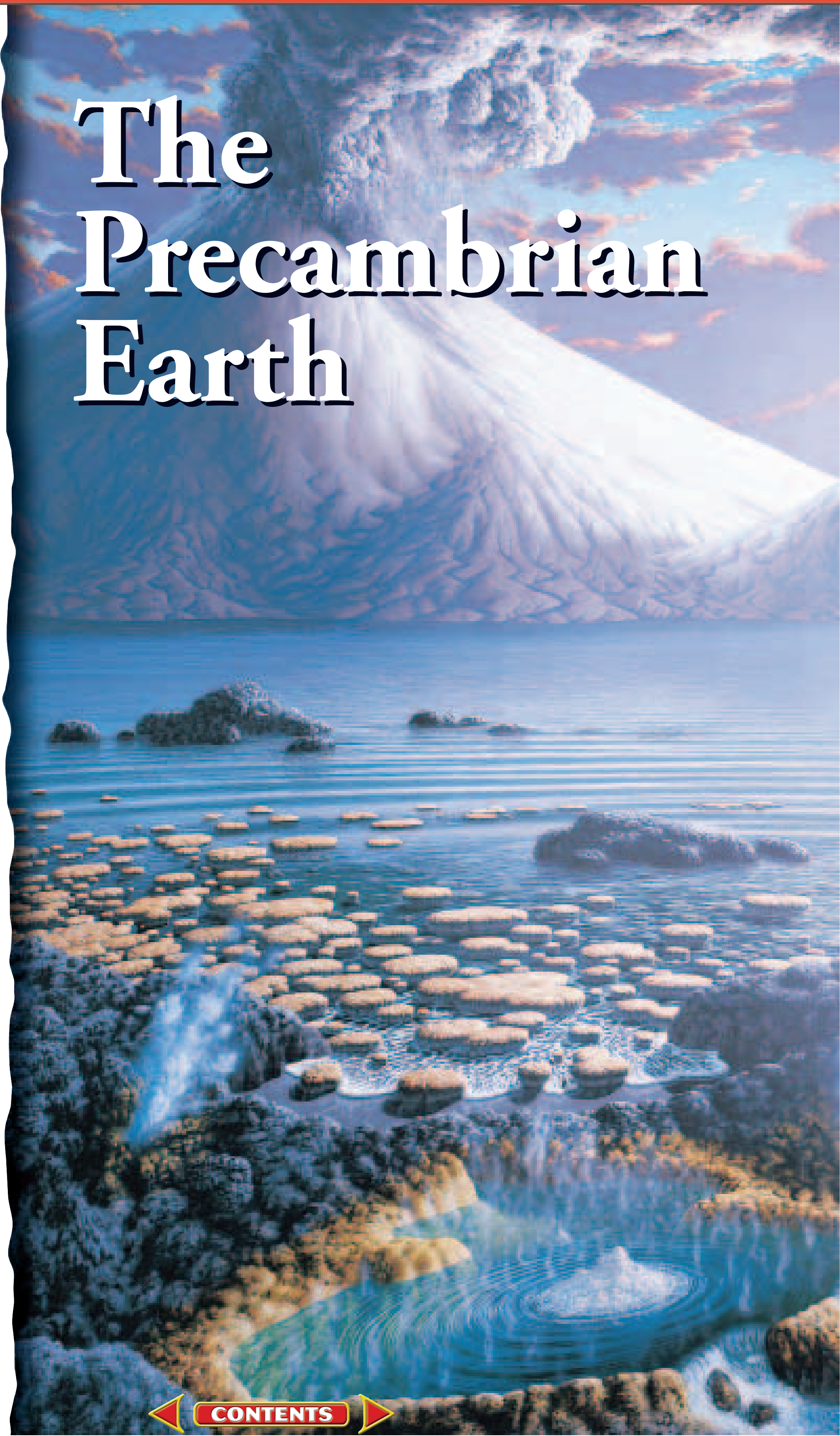
Chapter 22

The Precambrian Earth



What You'll Learn

- How the age of Earth is determined.
- How the continents, atmosphere, and oceans formed.
- When life first appeared on Earth.
- What kinds of organisms populated the Precambrian Earth.

Why It's important

Most of Earth's history occurred during the Precambrian. During this time, the crust, atmosphere and oceans formed and life first appeared. Early lifeforms produced oxygen through photosynthesis, and, thus, changed the atmosphere and the history of life on Earth.

Earth Science Online

To find out more about Precambrian Earth, visit the Earth Science Web Site at earthgeu.com

CONTENTS

Discovery Lab

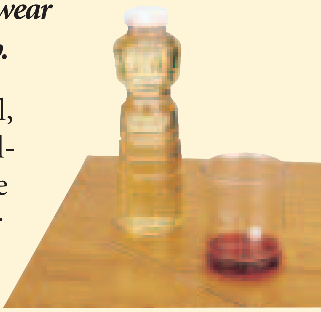
Density Separation

Earth's core, mantle, and crust have different average densities. The core is the densest, and the crust is the least dense. Scientists hypothesize that when Earth formed, temperatures were hot enough for the materials that make up Earth to act, in part, like a liquid and flow. In this activity, you will model how liquids of different densities react when they are mixed together.

1. Fill a 250-mL beaker with 50 mL of tap water.
2. Add 2–3 drops of dark food coloring to the water.
3. Poor 175 mL of vegetable oil into the beaker and stir the contents.

CAUTION: Always wear safety goggles and an apron in the lab.

Observe In your science journal, describe what happened to the colored water and vegetable oil in the beaker. Explain how this is similar to what happened to the core and mantle when Earth formed.



SECTION 22.1 The Early Earth

OBJECTIVES

- **Describe** *the evidence used to determine the age of Earth.*
- **Understand** *why scientists theorize that the early Earth was hot.*

VOCABULARY

zircon
asteroid
meteorite

For most of Earth's history, there was nothing like the plants and animals that exist today. In Chapter 21, you learned about the geologic time scale and how Earth's history is divided into time periods. In this chapter, you will learn about the earliest part of the geologic time scale, the Precambrian.

EARTH'S "BIRTH"

For about the first 4 billion years of Earth's 4.6-billion-year existence, most of the life-forms that inhabited Earth were unicellular organisms. What evidence did these organisms leave of their existence? What was Earth like when these organisms lived? How did Earth change during the Precambrian? How did these changes set the stage for the animal life that exists today? Answers to these questions not only help us to understand the history of Earth, but they also serve as a model for the search for life on other planets. In 1996, the announcement that a meteorite from Mars might contain microscopic fossils of bacteria rekindled scientific interest in the search for life elsewhere in the universe. You can read more about this meteorite in this chapter's *Science in the News* feature. It may be possible to

CONTENTS

identify clues to the possible existence of life on other planets, even if rocks from those planets are the only evidence we have. After all, rocks are all that we have left of the Precambrian Earth, and as you will learn, there is evidence of life's humble beginnings on Earth in Precambrian rocks. The Precambrian portion of the geologic time scale is shown in ***Figure 22-1.***

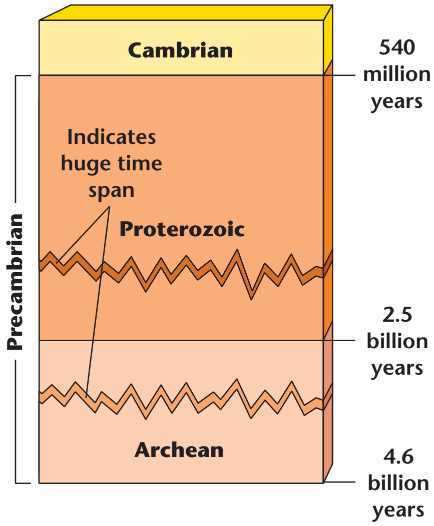


Figure 22-1 Most of Earth's history is contained within the 4 billion years that make up the Precambrian.

How old is Earth?

We know that Earth must be at least as old as the oldest rocks in the crust. Radiometric dating has determined that the age of the oldest rocks on Earth is between 3.96 to 3.8 billion years. But the rocks that form Earth's crust have been eroded over time. Evidence of 4.1- to 4.2-billion-year-old crust exists in the mineral zircon that is contained in metamorphosed sedimentary rocks in Australia. **Zircon** is a very stable mineral that commonly occurs in small amounts in granite. Radiometric dating has determined that the zircon grains in these sedimentary rocks are between 4.1 and 4.2 billion years old. The zircon existed before it became cemented into the sedimentary rocks, and scientists theorize that the zircon is the eroded residue left behind from 4.1- to 4.2-billion-year-old granitic crustal rocks. Based on this evidence, Earth must be at least 4.2 billion years old.

