For example, **Figure 20-9** does not suggest that any extinct species shown are direct ancestors of modern birds. Instead, the extinct species shown descended over time from a line of common ancestors that they share with modern birds.

Adaptation and Extinction When environmental conditions change, natural selection and other evolutionary mechanisms enable some species to evolve adaptations to the new conditions. Species that evolve such adaptations thrive. Species that fail to adapt to changing environments become extinct. Interestingly, the rates at which species appear, adapt, and become extinct vary from one clade to another and from one period of geologic time to another.

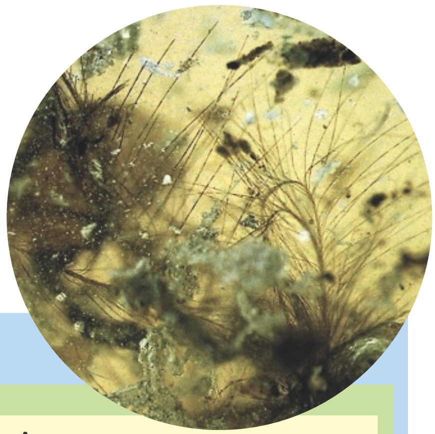
Why have some clades produced many species and survived for long periods, while other clades have given rise to only a few species that vanished? Paleontologists look for part of the answer by studying patterns of speciation and extinction in different clades. One way to think about this process is in terms of species diversity. High species diversity within a clade can serve as "raw material" for macroevolutionary change in that clade. In some cases, the more varied the adaptations of species in a clade are, the more likely the clade is to survive environmental change. This is similar to the way in which genetic diversity serves as raw material for evolutionary change for populations within a species. If the rate of speciation in a clade is equal to or greater than the rate of extinction, the clade will continue to exist. If the rate of extinction in a clade is greater than the rate of speciation, the clade will eventually become extinct.

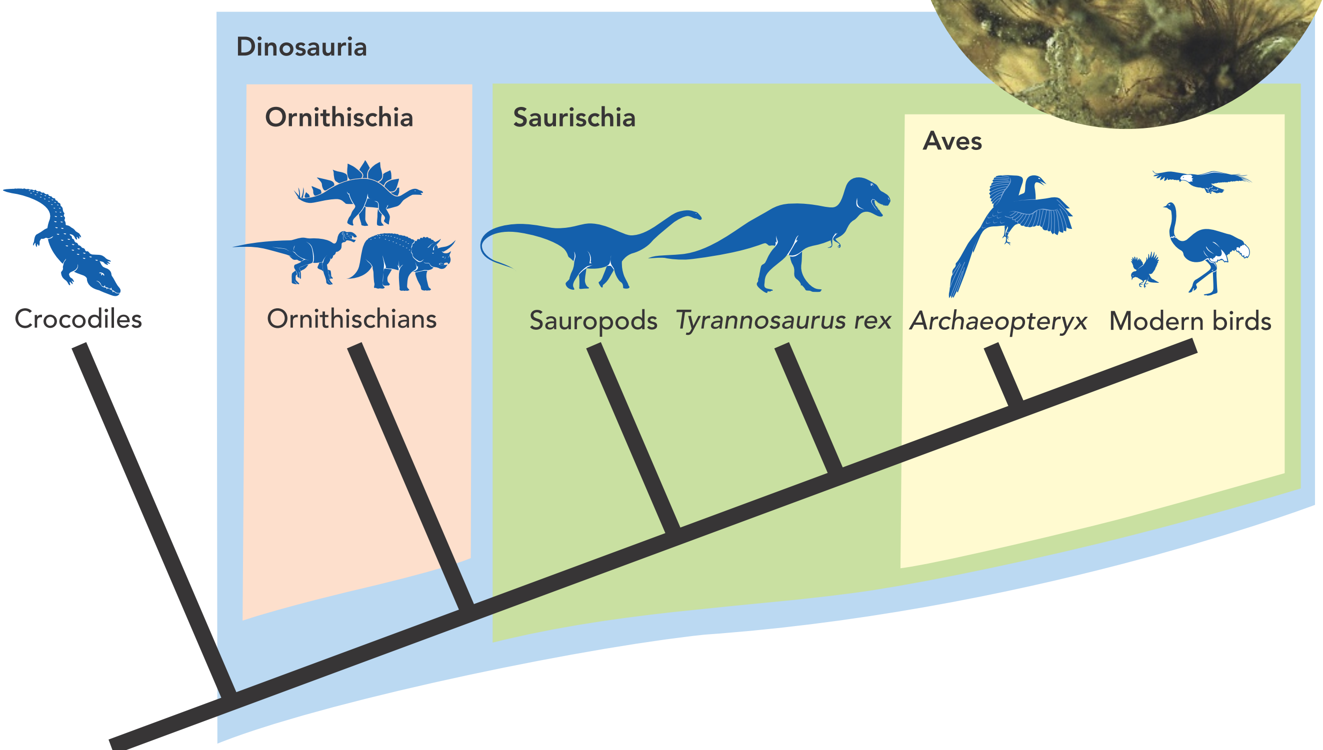
The clade Reptilia is one example of a highly successful clade. The reptile cladogram in Figure 20-9 includes living snakes, lizards, turtles, and crocodiles, and also dinosaurs that thrived for tens of millions of years. It also includes the common ancestors shared by all members of this clade. Most species in the clade Dinosauria are now extinct, but the clade survived because it produced groups of new species that adapted to changing conditions. One small dinosaur clade survives today—we call them birds.

Figure 20-9

The Lineage of Modern Birds

This cladogram shows some of the clades within the large clade Reptilia. The photograph shows fossilized feathers in amber. Notice that clade Dinosauria is represented today by modern birds. **Classify** What are the two major clades of dinosaurs shown in this figure?





READING TOOL

Compare the causes and effects of background extinction and mass extinction.

Patterns of Extinction Species become extinct when they fail to adapt to competition and changing environments. Paleontologists describe this kind of "business as usual" extinction as **background extinction**. Rates of background extinction vary over time, but tend to leave functioning ecosystems and many species intact.

However, every few hundred million years or so, something dramatic happens that affects species and ecosystems on a global scale. This type of event is called a **mass extinction**. In a mass extinction, a large number of species become extinct over a relatively short time. A mass extinction isn't just a small increase in background extinction. Entire ecosystems vanish, and whole food webs collapse. Species become extinct because their environment breaks down and the ordinary process of natural selection cannot compensate quickly enough.

Mass extinctions reduce biodiversity rapidly and dramatically. Some groups of organisms survive while other groups do not. What happens then? Survivors face a changed world. There is less competition. Climate may have changed. Many new ecological niches open up. As adaptation and speciation produce new species that fill those niches, biodiversity slowly recovers—typically over 5 to 10 million years.

READING CHECK **Describe** What is the difference between background extinction and mass extinction?

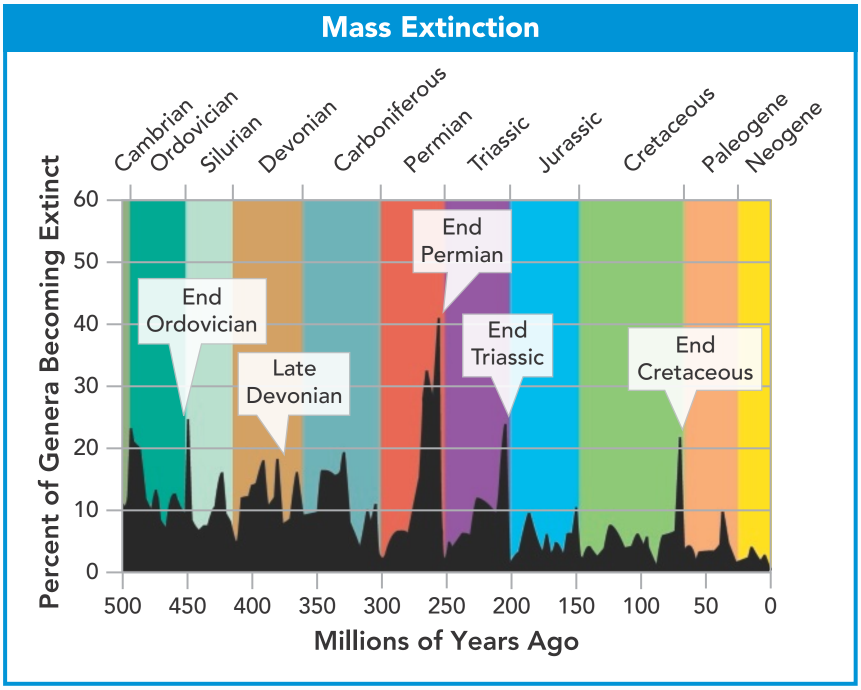
HS-LS4-5

Analyzing Data

Extinctions Through Time

The graph shows how the rate of extinction has changed over time.

1. **Analyze Data** What is the likely source for the data in this graph?
2. **Analyze Graphs** Which mass extinction killed off the highest percentage of genera?
3. **Identify Patterns** Describe the overall pattern of extinction shown in the graph.
4. **Apply Scientific Reasoning** What changes in environmental conditions could have led to these mass extinctions?



