Earth History

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CHAPTER 1 Earth History

CHAPTER OUTLINE

Introduction

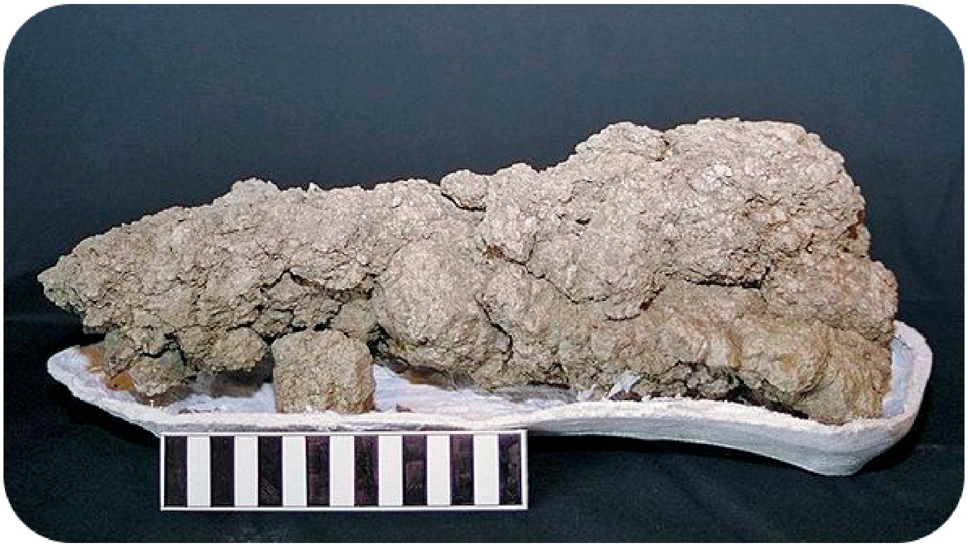
How do you apply what you've learned so far to understanding Earth history?

Something that we hope you have learned from these concepts and from your own life experience is that the laws of nature never change. They are the same today as they were billions of years ago. Water freezes at 0°C at 1 atmosphere pressure; this is always true.

Knowing that natural laws never change helps scientists understand Earth's past because it allows them to interpret clues about how things happened long ago. Geologists always use present-day processes to interpret the past. If you find a fossil of a fish in a dry terrestrial environment did the fish flop around on land? Did the rock form in water and then move? Since fish do not flop around on land today, the explanation that adheres to the philosophy that natural laws do not change is that the rock moved.

1.1 How Fossilization Creates Fossils

- Describes the conditions necessary for fossilization.



What kind of fossil is this?

As a paleontologist it would be great to find a new species of dinosaur or the best preserved specimen of a species like Tyrannosaurus rex. But lots of important information can be gained from less....um...glamorous finds. One example is this fossil coprolite from a meat-eating dinosaur. Fortunately, fossil poo doesn't stink!

Fossils were Parts of Living Organisms

It wasn't always known that fossils were parts of living organisms. In 1666, a young doctor named Nicholas Steno dissected the head of an enormous great white shark that had been caught by fisherman near Florence, Italy. Steno was struck by the resemblance of the shark's teeth to fossils found in inland mountains and hills (**Figure** 1.1).

Most people at the time did not believe that fossils were once part of living creatures. Authors in that day thought that the fossils of marine animals found in tall mountains, miles from any ocean could be explained in one of two ways:

- The shells were washed up during the Biblical flood. (This explanation could not account for the fact that fossils were not only found on mountains, but also within mountains, in rocks that had been quarried from deep below Earth's surface.)
- The fossils formed within the rocks as a result of mysterious forces.

But for Steno, the close resemblance between fossils and modern organisms was impossible to ignore. Instead of invoking supernatural forces, Steno concluded that fossils were once parts of living creatures.

How Fossils Form

A fossil is any remains or traces of an ancient organism. Fossils include **body fossils**, left behind when the soft parts have decayed away, and **trace fossils**, such as burrows, tracks, or fossilized coprolites (feces). Collections of fossils

FIGURE 1.1
Fossil Shark Tooth (left) and Modern Shark Tooth (right).

are known as fossil assemblages.