Meteorites, such as the one shown in ***Figure 22-2,*** have been radiometrically dated at between 4.5 and 4.7 billion years old. Most astronomers agree that the solar system, including Earth, formed at the same time, and therefore, Earth and meteorites should be about the same age. In addition, the oldest rock samples from the Moon, collected during the Apollo missions, are approximately 4.6 billion years old. Thus, taking all of the evidence into consideration, scientists commonly agree that the age of Earth is 4.6 billion years.

Earth's Heat Sources

Earth was most likely extremely hot shortly after it formed, and there were three likely sources of this heat. The first source was radioactivity. Radioactive isotopes were more abundant during the past because, over time, radioactive decay has reduced the original amount of Earth's radioactive isotopes. One product of radioactive decay is energy, which generates heat. Much of Earth's current internal heat is attributed to the energy released by radioactivity. Because there were more radioactive isotopes in Earth's distant past, scientists infer that more heat was being generated then and that Earth was hotter.

The second source of Earth's heat was the impact of asteroids and meteorites. **Asteroids** are metallic or silica-rich objects that are

1 km to 950 km in diameter. Today, most asteroids orbit the Sun between the orbit of Mars and Jupiter. Meteoroids are small asteroids or fragments of asteroids. When meteoroids fall to Earth, we call them **meteorites.** Evidence from the surfaces of the Moon and other planets suggests that there were many more meteoroids and asteroids distributed throughout the early solar system than there are today, and therefore collisions were much more common. For this reason, scientists infer that for the first 500 to 700 million years of Earth's history, bombardment by meteorites and asteroids was common. These impacts generated a tremendous amount of thermal energy.

Figure 22-2 This 10 000-year-old, 16-ton meteorite was found in Oregon on the tribal lands of the Willamette Native Americans.

The third source of Earth's heat was gravitational contraction. As a result of meteor bombardment and the subsequent accumulation of meteorite material on Earth, the size of Earth increased. The weight of the material caused gravitational contraction of the underlying zones. The energy of the contraction was converted to thermal energy. The new material also caused a blanketing effect, which prevented the newly generated heat from escaping.

The combined effects of radioactive decay, meteorite and asteroid bombardment, and gravitational contraction made a hot and rather inhospitable beginning for Earth. However, cooling and subsequent crystallization laid the foundation for Earth's crust to form and prepared Earth for the next phase in its development.

SECTION ASSESSMENT

1. What is the age of Earth?
2. Describe the evidence used to determine the age of Earth.
3. How is zircon used to date igneous rocks?
4. Which of Earth's early sources of heat are not major contributors to Earth's present-day internal heat?
5. **Thinking Critically** If most astronomers hypothesize that the solar system formed all at once, why is it important that we use the age of the oldest rocks on Earth to determine the age of Earth rather than using only the age of meteorites?

SKILL REVIEW

6. **Comparing and Contrasting** Compare and contrast Earth's three early sources of heat. For more help, refer to the *Skill Handbook.*

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SECTION 22.2

Formation of the Crust and Continents

OBJECTIVES

- **Explain** *the origin of Earth's crust.*
- **Describe** *the formation of the Archean and Proterozoic continents.*

VOCABULARY

differentiation
Precambrian shield
Canadian Shield
microcontinent
Laurentia

Were continents always present on Earth's surface? Early in the formation of Earth, the planet was molten, and numerous elements and minerals were mixed throughout the magma. Over time, the minerals became concentrated in specific zones and Earth became layered. As the magma reached the surface and cooled, landmasses began to form.

FORMATION OF THE CRUST

When Earth formed, iron and nickel, which are dense elements, concentrated in its core. Minerals with low densities tend to crystallize from magma at cooler temperatures than denser minerals do. Therefore, near the surface of Earth, where it is cooler, the rocks are generally composed of a high proportion of the less-dense minerals. For example, granite is common at Earth's surface. Granite is mainly composed of feldspar, quartz, and mica, which, as you learned in Chapter 4, are minerals with low densities. Lava flowing from the hot and partly molten interior of Earth concentrated the less-dense minerals near the surface of Earth over time. In contrast, the denser minerals, which crystallize at higher temperatures, concentrated deeper within Earth and formed the rocks that make up Earth's mantle. The process by which a planet becomes internally zoned when heavy materials sink toward its center and lighter materials accumulate near its surface is called **differentiation.** The differentiated zones of Earth are illustrated in ***Figure 22-3.***

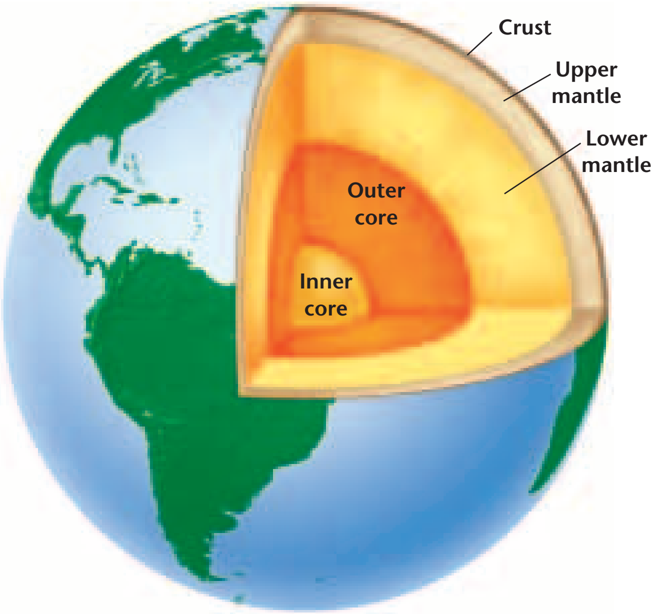


Figure 22-3 Earth's layers formed as a result of differentiation. The density of the minerals found within each layer decreases toward the crust.

Geologists hypothesize that Earth's earliest crust formed as a result of the cooling of the uppermost mantle. Thus, the crust likely consisted of iron and magnesium-rich minerals similar to those found in basalt. As these minerals weathered, they formed sediments that covered the early crust. Geologists also hypothesize that as sediment-covered slabs of the crust were recycled into the mantle at subduction zones, the slabs partly melted and generated magmas with different mineral compositions. These magmas crystallized to form the first granitic continental crust, which was rich in feldspar, quartz, and mica. The formation of

CONTENTS

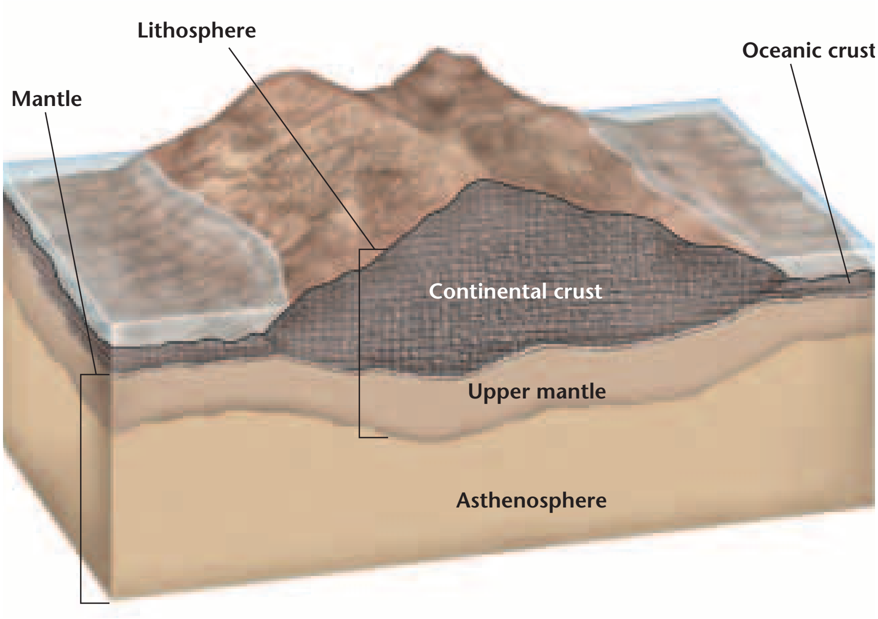


Figure 22-4 The difference in density between the heavier ocean crust and the lighter continental crust allows the continental crust to float higher on the mantle, even when its thickness is greater.