Rate of Evolution

Evolution does not occur at exactly the same rate for all species all of the time. ***Fossil evidence supports the hypothesis that evolution can occur at different rates in different clades, and at different times.*** Species may evolve gradually or rapidly, or appear or disappear suddenly. Those data support the hypothesis that, at certain times, some organisms have experienced periods of little or no visible evolutionary change. Other times, the fossil record documents the relatively sudden appearance or disappearance of certain species and supports a dynamic model of evolutionary change. Two models of evolutionary change are shown in **Figure 20-10**.

Gradualism Darwin suggested that evolution proceeded slowly and steadily, an idea called **gradualism**. The fossil record shows that many organisms have indeed changed gradually. Sometimes, however, the physical structures preserved in the fossil record don't appear to have changed much over long periods of time. Major body structures of horseshoe crabs, for example, have changed little from the time these species first appeared in the fossil record. For much of their history, these species are said to have been in a state of equilibrium, or *stasis*. This means that their structures do not change much even though they continue to evolve genetically.

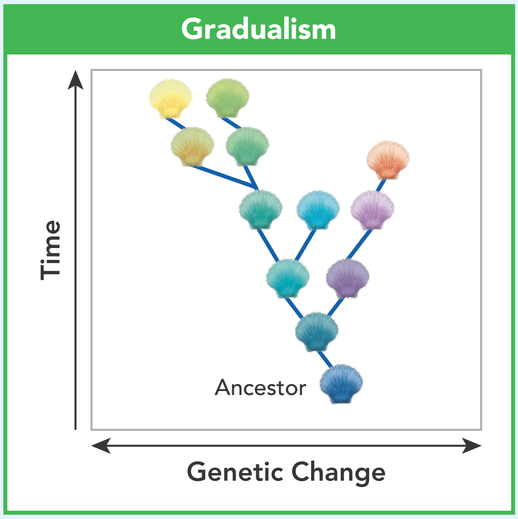
Punctuated Equilibrium ***Now and then, the fossil record shows that equilibrium can be interrupted by brief periods of geologically rapid change.*** This pattern is called **punctuated equilibrium**. During such "punctuations," existing species may change and new species may appear rapidly. In fact, some biologists suggest that many new species evolve during periods of relatively rapid change. It is important to remember that words like "rapid" and "relatively rapid" here are in relation to time measured by the 4.5-billion-year geologic time scale. The meaning of "rapid change" in paleontology is different from what you think of when you hear about a rapid change in your daily life. Geologically "rapid" change can take place over many thousands or millions of years.

INTERACTIVITY

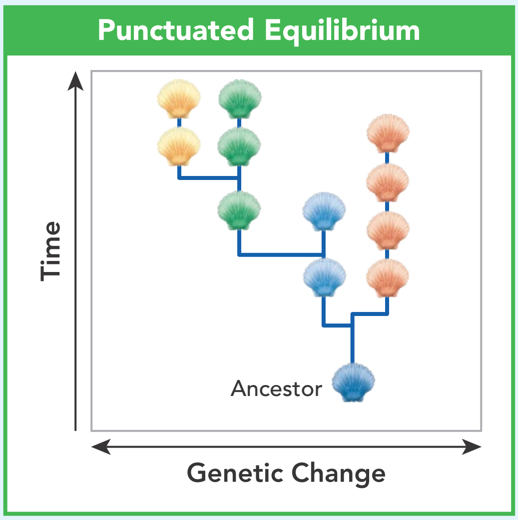
Figure 20-10

Gradualism and Punctuated Equilibrium

Biologists have considered two different patterns for the rate of evolution: gradualism and punctuated equilibrium. These illustrations are simplified to show the general trend of each model.



Gradualism involves a slow, steady change in a particular line of descent.



Punctuated equilibrium involves stable periods interrupted by rapid changes.

Rapid Evolution After Equilibrium Evolution of species may proceed at different rates at different times. You learned earlier in this unit about some mechanisms that can explain this variation in rates of change. Two types of events that can lead to rapid evolution are genetic drift and mass extinctions.

Genetic Drift Recall that in small populations, a trait can become more or less common simply by chance. Rapid evolution may occur after a small population becomes isolated from the main population. This founder effect could happen when a small population colonizes a new environment, such as the finches that left South America and colonized the Galápagos Islands.

A genetic bottleneck may occur when a disease or natural disaster greatly reduces the size of a population. By chance, the smaller population may have a different allele frequency than the larger population had.

Mass Extinction Mass extinctions open ecological niches, creating new opportunities for many populations of surviving organisms. Groups of organisms that survive mass extinctions can evolve "rapidly" during the first several million years after the extinction. At the end of the Permian Period, for example, a mass extinction occurred, known as "The Great Dying." A large majority of species on Earth became extinct. Evidence suggests that life rebounded relatively quickly after the Permian extinction as the survivors thrived in environments with limited competition.

READING CHECK **Compare and Contrast** How do patterns of change differ in gradualism and punctuated equilibrium?

Figure 20-11

Adaptive Radiation

This diagram shows part of the adaptive radiation of mammals. Note how the groups of animals shown have adapted to different ways of life—including two groups that became aquatic.

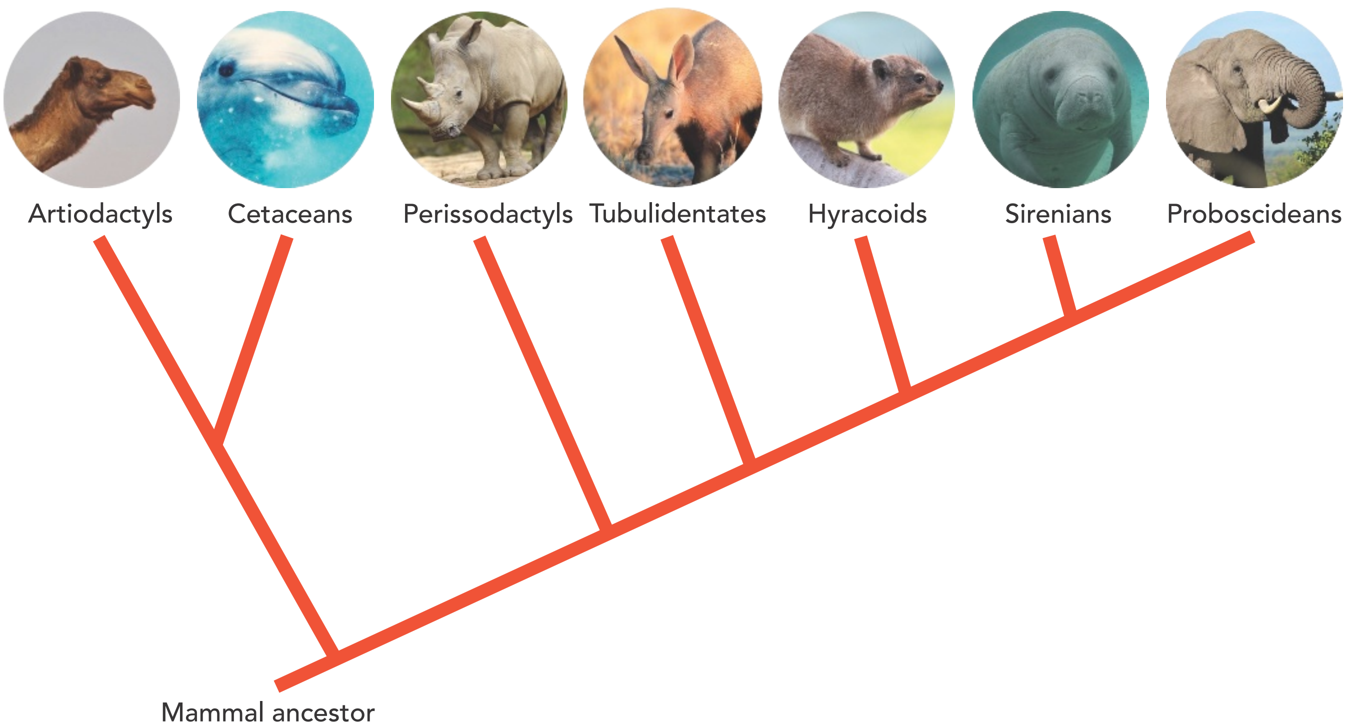


Figure 20-12

Convergent Evolution

Animals from different lineages may independently evolve structures or systems that perform similar functions. Flight, for example, has evolved in many different animal lineages. Animals in these pictures are all said to have "wings." But the structures used in flight are made of different parts, and operate in different ways. The pterodactyl, whose fossil is shown here, is an extinct flying reptile.

Macroevolutionary Patterns

As evolutionary biologists study the fossil record, they look for patterns. ***Two important patterns of macroevolution are adaptive radiation and convergent evolution.***

Adaptive Radiation Descendants of an ancestral species may diversify over time into related species adapted to different niches. This process, where a single species evolves into several distinct species, is called **adaptive radiation**. Adaptive radiation may occur when species migrate to new environments or when extinction eliminates competing species.

Dinosaurs underwent adaptive radiations during the Mesozoic Era. After most dinosaurs became extinct, mammals began a new adaptive radiation, as shown in **Figure 20-11**. Galápagos finches also experienced an adaptive radiation, as they adapted to islands with different kinds of available food.