Fossilization is Rare

Becoming a fossil isn't easy. Only a tiny percentage of the organisms that have ever lived become fossils.

Why do you think only a tiny percentage of living organisms become fossils after death? Think about an antelope that dies on the African plain (**Figure** 1.2).

Most of its body is eaten by hyenas and other scavengers and the remaining flesh is devoured by insects and bacteria. Only bones are left behind. As the years go by, the bones are scattered and fragmented into small pieces, eventually turning into dust. The remaining nutrients return to the soil. This antelope will not be preserved as a fossil.

Is it more likely that a marine organism will become a fossil? When clams, oysters, and other shellfish die, the soft parts quickly decay, and the shells are scattered. In shallow water, wave action grinds them into sand-sized pieces. The shells are also attacked by worms, sponges, and other animals (**Figure** 1.3).

How about a soft bodied organism? Will a creature without hard shells or bones become a fossil? There is virtually no fossil record of soft bodied organisms such as jellyfish, worms, or slugs. Insects, which are by far the most common land animals, are only rarely found as fossils (**Figure** 1.4).

Conditions that Create Fossils

Despite these problems, there is a rich fossil record. How does an organism become fossilized?

FIGURE 1.2
Hyenas eating an antelope. Will the antelope in this photo become a fossil?

FIGURE 1.3
Fossil shell that has been attacked by a boring sponge.

Hard Parts

Usually it's only the hard parts that are fossilized. The fossil record consists almost entirely of the shells, bones, or other hard parts of animals. Mammal teeth are much more resistant than other bones, so a large portion of the mammal fossil record consists of teeth. The shells of marine creatures are common also.

Quick Burial

Quick burial is essential because most decay and fragmentation occurs at the surface. Marine animals that die near a river delta may be rapidly buried by river sediments. A storm at sea may shift sediment on the ocean floor, covering a body and helping to preserve its skeletal remains (**Figure** 1.5).

Quick burial is rare on land, so fossils of land animals and plants are less common than marine fossils. Land

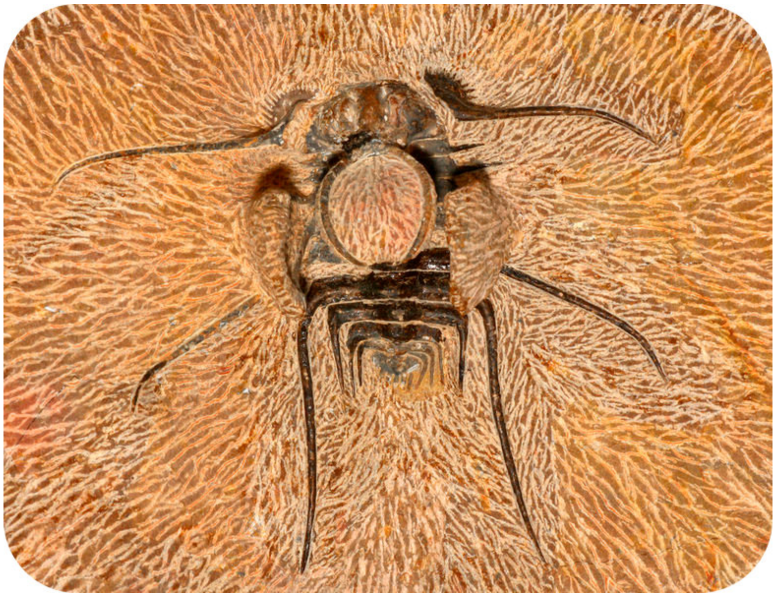


FIGURE 1.4
A rare insect fossil.

FIGURE 1.5
This fish was quickly buried in sediment to become a fossil.

organisms can be buried by mudslides, volcanic ash, or covered by sand in a sandstorm (**Figure** 1.6). Skeletons can be covered by mud in lakes, swamps, or bogs.

Unusual Circumstances

Unusual circumstances may lead to the preservation of a variety of fossils, as at the La Brea Tar Pits in Los Angeles, California. Although the animals trapped in the La Brea Tar Pits probably suffered a slow, miserable death, their bones were preserved perfectly by the sticky tar. (**Figure** 1.7).