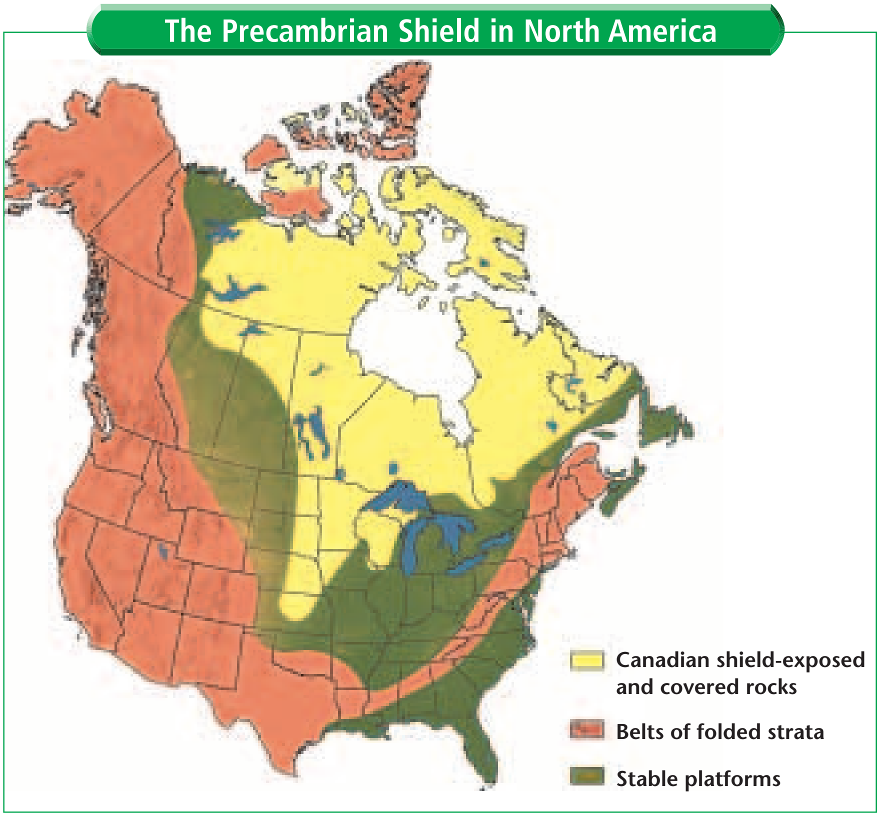
granitic crust was a slow process. Most geologists hypothesize that the formation of the majority of crustal rocks that make up the low-density, granitic cores of continents was completed by about 2.5 billion years ago. The rocks of the earliest crust no longer exist because they were recycled in subduction zones long ago.

Less-dense material has a tendency to float on more-dense material. In the *Discovery Lab* at the beginning of this chapter, you observed that oil floats on top of water. This happens because oil is less dense than water. For this same reason, continental crust "floats" on top of the mantle below it. In addition, basaltic crust is more dense than granitic crust, and therefore, it does not float as high on the mantle as granitic, continental crust does. This difference in density is what causes the basaltic ocean floor to be lower in elevation than the less-dense granitic continental crust, as illustrated in ***Figure 22-4.***

THE CORES OF THE CONTINENTS

Today's continents each contain a core of Archean and Proterozoic rock called a **Precambrian shield.** In some areas, the Precambrian shields are exposed at the surface, whereas in other areas, younger sedimentary rocks bury them. The buried and exposed parts of a shield together compose the craton, which is the stable part of a continent. In North America, the Precambrian shield is called the **Canadian Shield** because much of it is exposed in Canada. As shown in ***Figure 22-5*** on page 582, the Canadian Shield is also exposed in the northern parts of Minnesota, Wisconsin, and Michigan; in the Adirondack Mountains of New York; and over a large part of Greenland.

Figure 22-5 The oldest rocks in North America are found in the Precambrian shield rocks in Canada. They were the first-formed rocks of the North American continent.



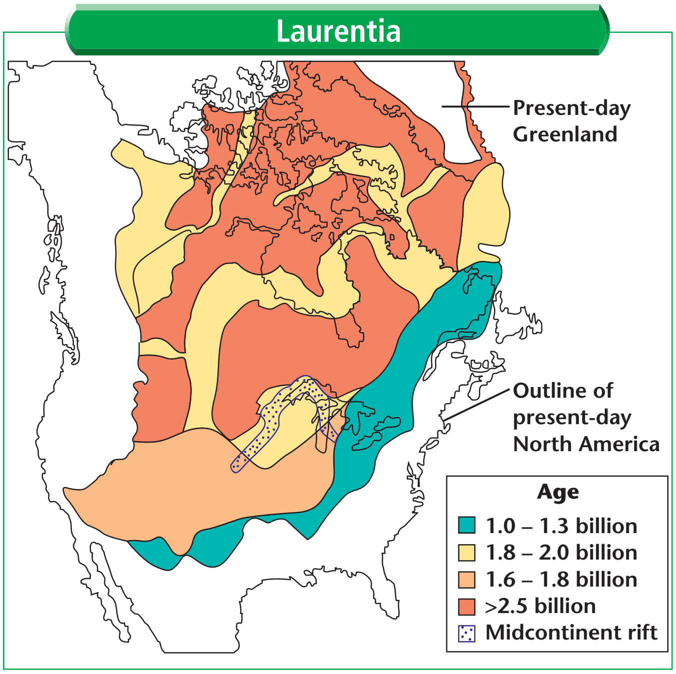


Figure 22-6 From the beginning of its formation, the continent of Laurentia resembled the familiar shape of present-day North America.

GROWTH OF CONTINENTS

Early during the Proterozoic, small pieces of continental crust, called **microcontinents,** that formed during the Archean began to collide as a result of plate tectonics. The impact of the collisions jammed the microcontinents together, and they became larger continents. At each of these collision sites, the Archean microcontinents were sutured or fused together at orogens. These orogens are belts of rocks that were deformed by the immense energy of the colliding continents. The resulting mountain ranges have been deeply eroded since that time. By about 1.8 billion years ago, the core of modern-day North America had been assembled; it formed the ancient continent known as **Laurentia,** as shown in ***Figure 22-6.*** You will explore the technique of interpreting continental growth in the *Mapping GeoLab* at the end of this chapter.

◀ CONTENTS ▶

Near the end of the Early Proterozoic, between 1.8 and 1.6 billion years ago, volcanic island arcs collided with the southern margin of Laurentia. This added more than 1000 km of continental crust to southern Laurentia. The final phase of Proterozoic growth of Laurentia is called the Grenville Orogeny. Recall that an orogeny is a mountain-building event. The Grenville Orogeny occurred between 1.2 billion and 900 million years ago and added a considerable amount of continental crust to the southern and eastern margins of Laurentia. Also by the end of the Proterozoic, nearly 75 percent of present-day North America had formed. The remaining 25 percent, as you will learn in Chapter 24, was added to the eastern and western margins of the North American craton during the Phanerozoic.

By the end of the Proterozoic, all of the major masses of continental lithosphere had formed on Earth. The lithospheric plates were moving around, periodically colliding with each other and suturing together. By the end of the Proterozoic, so many of these collisions had occurred that Rodinia, the first supercontinent, had formed. It was positioned so that the equator ran through Laurentia, as shown in ***Figure 22-7.*** Rodinia began to break apart at the end of the Proterozoic and continued to do so during the Early Phanerozoic. During this time, Earth also acquired an atmosphere and oceans. You will learn how they formed in the next section.

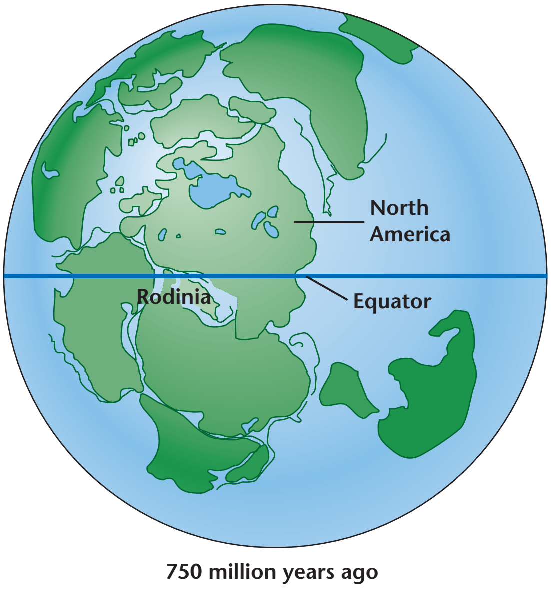


Figure 22-7 Rodinia was the first supercontinent to form on Earth's surface. Similar rock types in eastern North America and western Africa are evidence of its existence.