Convergent Evolution Unrelated organisms in similar environments may evolve adaptations to similar niches. The appearance of similar characteristics in unrelated organisms is known as **convergent evolution**. For example, mammals that feed on ants and termites evolved five times in different regions across the world. Large grassland birds, such as the emus, rheas, and ostriches Darwin observed, are also examples of convergent evolution. Flight has also evolved in unrelated species, as shown in **Figure 20-12**.

BUILD VOCABULARY

Prefixes The prefix *macro-* comes from the Greek *makro-*, meaning "large." Macroevolutionary patterns are large patterns of evolution.

INTERACTIVITY

Build and analyze cladograms to determine evolutionary relationships between bats and birds.

INTERACTIVITY

Investigate evolutionary processes that can lead to the formation of new species.

Figure 20-13

Plants and Herbivorous Insects

Milkweed plants produce toxic chemicals. However, they are the only food source for monarch caterpillars. The caterpillars can tolerate the toxin and store it in their own body tissues as a defense against predators.

Coevolution

Sometimes two or more species are so closely connected ecologically that they evolve together. The process by which two species evolve in response to changes in each other over time is called **coevolution**. Many flowering plants, for example, can reproduce only if their flowers attract a specific pollinator species. Pollinators, in turn, may depend on the flowers of certain plants for pollen or nectar. ***The relationship between coevolving organisms often becomes so specific that neither organism can survive without the other. Evolutionary change in one organism is usually followed by a change in the other organism.***

Flowers and Pollinators Coevolution of flowers and pollinators can lead to unusual results. For example, Darwin described an orchid whose nectar was at the bottom of a tube nearly 40 centimeters long. He predicted the existence of an insect with a feeding structure long enough to reach that nectar.

Darwin never discovered the insect. However, about 40 years after Darwin's hypothesis, researchers discovered a moth with a 40-centimeter-long feeding tube that was eating the nectar of the orchid. The discovery was exactly what Darwin predicted!

Plants and Herbivorous Insects Plants and herbivorous insects also coevolve. Insects have been feeding on flowering plants since both groups emerged. Over time, many plants have evolved bad-tasting or poisonous compounds that discourage insects from eating them. But once plants produce poisons, natural selection on herbivorous insects favors any variants that can alter, inactivate, or eliminate those poisons. Time and again, a group of insects, like the caterpillar shown in **Figure 20-13**, have evolved a way to deal with the particular poisons produced by a certain group of plants.

HS-LS4-1, HS-LS4-4, HS-LS4-5

LESSON 20.2 Review

KEY QUESTIONS

1. How does variation within a clade affect the clade's chance of surviving environmental change?
2. What patterns, if any, are formed by the rates of evolution in different lineages?
3. How does adaptive radiation compare to convergent evolution?
4. How can evolutionary change in one species lead to evolutionary change in another species that it is associated with? Include an example to support your answer.

CRITICAL THINKING

5. **Stability and Change** Major geologic changes often go hand in hand with mass extinctions. Why do you think this is true?
6. **Draw Conclusions** Mammals that have horns or antlers include deer, antelope, goats, and sheep. Is it reasonable to conclude that the trait of horns evolved in a common ancestor of all these mammals? Explain.
7. **CASE STUDY** During the Devonian Period, when *Tiktaalik* lived, the only land animals were invertebrates, such as worms and insects. Which macroevolutionary pattern do you think occurred once animals were able to survive outside of the water? Explain your answer.

Earth's Early History

LESSON 20.3

KEY QUESTIONS
- *What do scientists hypothesize about early Earth and the origin of life?*
- *What theory explains the origin of eukaryotic cells?*

HS-ESS1-6: Apply scientific reasoning and evidence from ancient Earth materials, meteorites, and other planetary surfaces to construct an account of Earth's formation and early history.
HS-ESS2-6: Develop a quantitative model to describe the cycling of carbon among the hydrosphere, atmosphere, geosphere, and biosphere.
HS-ESS2-7: Construct an argument based on evidence about the simultaneous coevolution of Earth's systems and life on Earth.

VOCABULARY
endosymbiotic theory

READING TOOL
List the events described in the text in the order in which they occur. Take notes in your **Biology Foundations Workbook.**

VIDEO
Learn how scientists classify a new organism from fossil records.

How did life on Earth begin? What were the earliest forms of life? Origin-of-life research is a dynamic field. Current hypotheses will probably change as our understanding of the story continues to grow.

Mysteries of Life's Origins

Geological and astronomical evidence suggest that Earth formed as pieces of cosmic debris collided. The rest of the solar system formed in much the same way, and at the same time. For millions of years, volcanic activity rocked Earth, as comets and asteroids bombarded its surface. About 4.2 billion years ago, Earth cooled enough to allow solid rocks to form. The cooling allowed water to condense as rain, which formed the oceans. Liquid water on the surface was essential for the first living things, just as it is essential today.

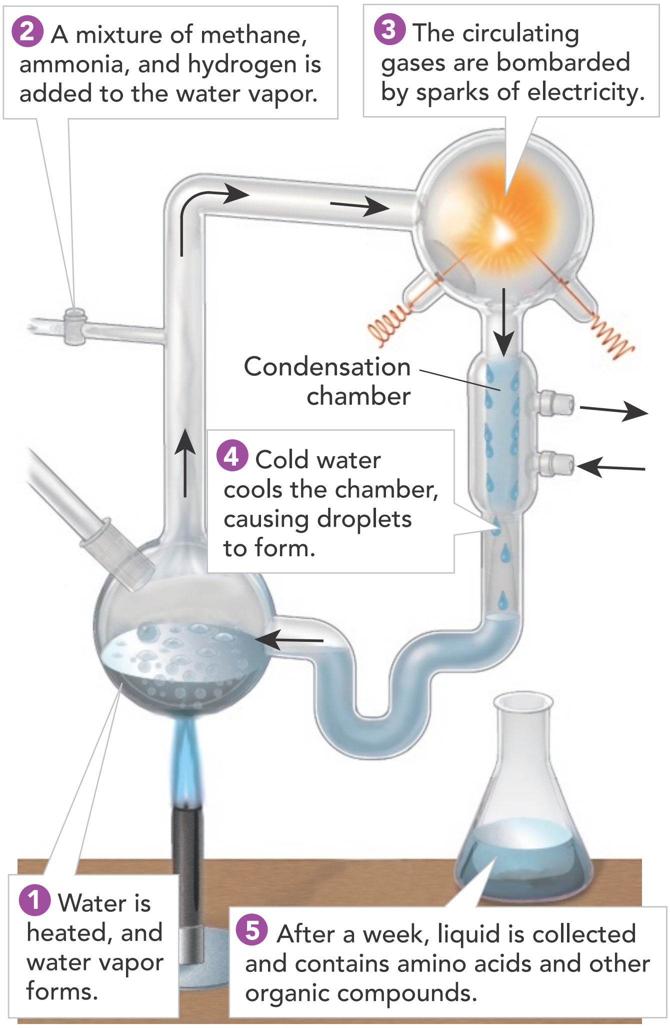
This infant planet was very different from Earth today. ***Earth's early atmosphere contained little or no oxygen. It was mainly composed of carbon dioxide, water vapor, and nitrogen, with smaller amounts of carbon monoxide, hydrogen sulfide, and hydrogen cyanide.*** Because of these gases, the sky was probably pinkish-orange. If you had been there, a deep breath might have killed you! Even though the young planet seems like it would have been inhospitable to life, this was the Earth on which life began.

Organic Molecules in Space We now know that many basic building blocks of life form naturally in our solar system. Meteorites and comets contain several amino acids, including those used by living organisms to make proteins. These data suggest that similar molecules were present on early Earth.

Figure 20-14

The Miller-Urey Experiment

Miller and Urey produced amino acids, which are needed to make proteins, by passing sparks of electricity through a mixture of hydrogen, methane, ammonia, and water vapor. Evidence now suggests that the composition of Earth's atmosphere was different from their 1953 experiments. More recent experiments with different mixtures of gases have produced similar amino acids.



INTERACTIVITY

Investigate the origin of life on Earth.

The Miller-Urey Experiment In 1953, chemists Stanley Miller and Harold Urey tried to test the hypothesis that organic compounds could have been produced on early Earth. They warmed water in a sterile flask and added methane, ammonia, and hydrogen to simulate Earth's early atmosphere. Then, as shown in **Figure 20-14**, they passed sparks of electricity through the gases to simulate lightning. The liquid circulated through the experimental apparatus for a week.

The results were spectacular. Miller and Urey's analysis revealed that 21 amino acids had been produced in their apparatus. A more recent analysis of one of Miller's experiments not only confirmed that result, but also found that the experiment had produced two additional amino acids for a total of 23! ***Miller and Urey's experiment suggests that organic compounds necessary for life could have arisen from simpler compounds on a primitive Earth.***

While Miller and Urey's hypotheses about the composition of the early atmosphere were incorrect, more recent experiments using current ideas about the early atmosphere have validated their conclusion: Organic compounds could have been produced on early Earth. The discovery of organic compounds on meteorites and comets has confirmed these lab experiments.

Formation of Protocells Amino acids may be easy to make, but what about membranes? Studies show that molecules similar to fatty acids—the building blocks of membrane lipids—can form spontaneously under certain conditions. These molecules can then assemble to form membrane-like vesicles. Similar compounds from a meteorite that fell in Australia in 1969 also formed vesicles in laboratory experiments. Nobel Prize–winner Jack Szostak, an origin-of-life researcher at Harvard University, calls these structures protocells. He suggests that protocells may have formed around molecules similar to RNA, which may have been able to copy themselves.