In spite of the difficulties of preservation, billions of fossils have been discovered, examined, and identified by thousands of scientists. The fossil record is our best clue to the history of life on Earth, and an important indicator of past climates and geological conditions as well.

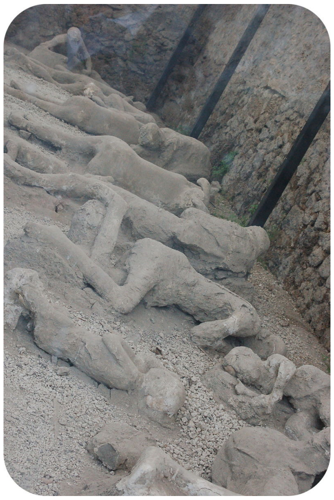


FIGURE 1.6
People buried by the extremely hot eruption of ash and gases at Mt. Vesuvius in 79 AD.

FIGURE 1.7
Artist's concept of animals surrounding the La Brea Tar Pits.

Exceptional Preservation

Some rock beds contain exceptional fossils or fossil assemblages. Two of the most famous examples of soft organism preservation are from the 505 million-year-old Burgess Shale in Canada (**Figure** 1.8). The 145 million-year-old Solnhofen Limestone in Germany has fossils of soft body parts that are not normally preserved (**Figure** 1.8).

Summary

- Fossils are the remains or traces of living organisms: body fossils are the remains and trace fossils are the traces.
- Fossils are mostly made of the hard parts of organisms; there are few soft-bodied fossils.