SECTION ASSESSMENT

1. Describe the origin of Earth's crust.
2. How did the Archean and Proterozoic continents form?
3. How does a planet become internally zoned?
4. **Thinking Critically** The oceans are underlain by basaltic crust, and the continents are underlain by granitic crust. What would Earth be like if all of its crust were made of the same material?

SKILL REVIEW

5. **Sequencing** Suppose that you are a reporter about to witness the formation of a large continent. In your science journal, write your step-by-step eyewitness account of the event. For more help, refer to the *Skill Handbook.*

SECTION 22.3 Formation of the Atmosphere and Oceans

OBJECTIVES

- **Describe** *the formation of Earth's atmosphere and oceans.*
- **Identify** *the origin of oxygen in the atmosphere.*
- **Explain** *the evidence that oxygen existed in the atmosphere during the Proterozoic.*

VOCABULARY

cyanobacteria
stromatolite
banded iron formation
red bed

If you could travel back in time to the Early Precambrian, what would you take with you? Probably the most important thing that you could take for your survival would be a supply of oxygen! This is because Earth's early atmosphere was nothing like what it is today. The oxygen that early forms of algae produced through the process of photosynthesis affected the development of life on Earth in two very important ways. First, it changed the composition of the atmosphere and thus made life possible for oxygen-breathing animals. Second, it produced the ozone layer that filters ultraviolet (UV) radiation. Scientists refer to these types of processes, which modify a system, as feedback.

THE PRECAMBRIAN ATMOSPHERE

Hydrogen and helium probably dominated Earth's earliest atmosphere. However, because of their small masses, these gases could not remain near Earth for long. Earth's gravity is not strong enough to keep hydrogen and helium from escaping to space. However, gases that have greater masses, such as carbon dioxide and nitrogen, cannot escape Earth's gravity. This is why Earth's atmosphere is rich in carbon dioxide and nitrogen today.

There was considerable volcanic activity during the Early Precambrian. In Chapter 18, you learned that lava is not the only substance that erupts from volcanoes. Tremendous amounts of gases are also vented during volcanic eruptions in a process called outgassing, shown in ***Figure 22-8.*** The most abundant gases vented from volcanoes are water vapor (H_2O), carbon dioxide (CO_2), nitrogen (N_2), and carbon monoxide (CO). Many geologists hypothesize that outgassing formed Earth's early atmosphere. Thus, the early atmosphere must have contained large concentrations of water vapor, carbon dioxide, and nitrogen. In addition, the early atmosphere most likely contained methane (CH_4) and ammonia (NH_3), both of which may have formed as a result of chemical reactions among the volcanic gases. The argon (Ar) that is present in today's atmosphere began to accumulate during the Early Precambrian. It forms when the radioactive isotope potassium-40 (K-40) decays to argon-40 (Ar-40). Through this reaction, the amount of argon has increased in the atmosphere at about the same rate that K-40 decays.

Figure 22-8 Steam and gas from Poas Volcano in Poas National Park, Costa Rica, rise high above the volcano's summit.

OXYGEN IN THE ATMOSPHERE

No wonder life as we know it today did not exist during the Precambrian—there was no oxygen in the atmosphere to breathe! Volcanoes do not commonly give off oxygen; so, scientists do not think that the oxygen in Earth's atmosphere came from volcanoes. Where did the oxygen come from? The oldest known fossils which can help answer this question, are preserved in rocks that are about 3.5 billion years old. These fossils are the remains of tiny, threadlike chlorophyll bearing filaments of **cyanobacteria.** Such fossils are contained in 3.46-billion-year-old rocks called the Warrawoona Group, from western Australia. ***Figure 22-9*** compares fossilized cyanobacteria and modern cyanobacteria. Like their present-day counterparts, ancient cyanobacteria used photosynthesis to produce the nutrients they needed to survive. In the process of photosynthesis, solar energy is used to convert carbon dioxide and water into sugar. Oxygen is given off as a waste product.

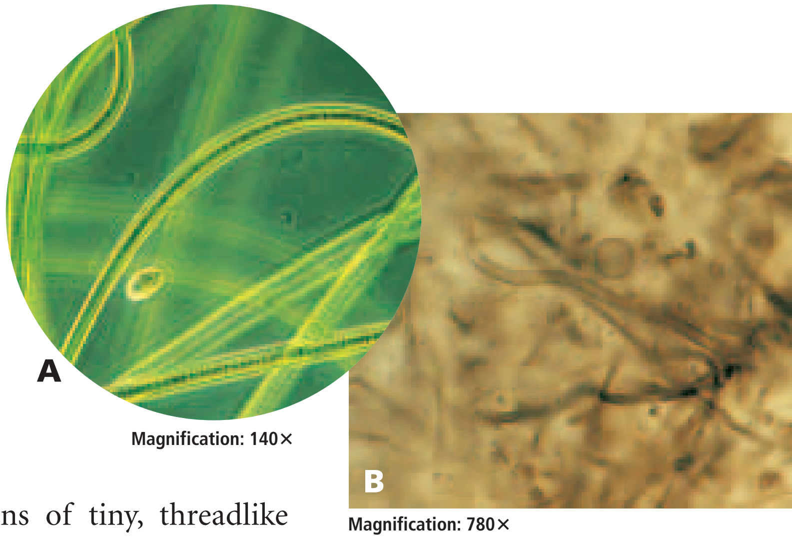


Figure 22-9 The cells of modern cyanobacteria are often identical in shape and size to some fossil cyanobacteria that are billions of years old. This micrograph is of the filamentous cyanobacterium, *Oscillatoria* **(A).** This fossil cyanobacterium is from the Gunflint Chert, Ontario, Canada **(B).**

Oxygen Producers Could microscopic cyanobacteria have produced enough oxygen to change the composition of Earth's early atmosphere? The abundance of cyanobacteria increased throughout the Archean until they became truly abundant during the Proterozoic. Large mats and mounds of billions of cyanobacteria, called **stromatolites,** dominated the shallow oceans of the Proterozoic. Modern stromatolites, such as those found in Australia today and shown in ***Figure 22-10,*** do not differ much from their ancient counterparts. The oldest stromatolites are preserved in 3.4-billion-year-old rocks from the Swaziland Supergroup of South Africa.

ENVIRONMENTAL CONNECTION

Evidence in the Rocks One way to test the hypothesis that there was oxygen in Earth's early atmosphere is to look for oxidized iron, or iron oxides, in Archean and Proterozoic rocks. The iron in rocks

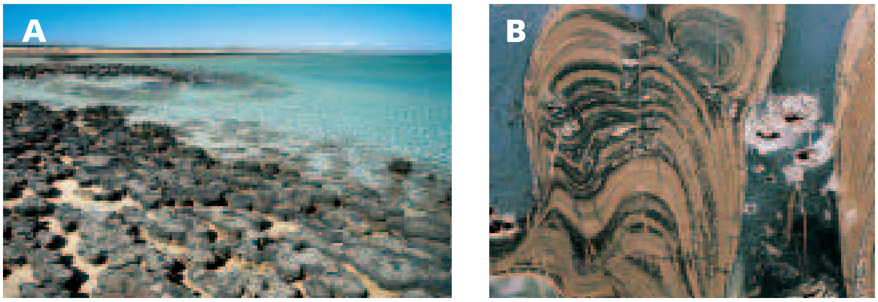


Figure 22-10 Colonies of cyanobacteria form modern stromatolites in Hamelin Pool, Australia. Millions of individual cyanobacteria cells make up each colony **(A).** Fossil stromatolites are nearly identical to modern stromatolites. They provide evidence for the existence of a shallow sea in the areas where they are found **(B).**