RNA First? Several lines of evidence suggest that RNA, rather than DNA, was the first information-carrying molecule. ***The "RNA world" hypothesis proposes that RNA existed before DNA. From this simple RNA-based system, several steps could have led to today's DNA-directed protein synthesis.*** This hypothesis, shown in **Figure 20-15**, is still being tested, but a number of facts make it credible. Recent experiments show that at least two RNA nucleotides can form in the absence of life. Other experiments show how simple clay minerals can bind nucleotides, which can polymerize to form RNA polynucleotides. In addition, certain RNA sequences are capable of catalyzing chemical reactions that include RNA self-replication.

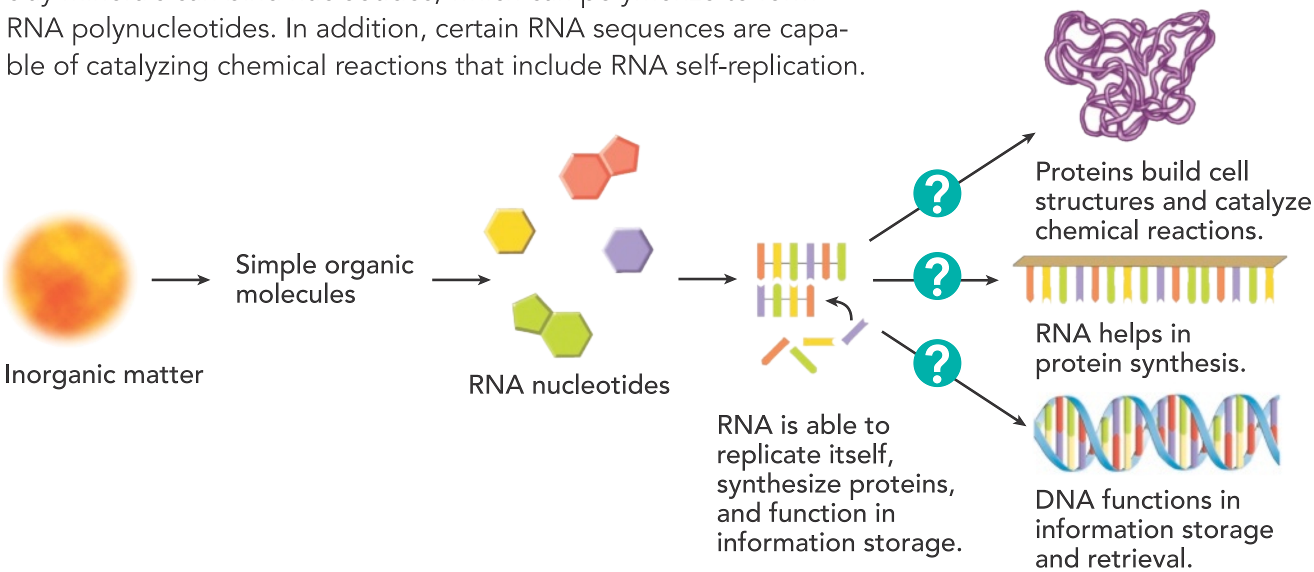


Figure 20-15

Origin of RNA and DNA

The "RNA world" hypothesis about the origin of life suggests that RNA evolved before DNA. Scientists have not yet demonstrated the later stages of this process in a laboratory setting. **Interpret Visuals** How would RNA have stored genetic information?

Furthermore, several molecules important to cell metabolism, such as ATP, NADH, and coenzyme A, are built around RNA-like nucleotides. All cells make proteins by first copying genetic information into RNA. DNA nucleotides themselves are first synthesized as RNA nucleotides. Finally, the ribosomes that build proteins in all cells are "RNA machines" in which RNA, not DNA, performs the key function of linking amino acids together. All these data support the hypothesis that an "RNA world" was a stage in the origin of life on Earth.

Researchers have made major progress in understanding the origin of life. Still, Szostak himself has written that "the exact circumstances of the origin of life may be forever lost to science." That may be true, but experiments have shown that complex molecules like RNA can form in the absence of life, replicate, and carry information. These data give many scientists confidence that, as Szostak has also said, "Research can at least help us understand what is possible."

ANIMATION

hhmi | BioInteractive

Figure 20-16

Banded Iron Formation

When photosynthesis evolved, early life began to release oxygen. Oxygen reacted with dissolved iron in the oceans, which led to the formation of iron oxide minerals. This rock, with its layers of red jasper and iron magnetite, was formed billions of years ago as part of that process.

Life Changes the Atmosphere Microscopic fossils of prokaryotes have been found in rocks more than 3.5 billion years old. When these first life forms evolved, and for more than a billion years afterward, Earth's atmosphere contained very little oxygen. Then, during the early Proterozoic Eon, roughly 2.2 billion years ago, photosynthesis evolved, and photosynthetic bacteria began to churn out oxygen. This highly reactive gas had dramatic effects. Oxygen combined with iron in the oceans, producing iron oxide. The iron oxide sank to the ocean floor and is now the source of most iron ore mined today. You can see bands of iron oxide that formed billions of years ago in **Figure 20-16**.

Next, oxygen accumulated in the atmosphere, forming the ozone layer, which turned the sky a shade of blue. Over several hundred million years, the concentration of oxygen in the atmosphere increased to the point where it drove some early anaerobic life forms to extinction. Other organisms, however, evolved new metabolic pathways that used oxygen for respiration. These organisms also evolved ways to protect themselves from oxygen's powerful reactive properties.

VIDEO

Learn how microorganisms changed Earth's atmosphere and made the planet more hospitable for higher life forms.

READING CHECK **Summarize** How did photosynthesis change the composition of the atmosphere?

Origin of the Eukaryotic Cell

Eukaryotic cells, as you've learned, contain several kinds of complex cytoplasmic organelles, including lysosomes, endoplasmic reticula, cilia, and flagella. Two other organelles—chloroplasts and mitochondria—are even more complicated. The evolution of these complex eukaryotic cells from much simpler prokaryotic cells was one of the most important events in the history of life. How did this cellular complexity evolve?

READING TOOL

Recall the symbiotic relationships you learned about in Chapter 6 and describe how the concept relates to the evolution of eukaryotic cells.

The Earliest Eukaryotes The fossil record provides few clues to the evolution of cells. The oldest eukaryotic cell fossils have been found in rocks 2.1 billion years old. Unfortunately, these microscopic fossils don't usually show details of internal cell structure, so they provide few clues about early eukaryote evolution.

Studies of living cells, however, have led to several ideas. The **endosymbiotic theory**, developed in the 1960s by Lynn Margulis of the University of Massachusetts, proposes that organelles in eukaryotic cells were formed when different types of cells joined in a kind of merger, as shown in **Figure 20-17**. Margulis called her idea endosymbiosis, which literally means "living together within." In recent years, molecular biology has been able to evaluate this theory with new techniques and greater precision. ***A great deal of evidence now supports the theory that many of the complex features of eukaryotic cells evolved through endosymbiosis.*** The fact that some cells today contain bacteria and algae living as endosymbionts further supports this theory.

Mitochondria, for example, are similar in size to bacteria, have their own DNA genomes, synthesize some of their own proteins, and are formed when preexisting mitochondria divide. Most biologists now agree with Margulis's evaluation that mitochondria are the descendants of free-living bacteria that took up residence in the earliest eukaryotes.

Similar evidence supports an endosymbiotic origin for chloroplasts. Chloroplast membranes resemble those of photosynthetic prokaryotes. Chloroplast DNA has many similarities to prokaryotes as well. This suggests that chloroplasts evolved from free living photosynthetic cells that paired with the earliest eukaryotes.

Living cells are filled with complex biochemical systems. Some of these are biochemical pathways like the Krebs cycle. Others are complex processes like mitotic cell division. Still others are complicated structures, such as ribosomes, cilia, and flagella. Many of these systems date back billions of years, so it is difficult to determine their exact origins. Nonetheless, analysis of these systems in living cells today provides some interesting clues.