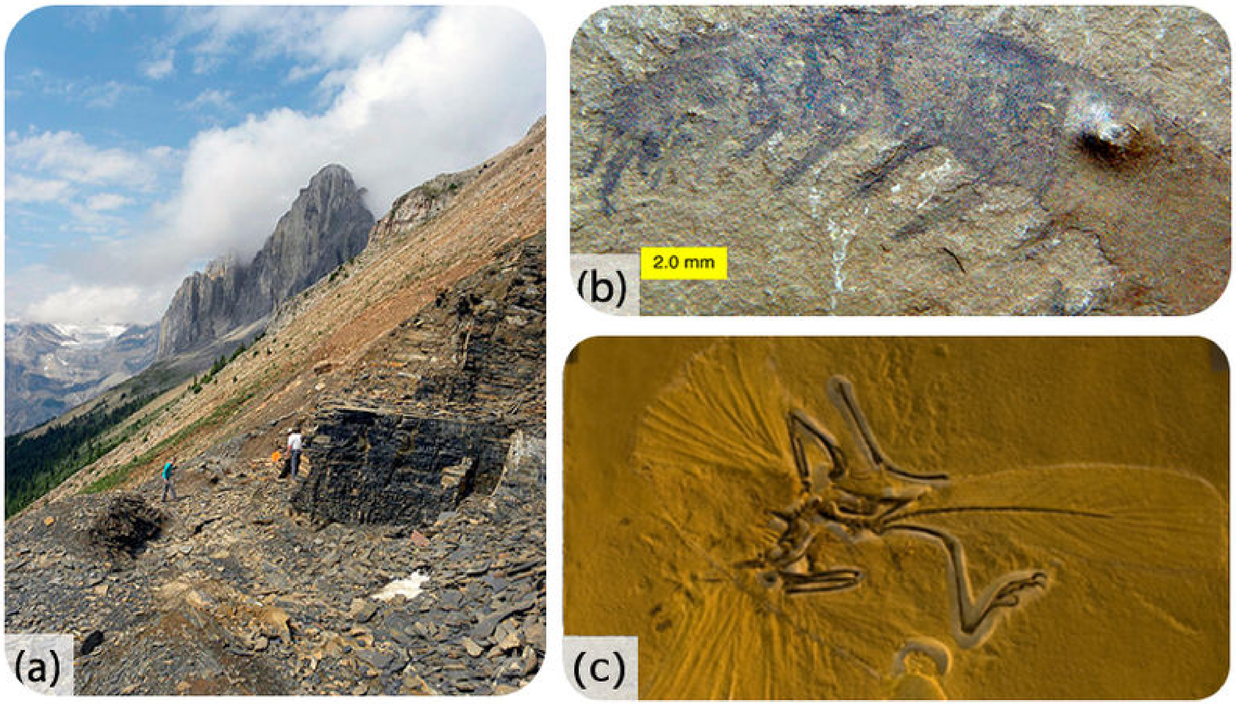


FIGURE 1.8

(a) The Burgess shale contains soft-bodied fossils. (b) Anomalocaris, meaning "abnormal shrimp" is now extinct. The image is of a fossil. (c) The famous Archeopteryx fossil from the Solnhofen Limestone has distinct feathers and was one of the earliest birds.

- Some of the best preserved fossils form in extremely unusual circumstances like the La Brea tar pits.

Practice

Use this resource to answer the questions that follow.

http://on.aol.com/video/pompeii-style-volcanic-eruptions-fossilized-chinese-dinos-518111446

1. What is unusual about this group of fossils?
2. How did these fossils form?
3. What type of deposits are they?
4. What supports the idea that the animals died due to volcanic activity?
5. How did these animals not escape in time?
6. Why are these fossils important?

Practice Answers

1. There are a lot of them and they are very well preserved.
2. A series of volcanic eruptions of the type that buried Pompeii.
3. Fast moving flows of hot ash and gas called pyroclastic flows.

4. The positions of the bodies and the black streaks that suggest charring.
5. They were killed by a pyroclastic density current, a wave of hot gs emitted from a volcano that can move up to 450 miles per hour.
6. They are so well preserved they give a good look at the early Cretaceous ecosystem.

Review

1. Give three examples of body fossils and trace fossils.
2. Under what conditions do fossils form?
3. Why are more fossils of marine organisms than of land organisms?

Review Answers

1. Body:shells, bones, teeth; Trace: feces, tracks, nests
2. The body is quickly buried so that it can't decompose rapidly. If it is buried it can become mineralized.
3. Marine organisms fall to the bottom and are buried by fine sediments. Many marine organisms have shells, which fossilize relatively well.

1.2 Types of Fossilization

- Learn the five processes that create most of the fossils.

Are all fossils so complete and well-preserved?

Very few circumstances lead to fossils that are as beautiful and complete as this baby mammoth that was frozen in ice. An animal falling into a crevasse or a tar pit does not undergo the scattering and degradation that an animal dying at the surface does and so fossils from these types of rare sites are often fantastic.

Types of Fossilization

Most fossils are preserved by one of five processes outlined below (**Figure** 1.9):

Preserved Remains

Most uncommon is the preservation of soft-tissue original material. Insects have been preserved perfectly in **amber**, which is ancient tree sap. Mammoths and a Neanderthal hunter were frozen in glaciers, allowing scientists the rare opportunity to examine their skin, hair, and organs. Scientists collect DNA from these remains and compare the DNA sequences to those of modern counterparts.