CONTENTS

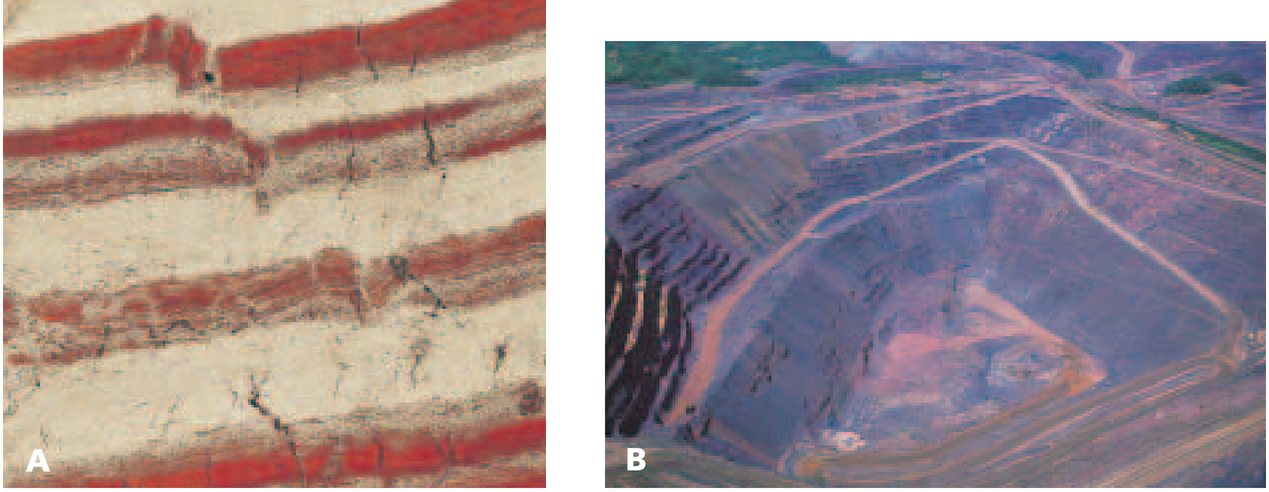


Figure 22-11 The beautiful rocks of the Banded Iron Formation give testimony to the oxygenated atmosphere of the Precambrian. This sample is from the 2.1 billion year old Negaunee Formation, Michigan **(A).** The Empire Iron Mine in Ishpeming, Michigan is well known for its iron production **(B).**

reacts with free oxygen in the atmosphere to form iron oxides. Iron oxides are identified by their red color and provide undeniable evidence of free oxygen in the atmosphere. Some metamorphosed Archean sedimentary rocks contain mineral grains that would have been oxidized if there had been oxygen in the atmosphere. However, these minerals were not oxidized, which indicates that there was little or no free oxygen in the atmosphere throughout most of the Archean. However, there is evidence that near the end of the Archean and by the beginning of the Proterozoic, photosynthesizing stromatolites in shallow marine water increased oxygen levels in localized areas. These locally high concentrations of oxygen in otherwise oxygen-poor, shallow, ocean water allowed unique deposits to form. These deposits, which consist of alternating bands of chert and iron oxides are called **banded iron formations.** Today, these formations are mined as a source of iron, as shown in ***Figure 22-11.*** The *Problem-Solving Lab* should give you an example

Problem-Solving Lab

Profits from the Precambrian

Calculate mining costs Precambrian rocks contain many important mineral deposits, such as uranium, which is used in nuclear reactors. In a uranium oxide (U_3O_8) ore deposit in southern Ontario, the ore-containing rocks are an average of 3 m thick over an area that is 750 m long and 1500 m wide. Geochemical analysis of the deposit indicates that there are, on average, 0.9 kg of uranium oxide per metric ton of rock. Additionally, 0.3 cubic meters of the uranium-bearing rock weighs one ton (2000 lbs).

Analysis

1. How many pounds of ore does this new deposit contain?
2. It will cost $45 per cubic yard and 10 years to mine and extract the ore from the deposit. How much will this cost?

Thinking Critically

3. The current market price is $9.25 per pound of uranium oxide. Based on your answer to question 2, can the ore be mined for a profit?

CONTENTS

of mining for a profit. Many sedimentary rocks that are younger than 1.8 billion years are rusty red in color and are called **red beds.** The presence of red beds in rocks that are Proterozoic and younger is strong evidence that the atmosphere by this time contained free oxygen. You will observe oxidation when you complete the *MiniLab* on this page.

IMPORTANCE OF OXYGEN

Oxygen is important not only because most animals require it for respiration, but also because it provides protection against UV radiation from the Sun. If you have ever read a label on sunscreen, you know that UV radiation can be harmful. Today, only a small fraction of the UV radiation that the Sun radiates toward Earth reaches its surface. This is because Earth is naturally protected from this radiation by ozone that is present in the lower part of Earth's upper atmosphere. An ozone molecule (O_3) consists of three oxygen atoms bonded together. Ozone forms when high-energy UV radiation splits oxygen gas molecules (O_2) and the single oxygen atoms combine with other oxygen molecules. This ozone layer filters out much of the Sun's UV radiation. Oxygen in Earth's atmosphere that was produced mainly through photosynthesis also contributes to the ozone layer. Early life, mainly the cyanobacteria that made up stromatolites, modified the atmosphere by generating large amounts of oxygen. Some of this oxygen also formed ozone, which, in turn, filtered out UV radiation so that other forms of life could survive on Earth's surface. It appears that nearly all the oxygen that we breathe today, and the oxygen that all animals have breathed in the geologic past, was released into the atmosphere by photosynthesis.

MiniLab

Why are red beds red?

Model the formation of red beds with iron, oxygen, and water.

Procedure

CAUTION: ***Steel wool can be sharp. Wear gloves in the lab.***

1. Place 40 mL of white sand in a 150-mL beaker.
2. Add water so that the total volume is 120 mL.
3. Add 15 mL of bleach.
4. Place a piece of steel wool about the size of your thumbnail, in the beaker. Cover the beaker with a petri dish and allow it to stand in a quiet place for one day.
5. Remove the steel wool and stir the contents of the beaker. Allow the mixture to settle for five minutes after stirring.
6. Slowly pour off the water so that the iron-oxide sediment is left behind.
7. Stir the mixture again, then spoon some of the sand onto a watch glass and allow it to dry.

Analyze and Conclude

1. In your science journal, describe how the color of the sediment changed.
2. Where does the iron in the experiment come from?
3. Where in nature does the red in rocks come from?
4. What do you think is the function of the bleach?

FORMATION OF THE OCEANS

Oceans are thought to have originated largely from the same process of outgassing that formed the atmosphere. A major component of the gas was water vapor. As the early atmosphere and the surface of Earth cooled, the water vapor condensed to form liquid water. You have probably observed the result of condensation on the sides of a cold glass of water. During the Archean, the entire atmosphere was rich with water vapor. When it began to cool, the result was a tremendous amount of rain, which slowly filled the low-lying, basalt-floored basins, thus forming the oceans. Rainwater dissolved the soluble minerals exposed at Earth's surface and just as they do today, rivers, runoff and groundwater transported these minerals to the oceans. These dissolved minerals made the oceans of the Precambrian salty just as they make the oceans salty today.

Another source of water may have played an important role in adding water vapor to Earth's atmosphere. A recent but controversial hypothesis suggests that some of Earth's water may have come from outer space! Earth is constantly bombarded with very small comets made of frozen gas and water. Based on the current rate of microcomet bombardment, some scientists calculate that a significant portion of Earth's surface waters might be extraterrestrial in origin.

Oxygen Causes Change The Precambrian began with an oxygen-free atmosphere and simple life-forms. Cyanobacteria then evolved, and their oxygen contribution caused the atmosphere to become filled with oxygen. This oxygen not only enabled new life-forms to evolve, but it also protected Earth's surface from the Sun's UV rays. Oceans formed from abundant water vapor in the atmosphere and possibly from outer space. Earth was then a hospitable place for new life-forms to inhabit.

Earth Science Online

Topic: Ozone Levels
To find out more about ozone in Earth's atmosphere, visit the Earth Science Web Site at earthgeu.com

Activity: Research the monthly concentrations of atmospheric ozone for a given year in the Antarctic or Arctic. Graph the ozone concentrations for each month in the year.

SECTION ASSESSMENT

1. What are banded iron formations?
2. Describe the origin of the oxygen in the atmosphere.
3. Explain the relationship between red beds and oxygen in the atmosphere.
4. **Thinking Critically** If cyanobacteria had not produced as much oxygen as they did, how might life on Earth be different from how it is today?

SKILL REVIEW

5. **Comparing and Contrasting** Compare and contrast the formation of the atmosphere and the formation of the oceans. For more help, refer to the *Skill Handbook*.

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CONTENTS

SECTION 22.4 Early Life on Earth

Of all the questions that humans have ever asked, none fascinates us more than those about the origin of life. "Where did life come from?" is a question that has been explored from many different perspectives. Today, we know that life comes from other life through reproduction. But where did the first life come from? What does science tell us about the origin of life?