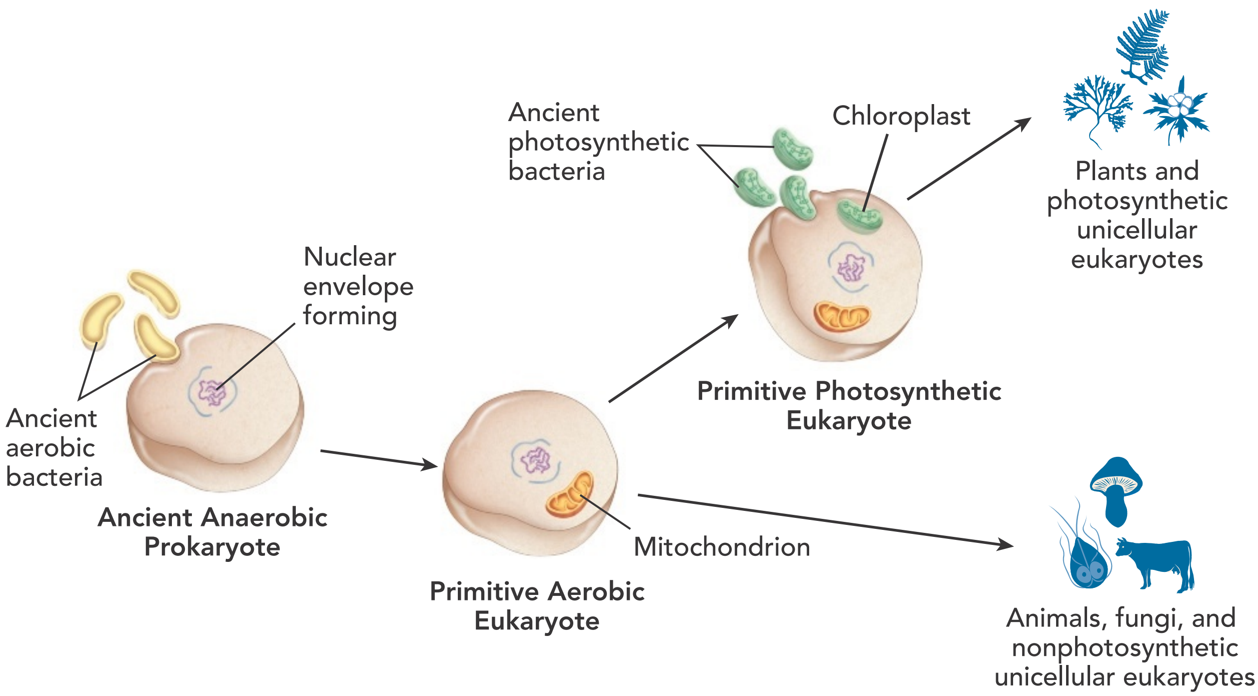
BUILD VOCABULARY

Prefixes The prefix *endo-* means "within" or "inner." The **endosymbiotic theory** involves a symbiotic relationship between eukaryotic cells and the prokaryotes within them.

Figure 20-17

The Endosymbiotic Theory

Ancient prokaryotes may have entered primitive eukaryotic cells, remained there, and evolved into organelles. **Infer** Is it likely that nonphotosynthetic prokaryotes could have evolved into chloroplasts? Explain your answer.



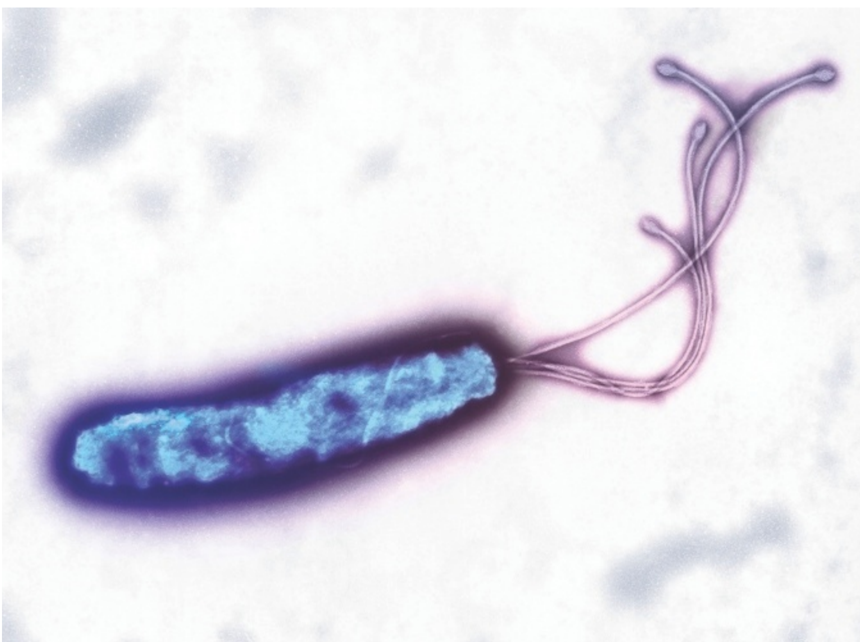
The Ribosome Ribosomes are complex organelles used by all living cells to translate the coded instructions of mRNA molecules into the sequences of amino acids that make up proteins. Ribosomes in eukaryotic cells consist of four ribosomal RNA molecules and more than 80 different proteins. The origin of this complex structure has long been a mystery. New research, however, has led to some surprising findings. One of these is that the part of the ribosome where chemical bonds are formed between amino acids completely lacks proteins. This is true of other key places in the ribosome as well, so it is now clear that ribosomal RNA itself carries out the most important tasks in protein synthesis. As a result, the evidence suggests that the earliest cells may have produced proteins using RNA alone. Over time, proteins were added to that RNA in ways that improved the efficiency of the process, leading to today's complex ribosomes.

Cilia and Flagella Cilia and flagella are complex structures that enable cells to move. **Figure 20-18** shows an example of a bacterium with flagella. The two main groups of prokaryotes have two types of flagella that differ biochemically. The flagella of Eubacteria contain 30 to 40 proteins, while the flagella of Archaea contain 10 to 20 proteins. Yet these flagella share a common feature that helps explain their origin. Each type of flagellum is assembled from protein subunits that serve other purposes elsewhere in the cell. For example, the flagella of Archaea contain proteins resembling those found in structures on the cell surface known as pili. Nearly every protein in the flagella of Eubacteria resembles proteins that are used for other purposes in bacteria that lack flagella. This suggests that these cells "borrowed" copies of these proteins as the flagellum evolved. In fact, a group of ten such proteins so closely resembles a channel structure in the cell membrane that the channel structure and the flagellum may share a common ancestor.

Figure 20-18

Bacterium with Flagella

Cilia and flagella remain features of bacteria today. Their structures show how cells can reuse proteins for new purposes (TEM 14,000×).



HS-ESS2-7

Argument-Based Inquiry — Guided Inquiry

Modeling Coacervates

Problem How can you model the early stages of life?

Coacervates are beadlike collections of amino acids, carbohydrates, and other compounds. In this lab, you will make a model of coacervates. Then you will analyze your model to make inferences about the role of coacervates in developing the first cells.

You can find this lab in your digital course.

In eukaryotes, these structures contain several hundred different proteins. The key proteins in eukaryotic cilia and flagella are tubulin and dynein. Both of these proteins are involved in many other systems in the cell that produce movement, including the movements of chromosomes during mitosis. This suggests that the major protein components of cilia and flagella were present before these structures evolved. With time, complex systems evolved by reusing old existing parts in new ways.

Do We Understand the Cell Completely? Of course not. Many uncertainties remain in our current understanding of cellular complexity. Biologists are still learning how cells function in response to their environments and how they interact with each other. Such uncertainties are as much a part of biology as they are for any other experimental science. In many ways, this is good news, because it means that there are plenty of mysteries to be solved by the next generation of biologists. Meanwhile, what we do understand suggests that complex cell structures and pathways were produced by known mechanisms of evolutionary change.

HS-ESS1-6, HS-ESS2-6, HS-ESS2-7

LESSON 20.3 Review

KEY QUESTIONS

1. What was Earth's early atmosphere like?
2. How could the basic compounds necessary for life have been formed on early Earth?
3. What does the endosymbiotic theory propose?

CRITICAL THINKING

4. **Construct an Explanation** Did the first living cell evolve suddenly in a single step or gradually as the result of many intermediate steps? Explain.
5. **Cite Evidence** What evidence and logical reasoning support the conclusion that anaerobic organisms evolved first, followed much later by aerobic organisms?
6. **Develop Models** What evidence supports the model of endosymbiotic origin for mitochondria and chloroplasts?

CASE STUDY WRAP-UP


Neil Shubin

How did fossil hunters find *Tiktaalik?*

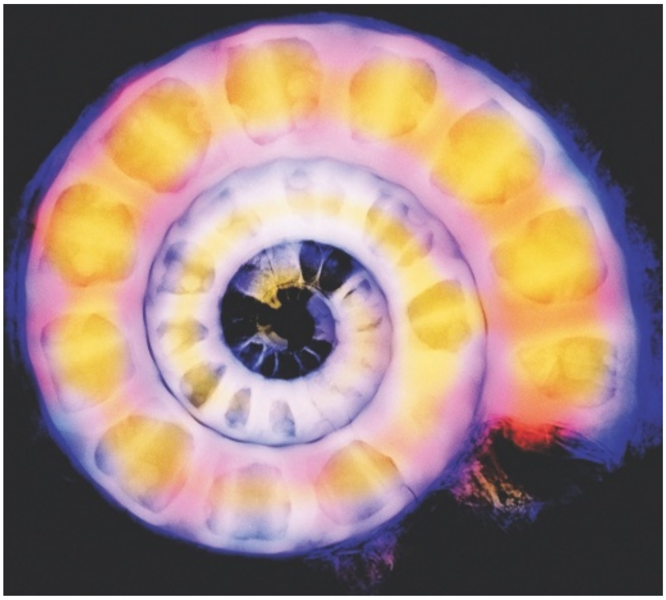
Finding *Tiktaalik* was as amazing as it is scientifically important. That discovery followed years of careful research and preparation, that helped Shubin and his colleagues to figure out where to look!

Make Your Case

Based on other fossils and radiometric dating, Neil Shubin and his colleagues knew that vertebrates first made the move from water to land during the Devonian period, between 380 and 363 million years ago. The island of Ellesmere, in the Canadian Arctic, had freshwater sedimentary rocks of exactly that age, so that's where they began their explorations. After four summers of hard work, one member of the group noticed something unusual in a rocky hillside. As they carefully chipped away at the rock, they discovered the first of many *Tiktaalik* fossils.