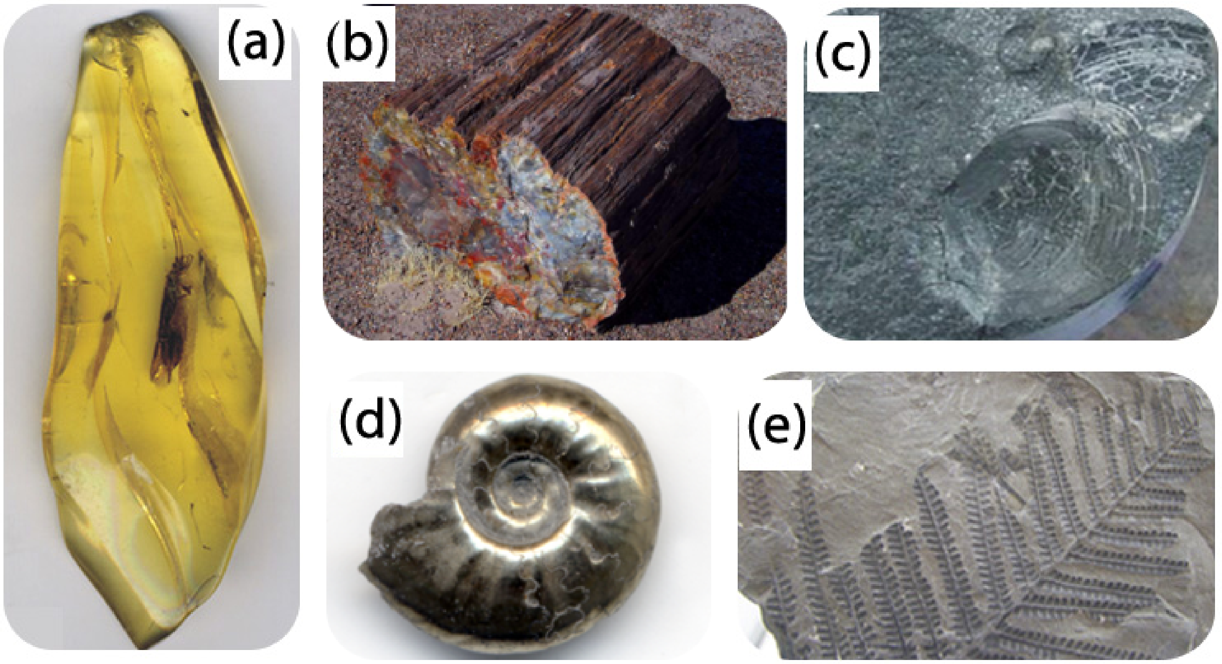


FIGURE 1.9

Five types of fossils: (a) insect preserved in amber, (b) petrified wood (permineralization), (c) cast and mold of a clam shell, (d) pyritized ammonite, and (e) compression fossil of a fern.

FIGURE 1.10

Trilobite.

Permineralization

The most common method of fossilization is **permineralization**. After a bone, wood fragment, or shell is buried in sediment, mineral-rich water moves through the sediment. This water deposits minerals into empty spaces and produces a fossil. Fossil dinosaur bones, petrified wood, and many marine fossils were formed by permineralization.

Molds and Casts

When the original bone or shell dissolves and leaves behind an empty space in the shape of the material, the depression is called a **mold**. The space is later filled with other sediments to form a matching **cast** within the mold that is the shape of the original organism or part. Many mollusks (clams, snails, octopi, and squid) are found as molds and casts because their shells dissolve easily.

Replacement

The original shell or bone dissolves and is replaced by a different mineral. For example, calcite shells may be replaced by dolomite, quartz, or pyrite. If a fossil that has been replace by quartz is surrounded by a calcite matrix, mildly acidic water may dissolve the calcite and leave behind an exquisitely preserved quartz fossil.

Compression

Some fossils form when their remains are compressed by high pressure, leaving behind a dark imprint. Compression is most common for fossils of leaves and ferns, but can occur with other organisms.

Summary

- Very few fossils preserve soft parts; some insects are preserved in amber and animals may be preserved in ice.
- Some fossils are created when minerals replace the organic material.
- A fossil may be in the form of a mold, which is the depression left in the shape of the material or a cast, which is rocky material that filled the mold.

Practice

Use this resource to answer the questions that follow.

https://www.youtube.com/watch?v=vqhAPEPByus

1. What are mold fossils?
2. What are cast fossils?
3. What are trace fossils?
4. What are true form fossils? What are the two main kinds talked about in the video?
5. How do insects get preserved by unaltered preservation typically?
6. What is permineralization?

Practice Answers

1. Mold fossils are impressions without the bones
2. Cast fossils are mold fossils that have been filled in, typically with minerals?
3. Trace fossils are traces of the existence of the creature, such as footprints, nests or burrows.
4. True form fossils have part of the animal in them, typically bones. The two kinds in the video are unaltered preservation and permineralization.
5. They get trapped in a thick substance like amber, hardened tree sap.
6. Permineralization is when minerals get into animal and replace its organic tissue and bone.

Review

1. Why are there so few fossils of soft parts? What are the exceptions to this?
2. If a snail shell is buried in mud and then infused with mineral rich water what type of fossilization has occurred?
3. What types of fossils are most likely to form by compression and why?