ORIGIN OF LIFE ON EARTH

You have learned that Earth is about 4.6 billion years old and that fossil evidence indicates that life existed on Earth about 3.5 billion years ago. Thus, life must have begun during Earth's first 1.1 billion years. Earth probably could not have supported life until about 3.9 billion years ago because meteorites were constantly striking its surface. If life did begin during this time of meteorite bombardment, it is unlikely that it could have survived for long. This places the origin of life somewhere between 3.9 and 3.5 billion years ago.

Experimental Evidence During the first half of the twentieth century, scientists hypothesized that the early atmosphere contained carbon dioxide, nitrogen, water vapor, methane, and ammonia, but no free oxygen. They also theorized that numerous storms produced lightning and that the surface of Earth was relatively warm. Molecular biologists in the 1920s also suggested that an atmosphere containing abundant ammonia and methane but lacking free oxygen would be an ideal setting for the "primordial soup" in which life may have begun. A young graduate student named Stanley Miller, who was working with his graduate advisor, Nobel prize-winning chemist Harold Urey in 1953, was aware of these hypotheses.

Miller and Urey decided to create their own primordial soup. They set up an apparatus, like that shown in ***Figure 22-12,*** that contained a chamber filled with hydrogen, methane, and ammonia to simulate the early atmosphere. This atmospheric chamber was connected to a lower chamber that was designed to catch any particles that condensed in the atmospheric chamber.

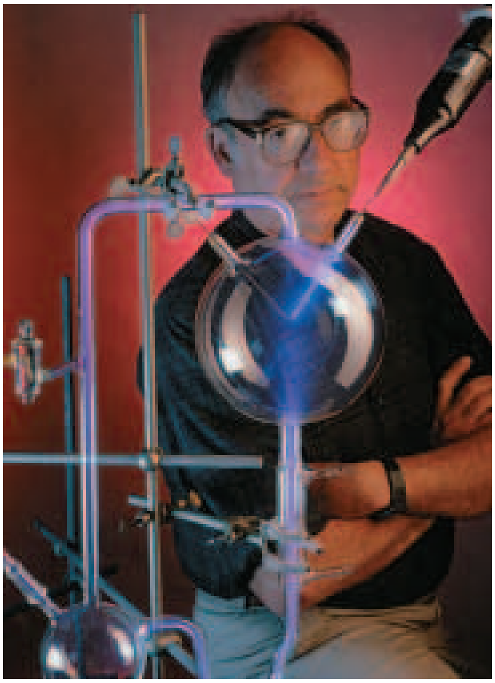


Figure 22-12 Dr. Stanley Miller is shown with a replica of the apparatus used to model Earth's early atmosphere in the Miller-Urey experiment.

OBJECTIVES

- **Describe** *the experimental evidence of how life developed on Earth.*
- **Distinguish** *between prokaryotes and eukaryotes.*
- **Identify** *when the first multicellular animals appeared in geologic time.*

VOCABULARY

amino acids
hydrothermal vent
prokaryote
eukaryote
Varangian Glaciation
Ediacara fauna

Using Math

Using Numbers Some scientists argue that the influx of small comets into the atmosphere could add about one inch of water to Earth's surface every 20 000 years. The average depth of Earth's oceans is 3795 meters. If this influx has been constant for the past 4.6 billion years, what should be the minimum average depth of the oceans? How can you account for the difference in water volume?

Miller and Urey added sparks from tungsten electrodes to simulate lightning in the atmosphere. Only one week after the start of the experiment, the lower chamber contained a murky, brown liquid—the primordial soup! The "soup" that formed in this experiment contained organic molecules such as formaldehyde (H_2CO), and four different amino acids. **Amino acids** are the building blocks of proteins, and proteins are the basic substances from which life is built.

Continued experiments showed that 13 of the 20 amino acids known to occur in living things could be formed using experimental set-ups similar to the Miller-Urey method. Further experiments demonstrated that heat, cyanide, and certain clay minerals could cause amino acids to join together in chains like proteins. Proteins provide structure for tissues and organs, and are important agents in cell metabolism. Thus, the discovery that amino acids could be formed in this way was amazing. What Miller and Urey demonstrated, is that however life first formed, the basic building blocks of life were most likely present on Earth during the Archean.

The Role of RNA Not much is known about the next step required for the development of life. It is one thing for the proteins that are required for life to exist on the Archean Earth, but quite another for organic life to actually exist. One essential characteristic of life is the ability to reproduce. The nucleic acids RNA and DNA, shown in ***Figure 22-13,*** are the basic requirements for reproduction.

In modern organisms, DNA carries the instructions necessary for cells in all living things to function. Both RNA and DNA need enzymes to replicate and at least one of them is necessary for the synthesis of enzymes. Recent experiments have shown that types of RNA molecules, called ribozymes, can act as an enzyme. These RNA ribozymes can, therefore, replicate without

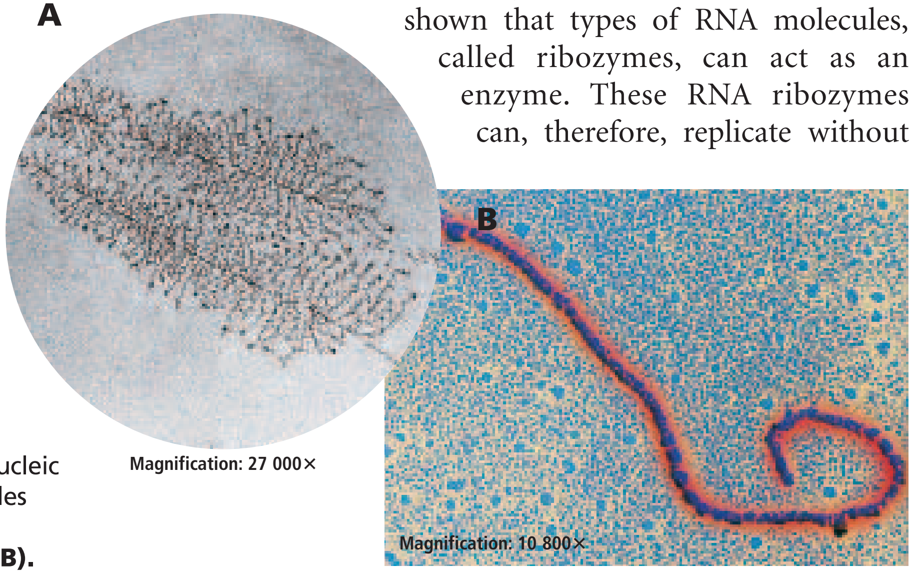


Figure 22-13 These are ribonucleic acid (RNA) polymerase molecules **(A).** This is a single strand of deoxyribonucleic acid (DNA) **(B).**

the aid of enzymes. This suggests that RNA molecules may have been the first replicating molecules on Earth. An RNA-based world may have been intermediate between an inorganic world and the DNA-based organic world that followed. The remaining mystery is figuring out how the first RNA molecule formed because RNA cannot be easily synthesized under the conditions that likely existed at the surface of the Archean Earth.

Figure 22-14 These sulfur encrusted, underwater geothermal vents bubble as volcanic gasses escape. They are located off Dobu Island, Papua, New Guinea.

Hydrothermal Vents and the Beginnings of Life

The Urey-Miller model places the origin of life in shallow surface waters. But, life on Earth may have originated deep in the ocean, near active volcanic seafloor rifts. Ocean water seeps through the cracks in the ocean floor and is heated by the magma at the rifts. This heated water rises and is expelled from the ocean floor at hot-water vents called **hydrothermal vents,** as shown in ***Figure 22-14.*** All of the energy and nutrients necessary for the origin of life are present at these deep-sea hydrothermal vents. In fact, amino acids have been found there. This has led some scientists to hypothesize that during the Archaean, near hydrothermal vents, amino acids joined together on the surfaces of clay minerals to form proteins. Other scientists contend that this is not possible in such an environment. It is important to note that life is not being synthesized at these vents today, only because amino acids are quickly devoured by organisms that live near the vents. But in the Archaean, no organisms existed to eat the amino acids being produced.

Earth Science Online

Update For an on-line update on recent discoveries of life-forms at hydrothermal vents, visit the Earth Science Web Site at earthgeu.com

PROTEROZOIC LIFE

At the beginning of the Proterozoic, life-forms were still quite simple. The only evidence of life-forms that existed before the Proterozoic is the fossilized remains of unicellular organisms called prokaryotes. A **prokaryote** is an organism that is composed of a single cell, which does not contain a nucleus and is the simplest kind of cell. All prokaryotes, including the cyanobacteria that make up stromatolites, belong to Kingdom Monera.