Construct an Explanation

1. **Cite Evidence** Shubin concluded that the fossil he sought was buried in rocks from the Devonian Period. What evidence supported this conclusion?
2. **Apply Scientific Reasoning** How does *Tiktaalik* provide evidence for the evolution of tetrapods and land-dwelling vertebrates?



Technology on the Case

X-Rays for Fossils

After technology is developed for one purpose, it often becomes useful in new ways. One example is X-ray technology. X-rays are a form of high-energy electromagnetic radiation. They pass through soft materials, but are stopped by hard, dense matter, such as bone. After their initial discovery, technology that uses X-rays was developed for doctors to identify broken bones and for dentists to find tooth decay. Now, paleontologists are using X-rays to study fossils.

In 2009, scientists at Stanford University used extremely powerful X-rays to study a fossil of *Archaeopetryx*. This animal was an intermediate species between dinosaur and bird. The X-rays showed the presence of trace elements that might have been a part of muscles or feathers.

In 2015, researchers studied a fossil of a sea urchin using computed tomography (CT). This technology uses X-rays to generate three-dimensional images of an object's interior. The results showed that a colony of tiny mollusks had lived inside the sea urchin.

In 2016, scientists at the University of Florida began using a micro-CT scanner. This scanner can resolve images to a micrometer, which is one millionth of a meter. In one project, the scanner is helping to depict the brain of an animal that lived 45 million years ago.

Careers on the Case

Work Toward a Solution

Neil Shubin is a paleontologist, a scientist who studies ancient life. People in other careers work with paleontologists to help find, study, prepare, and communicate about fossils.

Fossil Preparator

If you have enjoyed seeing fossils at a museum, then you have benefited from the work of a fossil preparator. Fossil preparators specialize in preparing fossils to study or for display. Sometimes, they remove a fossil from its surrounding rock. They may also repair damaged fossils.

VIDEO

Learn more about careers related to studying the history of life.

hhmi | BioInteractive

STUDY GUIDE

Lesson Review

Go to your Biology Foundations Workbook for longer versions of these lesson summaries.

20.1 The Fossil Record

From the fossil record, paleontologists learn about the structure of ancient organisms, their environment, and the ways in which they lived. The fossil record is incomplete because the remains of many organisms decay before they can be fossilized, or the organisms die in an environment where fossils are unlikely to form.

Relative dating allows paleontologists to determine whether a fossil is older or younger than other fossils. Radiometric dating uses the proportion of radioactive to stable isotopes to calculate the age of a sample.

The geologic time scale is based on both relative and absolute dating. The major divisions of the geologic time scale are eons, eras, and periods.

Rising mountains, changing coastlines, changing climates, and geological forces have altered habitats of living organisms repeatedly throughout Earth's history. In turn, the actions of living organisms over time have changed conditions in the land, water, and atmosphere.

- extinct
- relative dating
- index fossil
- radiometric dating
- half-life
- geologic time scale
- era
- period
- plate tectonics

Summarize What environmental conditions are important in order for intricate structures to be preserved in a fossil?

20.2 Evolutionary Patterns and Processes

If the rate of speciation in a clade is equal to or greater than the rate of extinction, the clade will continue to exist. If the rate of extinction in a clade is greater than the rate of speciation, the clade will eventually become extinct.

Evidence shows that evolution has often proceeded at different rates for different organisms at different times over the long history of life on Earth. Sometimes species change gradually over time. Sometimes an event occurs that disrupts the species equilibrium and change becomes relatively rapid.

Two important patterns of macroevolution are adaptive radiation and convergent evolution. Adaptive radiation occurs when a single species or a small group of species evolves over a relatively short time into several different forms that live in different ways. Convergent evolution occurs when unrelated organisms evolve into similar forms, such as the large grassland birds that Darwin observed.

The relationship between two coevolving organisms often becomes so specific that neither organism can survive without the other. Thus, an evolutionary change in one organism is usually followed by a change in the other organism.

- macroevolutionary pattern
- background extinction
- mass extinction
- gradualism
- punctuated equilibrium
- adaptive radiation
- convergent evolution
- coevolution

Explain How do the concepts of gradualism and punctuated equilibrium help to explain the fossil record?

20.3 Earth's Early History

The early Earth was very hot and experienced intense volcanic activity. Eventually Earth cooled which allowed solid rock and oceans to form. Earth's early atmosphere contained little or no oxygen. It was principally composed of carbon dioxide, water vapor, and nitrogen, with lesser amounts of carbon monoxide, hydrogen sulfide, and hydrogen cyanide.

Scientists have long wondered how life began on Earth. Miller and Urey's experiment suggested how mixtures of the organic compounds necessary for life could have arisen from simpler compounds on a primitive Earth. The "RNA world" hypothesis proposes that RNA existed by itself before DNA. From this simple RNA-based system, several steps could have led to DNA-directed protein synthesis.

The evolution of photosynthetic microorganisms changed Earth's oceans and atmosphere. The microorganisms removed carbon dioxide from the atmosphere and added oxygen to it. Over several hundred millions of years, this allowed for the evolution of microorganisms that use oxygen for respiration.

The endosymbiotic theory explains the evolution of eukaryotic cells by proposing that a symbiotic relationship evolved over time between primitive eukaryotic cells and the prokaryotic cells within them.

Research has shown that the structure of ribosomes would have allowed early cells to use RNA alone to produce proteins. Cellular research has also shown that cilia and flagella may have evolved from protein subunits that served other purposes in the cell.

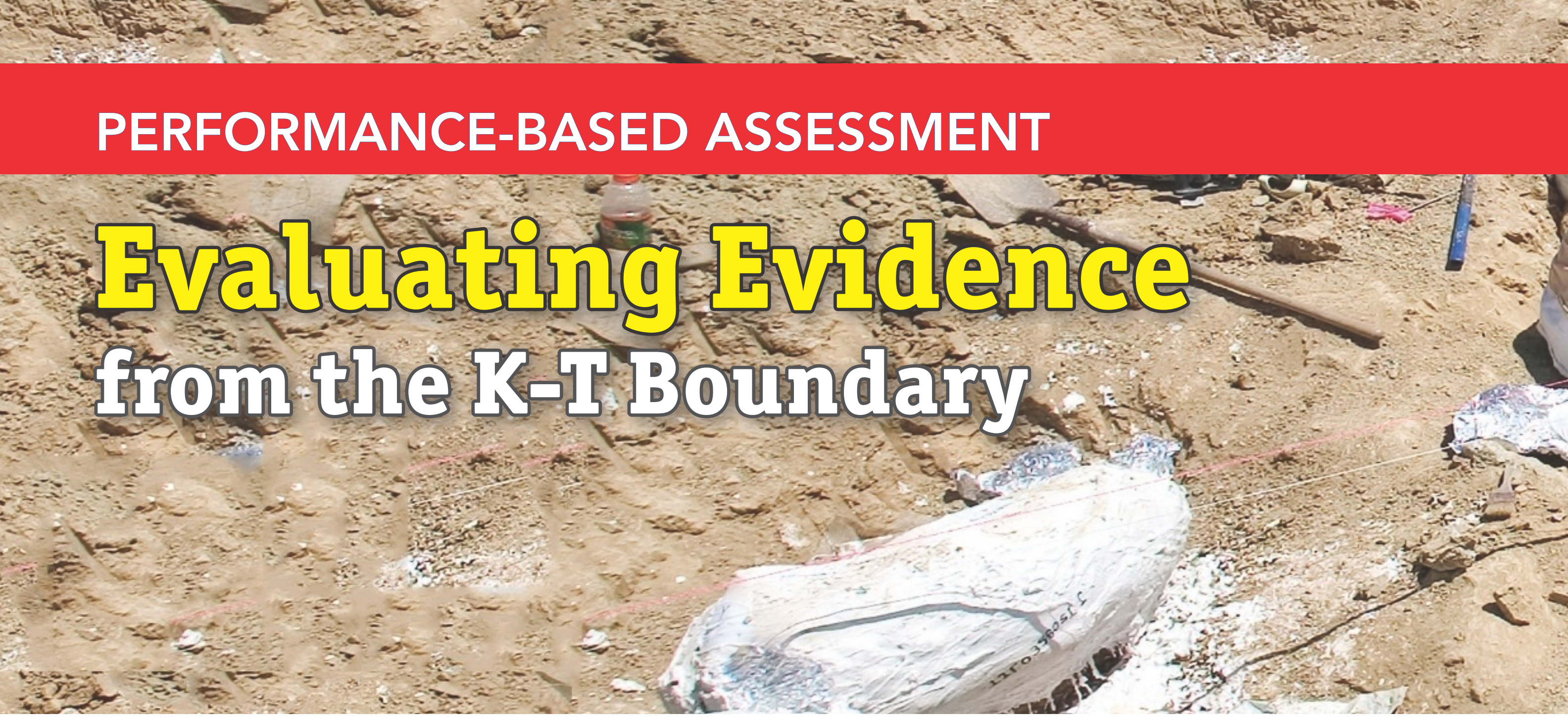
- endosymbiotic theory

Summarize How does this photo help explain the history of life on Earth?