A **eukaryote** is an organism that is composed of cells that contain a nucleus. One way to determine whether an organism is a prokaryote or a eukaryote is by its size. As a general rule, eukaryotes are larger than prokaryotes. This general observation is useful in determining whether a fossil was a prokaryote or a eukaryote because it is rare for a fossil to be preserved in enough detail to determine whether its cells had nuclei. The oldest known fossil eukaryotes occur in a 2.1-billion-year-old banded iron formation in northern Michigan.

There is growing evidence that a widespread glaciation, which occurred between 800 and 700 million years ago, played a critical role in the extinction of many members of a group of possible eukaryotes, the acritarchs. This glaciation event, called the **Varangian Glaciation,** was so widespread that some geologists liken Earth at that time to a giant snowball. Evidence from ancient glacial deposits suggests that glacial ice advanced nearly to the equator. Shortly after the ice retreated toward the poles, 700 million years ago, multicellular organisms first appeared in the fossil record.

EDIACARA FOSSILS

In 1947, the impressions of soft-bodied organisms were discovered in Late Proterozoic rocks in the Ediacara Hills of southern Australia. These fossils are collectively referred to as the **Ediacara fauna.** ***Figure 22-15*** shows an interpretation of the Ediacaran world. There has been much debate in the scientific community about the precise nature of these remarkable fossils. It is generally agreed that these fossils represent animals that were composed of different types of eukaryotic cells. Scientists are unsure, however, whether the Ediacara fauna are relatives of modern animal groups or whether they were completely different types of organisms.

The discovery of the Ediacara fauna at first seemed to solve one of the great mysteries in geology—why were there no fossils of the ancestors of the complex and diverse organisms that existed during the Cambrian Period. The Ediacara fauna seem to provide fossil

Figure 22-15 The Ediacara fauna contained a wide variety of organisms. It included floating organisms as well as those which were attached to the sea floor and possibly some organisms that were actively mobile.

CONTENTS

evidence of an ancestral stock of complex Proterozoic animals. Indeed, many of the Ediacara fossils look quite similar in overall body shape to jellyfish, sea pens, segmented worms, arthropods, and echinoderms—just the kind of ancestral stock that geologists had been hoping to find.

Some scientists, however, hypothesize that the Ediacara fauna does not represent an ancestral stock of any modern group. These scientists consider the similarity in shape to animals in other phyla coincidental and that the Ediacara fauna represents a virtual dead end. None of the Ediacara fossils shows any evidence of a mouth, anus, or gut, and there is little evidence these animals could move. Arthropods, for example, leave tracks and trails when they move across the seafloor, but there is no evidence of such trace fossils associated with the Ediacara fossils. This has led some geologists to hypothesize that the Ediacara organisms were relatively immobile and that they fed by passively absorbing nutrients from seawater. These geologists point out that in the absence of any animal predators, there would have been no disadvantage to being a defenseless creature basking in the warm seawater and absorbing nutrients.

In recent years, geologists have found Ediacara fossils in all parts of the world. This suggests that these organisms were widely distributed throughout the shallow oceans of the Late Proterozoic. They seemed to have flourished between 670 and 570 million years ago. Then, in an apparent mass extinction, they disappeared before organisms that are likely related to modern phyla took over the oceans of the world.

Earth Science Online

Topic: Ediacara Fossils
To find out more about the Ediacara fauna, visit the Earth Science Web Site at earthgeu.com

Activity: Research the locations of Ediacara fossils. List some locations in your state where they may be found.

SECTION ASSESSMENT

1. Explain why the Miller-Urey experiment was important.
2. What kind of organisms do the earliest fossils represent?
3. What is the significance of the Varangian Glaciation?
4. Discuss the differences between prokaryotes and eukaryotes.
5. **Thinking Critically** Describe how early life might have changed if some of the Ediacaran fauna had been able to move and if predators had been present in their environment.

SKILL REVIEW

6. **Concept Mapping** Rearrange the following events into an events chain that describes the results of the Miller-Urey experiment. For more help, refer to the *Skill Handbook.*

chamber with cyanide, formaldehyde, and amino acids

heat and clay minerals added

chains of amino acids

simulated atmospheric lightning

chamber with hydrogen, methane, and ammonia

Mapping GeoLab

Mapping Continental Growth

Plotting the distribution of the ages of rocks onto a map helps geologists to reconstruct the history of continental accretion. During the Precambrian, microcontinents and island arcs collided to form what would become the modern continents.

Preparation

Problem

How can the distribution of the ages of rocks plotted on a map be used to interpret the growth of a continent?

Materials

paper
pencil
colored pencils
metric ruler

Procedure

1. Your teacher will set up locations with a rock sample at each location.
2. Make an outline map of your classroom similar to the map on the next page, using the scale 1 cm = 100 km.
3. Visit each location where a rock sample has been set out. Plot each location and record the age of each rock on the map.
4. After you have recorded all the locations, use a pencil to draw lines on the map that separate rocks of different ages. Be careful not to simply connect the dots.
5. Use a different colored pencil to shade in the areas on the map that contain rocks of the same age. These are your geologic age provinces.
6. Make a key for your map by drawing a small rectangle for each different geologic age province. Name the oldest province “Province A,” the next oldest “Province B,” and so on for all provinces.

Analyze

1. Use the ruler to measure the east-to-west width of Province A. Convert the map scale to ground distance by using the scale 1 cm = 1 km.
2. Why do some of your classmates have different answers? Who is right?
3. Where is the oldest province located relative to all the other provinces?

CONTENTS

Conclude & Apply

1. Based on the distribution of the geologic age provinces, describe the sequence of collisional events that formed the craton represented by your map.
2. According to your map, where would you find metamorphic rocks? What type of metamorphism would have occurred?
3. If your map represents an area composed of Precambrian-aged rocks, would the mountains that formed from collisions still be high and rugged? Explain.
4. Compare the distribution of age provinces on your map with ***Figure 22-6.*** What are the similarities?
5. Based on what you learned in this activity, describe the formation of the North American Craton.

Science in the News

Martians or Meteorites?

Some of the rarest meteorites found on Earth come from Mars. One of these, ALH 84001, caused quite a stir in the scientific community when some scientists claimed to have found fossils in it. Many fossils, such as dinosaur bones and impressions of fern fronds, are obviously the remains of once-living things. Less-obvious evidence of life are the microscopic spheres and rods found in ALH 84001.

ALH 84001 is a potato-shaped rock that weighs 1.9 kg. It was found in the Allan Hills Ice Field, Antarctica, in 1984. The meteorite formed about 4.5 billion years ago, when Mars did. The "fossils," shown above, are found in cracks in the rock and are more than one million times smaller than a typical bacterial cell and are 1/100th the diameter of human hair.

Mystery on Earth

A similar situation took place in the 1860s, when features that were assumed to be fossils were found in limestone in Canada. The features were millimeter-thick bands of dark minerals separated into blobs and layers by light minerals. This "fossil" was named *Eozoon canadense,* the "dawn animal of Canada." This discovery created quite a stir, because *Eozoon canadense* came from the Precambrian, in some of the oldest rocks in North America. Scientists hailed it as "the greatest discovery in geology for half a century."

Not everyone was so taken with *Eozoon canadense,* however. Within months, the first doubts that it was truly a fossil were published.

Gradually, the weight of evidence turned against the possibility that *Eozoon canadense* had an organic origin. There were three main lines of evidence. First, it was found that the original layering of the rock cut across the "fossil," rather than being parallel to it as it should if the animal had actually lived on the bottom of an ancient sea. Second, mapping showed that *Eozoon canadense* occurred around igneous intrusions. The heat from the cooling magma, it seemed, had created the appearance of fossils. Finally, nearly identical features were found in limestone blocks ejected by a volcano, again showing that heat, not life, had formed these features.

What are they?

What about the so-called fossils in the Martian meteorite? Many scientists now do not think that they are fossils. One reason is their size. Their volume is 2000 times smaller than the smallest known living things—parasitic organisms that live in other cells. Many scientists think that something so tiny probably could not contain enough genetic information to direct life processes. The search goes on for extraterrestrial life.

Activity

What other kinds of geologic features can be mistaken for fossils? Visit the Earth Science Web Site at earthgeu.com or a library to find more examples of pseudofossils. Choose one and, in your science journal, describe how it forms.