Organize Information

Cite evidence for each statement from the text. Then draw a model to support each statement.

Statement	Evidence	Model
Fossils are a roadmap of evolution.	1.	2.
Evolution does not proceed at a constant rate.	3.	4.
Symbiosis was crucial to cell development.	5.	6.



PERFORMANCE-BASED ASSESSMENT

Evaluating Evidence from the K-T Boundary

Apply Scientific Reasoning

HS-LS4-5

The fossil record shows that dinosaurs once lived in nearly every habitable part of Earth. Fossils of widely known dinosaurs are particularly common in rocks dating from the Mesozoic Era, which ended around 66 million years ago. But after the Mesozoic, dinosaur fossils are nowhere to be found. What's more, many other Mesozoic species—plant and animal, terrestrial and marine—also disappeared.

What could have caused that mass extinction? Scientists been debating this question for many years, and new data are still being gathered to test two competing hypotheses.

The hypothesis that most people are familiar with was proposed by a father-son team: physicist Luis Alvarez and geologist Walter Alvarez. They were studying a layer of rocks called the K-T boundary, which marks the end of the Cretaceous Period ("K"), and the beginning of the Tertiary Period ("T"). (Recall that the Tertiary Period is now split into the Paleogene and Neogene Periods). They found that the K-T layer was rich in iridium, an element that is rare on Earth's surface, but common in objects from space such as meteorites. What could this mean?

Other studies showed that K-T boundary rocks from elsewhere, especially in North America, contain a type of deformed quartz called shocked quartz, along with glassy beads called spherules. Shocked quartz can form when powerful pressure waves move through rocks, and spherules form when rock vaporizes, then solidifies. They put these clues together with other evidence. In 1991, scientists discovered a huge crater just off the Yucatan peninsula, where an asteroid had punched through the floor of the Gulf of Mexico.

Some of the evidence from the K-T boundary is summarized in the table. Based in part on this evidence, the Alvarez team and other scientists propose the following hypothesis for the K-T mass extinction.

- For millions of years near the end of the Cenozoic Era, Earth's climate was relatively constant. Dinosaurs lived in many places around the world, and were diverse and numerous.

SCIENCE PROJECT

- About 65 million years ago, an asteroid struck Earth, in the region that is now Mexico's Yucatán peninsula. The asteroid strike raised a huge cloud of dust and ash that spread around the world. Sudden changes to the climate and other environmental factors caused most species to go extinct.
- Within 10 million years of the asteroid strike, mammalian diversity exploded, as surviving mammals evolved and filled the ecological niches left empty by the extinct dinosaurs.

Evidence from the K-T Boundary

Rock Layers	Observations
Beneath the K-T Boundary	• Contains fossils from a wide variety of dinosaurs, as well as other animals and plants • Thick rock layers are relatively uniform, indicating consistent conditions over millions of years
At the K-T Boundary	• Rocks are high in iridium • Rocks in North America contain shocked quartz and spherules
Above the K-T Boundary	• No fossils from 80% of Cretaceous animal species, including all dinosaur species • Fossil pollen shows 60% fewer plant species than during the Cretaceous Period • Fossils of small animals are common

1. **Apply Scientific Reasoning** How do observations of the K-T boundary support the conclusion that an asteroid hit Earth about 65 million years ago?
2. **Infer** Why might spherules and shocked quartz be common in K-T boundary rocks in North America, but not in other continents?
3. **Evaluate Evidence** Evaluate the evidence presented as support for the Alvarez hypothesis about the K-T extinction. Does this evidence support this hypothesis? Search for other scientific evidence about the K-T extinction that appears to support an alternative hypothesis. What does your research tell you about the current scientific consensus about this extinction?
4. **Construct an Explanation** After the extinction, mammals underwent a dramatic adaptive radiation from a few, mostly small species to the large-bodied, diverse forms we know today. Explain how a change in the environment made this possible.
5. **Communicate** Prepare a written or oral report, or a computer presentation, to share your evaluation of the evidence of the evolutionary changes that occurred 65 million years ago. In your evaluation, discuss these concepts from the chapter.
   - extinction
   - mass extinction
   - macroevolutionary patterns
   - adaptive radiation

CHAPTER 20

ASSESSMENT

KEY QUESTIONS AND TERMS

20.1 The Fossil Record

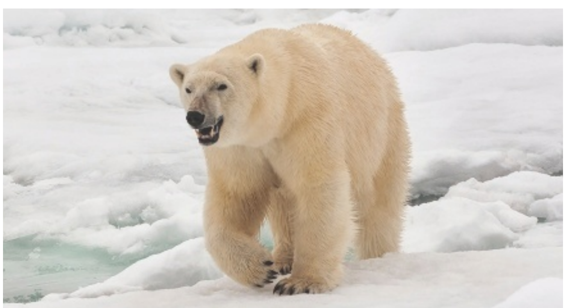
HS-LS4-1, HS-ESS1-5, HS-ESS2-7

1. Fossils are most often found in
   a. soil.
   b. sedimentary rock.
   c. igneous rock.
   d. clay.
2. Trilobite fossils are found in only a few rock layers, so they are useful
   a. index fossils.
   b. means of absolute dating.
   c. indicators of stratification.
   d. means of radiometric dating.
3. What type of information do fossils provide?
4. What is measured by the half-life of an element?
5. What changes to Earth's surface are explained by the theory of plate tectonics?
6. How did scientists determine the eras of the geologic time scale?
7. Compare the information learned from relative dating and absolute dating.

20.2 Evolutionary Patterns and Processes

HS-LS4-1, HS-LS4-4, HS-LS4-5

8. In convergent evolution, similar traits develop in two species that are
   a. closely related.
   b. not closely related.
   c. extinct.
   d. living.
9. A variety of bear species, including the polar bear, evolved from a common bear ancestor. This pattern of evolution is an example of
   a. adaptive radiation.
   b. convergent evolution.
   c. punctuated equilibrium.
   d. gradualism.



10. Cladograms that are based on the fossil record always show
    a. which organisms are direct ancestors of the others.
    b. relationships based on shared derived characteristics.
    c. that clades are made up of only extinct species.
    d. relative ages of organisms in the clade.
11. The evolution of species at a slow, relatively constant rate is called
    a. background extinction.
    b. mass extinction.
    c. gradualism.
    d. punctuated equilibrium.
12. Evolution by punctuated equilibrium is characterized by
    a. minor genetic change.
    b. slow, gradual change.
    c. varying rates of change.
    d. a constant rate of change.
13. Describe a biological example of a macroevolutionary pattern.
14. How does coevolution link a pair of species?

20.3 Earth's Early History

HS-ESS1-6, HS-ESS2-6, HS-ESS2-7

15. Earth's early atmosphere contained
    a. carbon dioxide, water vapor, nitrogen, and oxygen.
    b. carbon dioxide, water vapor, carbon monoxide, and oxygen.
    c. hydrogen sulfide, carbon monoxide, hydrogen cyanide, and water vapor.
    d. oxygen, carbon monoxide, water vapor, and nitrogen.
16. The Miller-Urey experiment demonstrated that the atmosphere of early Earth could support the development of
    a. amino acids.
    b. proteins.
    c. fatty acids.
    d. protocells.
17. The origin of the eukaryotic cell is explained by
    a. the RNA world hypothesis.
    b. protocells.
    c. the Miller-Urey experiment.
    d. the endosymbiotic theory.
18. How are protocells similar to living cells?
19. The sky of early Earth was probably pinkish-orange. As life became established, the sky turned blue. What was responsible for the color change?

20. What conclusion about life on Earth is supported by the Miller-Urey experiment?

CRITICAL THINKING

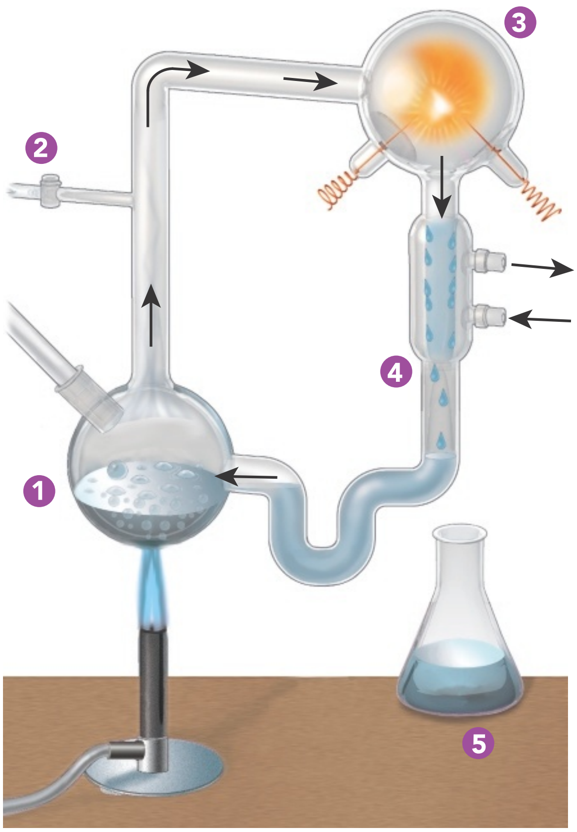
HS-LS4-1, HS-LS4-4, HS-LS4-5, HS-ESS1-5, HS-ESS1-6, HS-ESS2-7

21. **Construct an Explanation** Why do gaps exist in the fossil record?

22. **Evaluate Evidence** The fossil record shows that dinosaurs became extinct about 65 million years ago, after which mammals became more diverse. How does the fossil record support conclusions about environmental changes that began 65 million years ago?

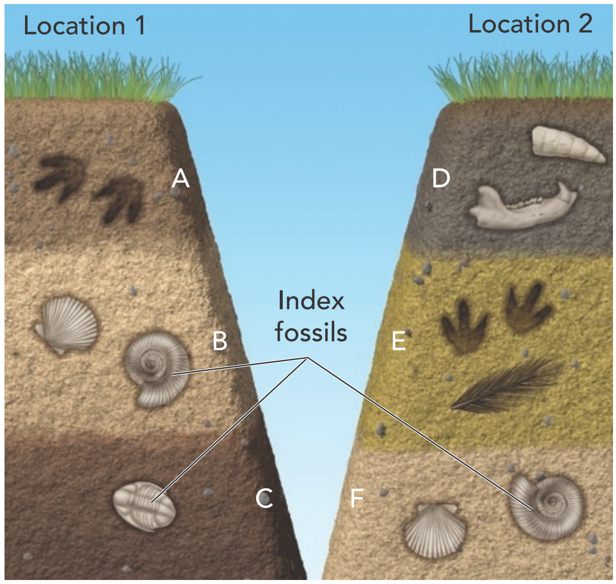
23. **Construct an Argument** After a mass extinction, does evolution generally occur rapidly or slowly? Cite evidence and logical reasoning to support your argument.

24. **Evaluate Models** The diagram shows part of the apparatus used in the Miller-Urey investigations on the origin of life on Earth. How does the apparatus represent early Earth? What are the limitations of the model?



25. **Draw Conclusions** How did the evolution of photosynthesis change Earth's atmosphere and living things?

Use the diagram of rock layers to answer questions 26 and 27. The diagram shows rock layers in two different places.



26. **Apply Scientific Reasoning** How do the ages of the fossils from layer A and layer C compare? Explain your reasoning.

27. **Synthesize Information** Which fossils in Location 2 are most likely the same age as the fossils in layer B? Explain.

28. **Apply Scientific Reasoning** Use the example of body shape in sharks, dolphins, and penguins to explain convergent evolution.

29. **Engage in Argument** A student claims that monarch butterflies and milkweed plants evolved together as an example of coevolution. What type of evidence could support this claim?

30. **Predict** Where are fossils most likely to be found: in rocks along the walls of a river canyon, along the mouth of an active volcano, or in the soil of a tropical rain forest? Explain your prediction.

31. **Evaluate Evidence** A scientist digs for fossils in the dry, dusty land in the state of Wyoming. She finds a fossil of fern leaves. What does the fossil evidence show about the natural history of Wyoming?

ASSESSMENT

CROSSCUTTING CONCEPTS

32. **Cause and Effect** Describe the cause-and-effect relationship between changes in the environment and adaptations in living things.

33. **Stability and Change** How is the concept of background extinction an example of both stability and change?

MATH CONNECTIONS

Analyze and Interpret Data

CCSS.MATH.CONTENT.MP2

34. **Reason Quantitatively** In the analogy of a 24-hour clock for geologic time, the Cenozoic Era would last from 11:39 PM to midnight. What percentage of geologic time is taken up by this era?

35. **Interpret Data** A recent newspaper article lists 12 species that were once common in your region, but have gone extinct during the past few years. Classify the type of extinction that the newspaper is reporting. What additional facts would help you evaluate the information?

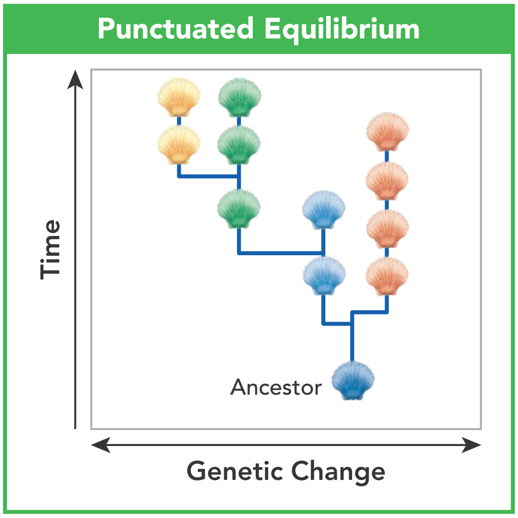
The table identifies the half-life of several isotopes. Use the table to answer questions 36 and 37.

Isotope and Decay Product	Half-Life (yrs)
Potassium-40 → Argon-40	1.25 billion
Rubidium-87 → Strontium-87	48.8 billion
Thorium-232 → Lead-208	14.0 billion
Uranium-235 → Lead-207	704.0 million
Uranium-238 → Lead-206	4.5 billion

36. **Interpret Data** A sample of thorium-232 has a mass of 12.0 micrograms. What can be concluded about the sample after 14.0 billion years has passed?

37. **Calculate** Earth is now about 4.5 billion years old. When will Earth have 1/4 of the uranium-238 that it had when the planet formed?

The diagram shows an example of evolution by punctuated equilibrium. Use the diagram to answer questions 38 and 39.



38. **Interpret Graphs** What does the graph show about the relationship between time and genetic change when species evolve in a pattern of punctuated equilibrium?

39. **Evaluate Conclusions** In this example, does the evidence support the conclusion that punctuated equilibrium will continue in this species as time goes on? Explain your evaluation.

LANGUAGE ARTS CONNECTION

Write About Science

HS-ESS2-7, CCSS.ELA-LITERACY.WHST.9-10.1, CCSS.ELA-LITERACY.WHST.9-10.2

40. **Write Explanatory Texts** Write a paragraph to explain how fossils may form in sedimentary rock.

41. **Write Arguments** Could life have evolved from nonliving compounds? Include evidence, such as from the Miller-Urey experiment, to support your argument.

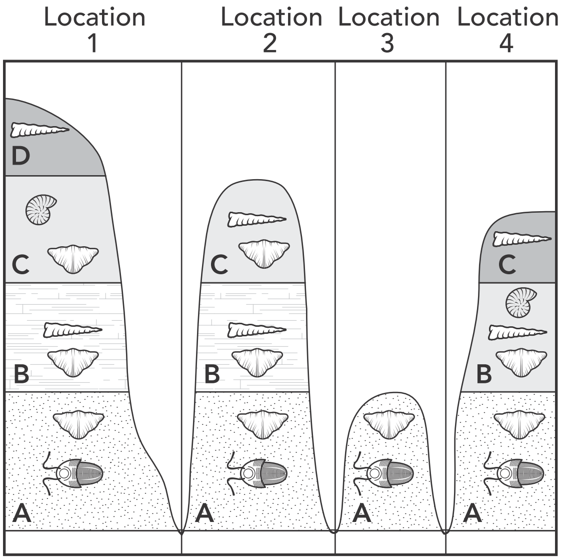
Read About Science

CCSS.ELA-LITERACY.RST.9-10.2

42. **Determine Meaning** When describing their theory of punctuated equilibrium, Stephen Jay Gould and Niles Eldredge often used the motto "Stasis is data." *Stasis* is another word for *equilibrium*. Explain what Gould and Eldredge meant.

END-OF-COURSE TEST PRACTICE

1. The diagram shows fossil layers in different locations. The different shading in the diagram indicates different types of rock.



How could fossils like the ones shown support the theory of evolution?

A. Fossil evidence supports the hypothesis that evolution can occur at different rates in different clades.
B. Fossil evidence supports the hypothesis that individual organisms and populations evolve to adapt to a changing environment.
C. Fossil evidence provides a complete record of the organisms that once lived and are ancestors to other organisms.
D. Fossil evidence provides information on the allele frequency in ancestral populations.
E. Fossil evidence supports the hypothesis that behavioral isolation contributes to evolutionary change.

2. At the end of the Permian Period, a mass extinction occurred known as "The Great Dying." How do mass extinctions affect the rate of evolutionary change?

A. Species that survive mass extinctions adapt rapidly because they face limited competition.
B. Species that survive mass extinctions adapt rapidly because they have been exposed to mutagens.
C. Species adapt quickly after mass extinctions because the environment has often changed significantly.
D. Species evolve slowly after mass extinctions because the environment has often changed significantly.
E. Evolutionary change occurs slowly after mass extinctions because a large number of species have become extinct over a relatively short time.

3. Over the course of Earth's history, Earth and the organisms that live on it have changed. How did early life on Earth affect Earth's systems?

A. As prokaryotes evolved, methane and ammonia in Earth's atmosphere were replaced with amino acids.
B. As the number of organisms increased, the size of the ozone layer in Earth's atmosphere decreased.
C. As the remains of early organisms accumulated, iron oxide formed in rock layers.
D. As prokaryotes evolved, Earth's atmosphere changed from having little oxygen to having enough oxygen to support cellular respiration.
E. As organisms produced organic compounds, the compounds were released into the atmosphere and formed meteorites and comets.

ASSESSMENT

For additional assessment practice, go online to access your digital course.

If You Have Trouble With...			
Question	1	2	3
See Lesson	20.1	20.2	20.3
Performance Expectation	HS-LS4-1	HS-LS4-5	HS-ESS2-7