CHAPTER 22
Study Guide

Summary

SECTION 22.1

The Early Earth

Main Ideas

- Geologists have used radiometric dating to show that Earth must be at least 4.2 billion years old.
- Because the solar system formed all at the same time, Moon rocks and meteorites that are approximately 4.6 billion years old suggest that Earth is 4.6 billion years old too.
- The early Earth was a very hot place because of abundant radioactive isotopes, bombardment by meteorites, and gravitational contraction.

Vocabulary

asteroid (p. 578)
meteorite (p. 579)
zircon (p. 578)

SECTION 22.2

Formation of the Crust and Continents

Main Ideas

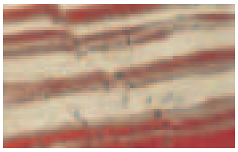
- Earth's early crust formed by the cooling of the uppermost mantle. This early crust weathered and formed sediments.
- Sediment-covered slabs of this early crust were subducted and generated magmas that contained granitic minerals.
- During the Archean, microcontinents collided with one another throughout the Proterozoic and formed the cores of the continents. By the end of the Proterozoic, the first supercontinent, Rodinia, had formed.

Vocabulary

Canadian Shield (p. 581)
differentiation (p. 580)
Laurentia (p. 582)
microcontinents (p. 582)
Precambrian shield (p. 581)

SECTION 22.3

Formation of the Atmosphere and Oceans



Main Ideas

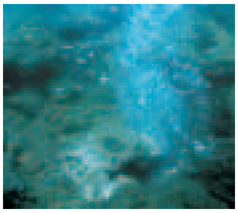
- Earth's early atmosphere and the oceans formed mainly by the process of outgassing.
- Nearly all of the oxygen in the atmosphere is a result of photosynthesis.
- Certain minerals oxidize, or rust, in the presence of free oxygen. Proterozoic red beds are sedimentary rock deposits that contain oxidized iron. They are the evidence that there was free oxygen in the atmosphere during the Proterozoic.

Vocabulary

banded iron formation (p. 586)
cyanobacteria (p. 585)
red bed (p. 587)
stromatolite (p. 585)

SECTION 22.4

Early Life on Earth



Main Ideas

- All the ingredients were present on the early Earth to form proteins, the building blocks of life. Amino acids, the molecules that make up proteins, were present on the surface of the early Earth.
- Prokaryotic cells are generallly small and contain no nuclei. Eukaryotic cells contain nuclei and are generally larger and more complex than prokaryotic cells.
- The first evidence of multicellular animals are fossils of 2.1 billion year old eukaryotic algae.

Vocabulary

amino acids (p. 590)
Ediacara fauna (p. 592)
eukaryote (p. 591)
hydrothermal vent (p. 591)
prokaryote (p. 591)
Varangian Glaciation (p. 592)

earthgeu.com/vocabulary_puzzlemaker

CONTENTS

CHAPTER 22
Assessment

Understanding Main Ideas

1. What is the commonly accepted age of Earth?
a. 4.6 million years
b. 46 million years
c. 4.6 billion years
d. 46 billion years

2. Which of the following was not a source of heat for the early Earth?
a. meteor bombardment
b. gravitational contraction
c. radioactivity
d. hydrothermal energy

3. What are small asteroids called?
a. comets
b. meteoroids
c. cratons
d. microcontinents

4. What is the process by which a planet becomes internally zoned when heavy materials sink toward its center and lighter materials accumulate near its surface?
a. photosynthesis
b. dewatering
c. accretion
d. differentiation

5. Where is most of the North American Precambrian shield exposed at the surface?
a. Canada
b. Minnesota
c. Wisconsin
d. Michigan

6. What mineral can be used to radiometrically date Earth's age?
a. zircon
b. quartz
c. hematite
d. feldspar

7. Refer to ***Figure 22-6.*** What name is given to the core of the modern-day North American continent that formed in the Proterozoic?
a. Baltica
b. Yavapai
c. Grenville
d. Laurentia

8. What is the name of the first supercontinent, which formed near the end of the Proterozoic?
a. Laurentia
b. Grenville
c. Rodinia
d. Pangaea

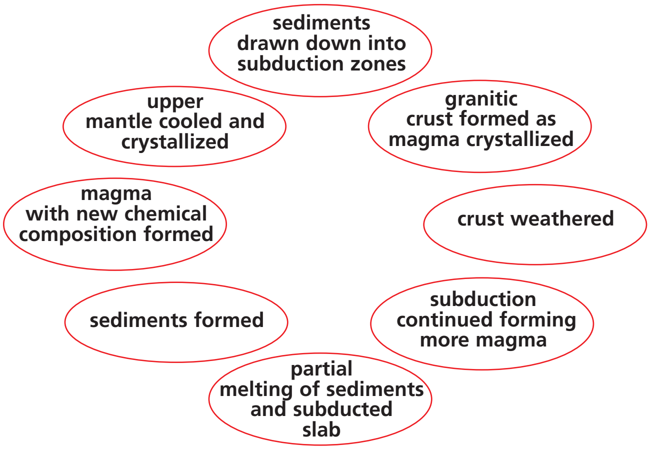
9. What volcanic process most likely formed Earth's atmosphere?
a. differentiation
b. outgassing
c. crystallization
d. photosynthesis

10. Why is ozone a necessary component of Earth's atmosphere?

11. Why is Earth's atmosphere rich in nitrogen (N) and carbon dioxide (CO_2) today?

Applying Main Ideas

12. Rearrange the following phrases to create a cycle map that describes the formation of Earth's early crust.



Test-Taking Tip

KEEP A CLEAR MIND When you take a test, each new question should be a clean slate. Once you have read a question, considered the answers, and chosen one, put that question behind you. Don't let one or two troublesome questions distract you while you're working on other questions.

CONTENTS

13. Explain how geologists have determined the age of Earth.
14. Discuss the relationships among the formation of the continents, the atmosphere, and the oceans.
15. What is the geologic significance of banded iron formations?
16. What geologic evidence suggests that free oxygen was accumulating in Earth's atmosphere during the Proterozoic?
17. What is the difference between prokaryotes and eukaryotes? Which appeared first in the fossil record?
18. What characteristics of continental crust allow it to "float" higher on the mantle than oceanic crust?
19. Why are orogens deformed?
20. What is the significance of the Ediacara fauna?
21. Discuss the evidence that suggests that most members of the Ediacara fauna were immobile.

Thinking Critically

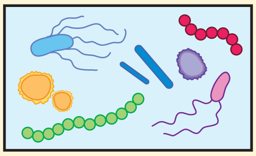
22. Explain how the production of oxygen through photosynthesis by cyanobacteria affected the composition of the atmosphere and the development of other organisms.
23. A rock sample from Mars is reported to contain fossil evidence of life. What kind of fossil would you expect it to be? Explain your answer.
24. Where in North America would you look if you wanted to find evidence of Archean life? Explain your answer.
25. When making a map of geologic age provinces, as you did in the *Mapping GeoLab* in this chapter, why did you draw the lines between the data points instead of connecting them?
26. How might Earth's surface be different if water vapor had not been a product of outgassing?

Standardized Test Practice

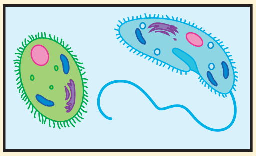
1. Which of the following is NOT a likely source of the Precambrian Earth's heat?
   - **a.** radioactivity
   - **b.** asteroid impact
   - **c.** increased solar activity
   - **d.** gravitational contraction

2. What does orogeny refer to?
   - **a.** the drifting of microcontinents
   - **b.** the building of mountain ranges
   - **c.** the formation of volcanic islands
   - **d.** the breaking apart of the supercontinents

3. Which of the following was NOT a source of information about the early presence of oxygen on Earth?
   - **a.** red beds
   - **b.** banded iron formations
   - **c.** stromatolites
   - **d.** meteorites



Group A



Group B

INTERPRETING SCIENTIFIC ILLUSTRATIONS
Use the diagrams to answer questions 4 and 5.

4. How do members of Group A differ from members of Group B?
   - **a.** They belong to the Kingdom Plantae.
   - **b.** They can be found in Proterozoic fossils.
   - **c.** They contain no nuclei.
   - **d.** They are all unicellular.

5. Where did members of Group B probably originate?
   - **a.** glaciers
   - **b.** hydrothermal vents
   - **c.** Australian fauna
   - **d.** oil deposits

CONTENTS