Review Answers

1. Soft parts decompose and aren't replaced by minerals. Insects get stuck in amber and some organisms fall into ice or tar pits, but that's rare.
2. permineralization
3. Leaves are the most common fossils formed by compression. They are compressed and leave behind their carbon as a dark imprint.

1.3 Earth History and Clues from Fossils

- Fossils are full of information about Earth's past and are essential for unraveling earth history.

Seashells at 20,000 feet!

On his voyage on the Beagle, Charles Darwin noticed many things besides just the Galapagos finches that made him famous. Another important discovery was shell beds high in the Andes Mountains. How did they get there? He determined that they must mean that mountains rise slowly above the ocean, an idea that was being championed at the time by Charles Lyell. If this is the case, Darwin reasoned, the mountains and Earth must be extremely old.

Clues from Fossils

Fossils are our best form of evidence about Earth history, including the history of life. Along with other geological evidence from rocks and structures, fossils even give us clues about past climates, the motions of plates, and other major geological events. Since the present is the key to the past, what we know about a type of organism that lives today can be applied to past environments.

History of Life on Earth

That life on Earth has changed over time is well illustrated by the fossil record. Fossils in relatively young rocks resemble animals and plants that are living today. In general, fossils in older rocks are less similar to modern organisms. We would know very little about the organisms that came before us if there were no fossils. Modern technology has allowed scientists to reconstruct images and learn about the biology of extinct animals like dinosaurs!

MEDIA

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Environment of Deposition

By knowing something about the type of organism the fossil was, geologists can determine whether the region was terrestrial (on land) or marine (underwater) or even if the water was shallow or deep. The rock may give clues to whether the rate of sedimentation was slow or rapid. The amount of wear and fragmentation of a fossil allows scientists to learn about what happened to the region after the organism died; for example, whether it was exposed to wave action.

Geologic History

The presence of marine organisms in a rock indicates that the region where the rock was deposited was once marine. Sometimes fossils of marine organisms are found on tall mountains indicating that rocks that formed on the seabed were uplifted.

Climate

By knowing something about the climate a type of organism lives in now, geologists can use fossils to decipher the climate at the time the fossil was deposited. For example, coal beds form in tropical environments but ancient coal beds are found in Antarctica. Geologists know that at that time the climate on the Antarctic continent was much warmer. Recall from the chapter Plate Tectonics that Wegener used the presence of coal beds in Antarctica as one of the lines of evidence for continental drift.

Index Fossils

An **index fossil** can be used to identify a specific period of time. Organisms that make good index fossils are distinctive, widespread, and lived briefly. Their presence in a rock layer can be used to identify rocks that were deposited at that period of time over a large area.

The fossil of a juvenile mammoth found near downtown San Jose California reveals an enormous amount about these majestic creatures: what they looked like, how they lived, and what the environment of the Bay Area was like so long ago.

Find out more at http://science.kqed.org/quest/video/science-on-the-spot-lupe-the-mammoth-comes-to-life/ .

MEDIA

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Summary

- Fossils tell a lot about the environment during the time they were deposited.
- Climate is one important thing that can be indicated by fossils since organisms have specific conditions in which they can live.
- An index fossil must be distinctive, widespread and short-lived so that it can identify a specific period of time.

Practice

Use this resource to answer the questions that follow.

https://www.youtube.com/watch?v=Z5DWKTNqByM

1. What shows up in rocks that are 3.8 billion years old?
2. What is found in rocks that are 3.5 billion years old?
3. When do the first large lifeforms show up and what are they?
4. What happens around 500 million years ago?
5. What big thing happens 400 million years ago? What are the organisms like?
6. What happens about 300 million years ago?
7. What happened about 250 million years ago and what caused it?
8. What are the next 150 million years like?
9. What happens 66 million years ago?
10. What does that set the stage for?
11. When and where do the first human ancestors appear?
12. When did humans arrive in North America?
13. Where did a lot of that story come from?

Practice Answers

1. The first chemical evidence of life is 3.8 billion years old.
2. bacterial mounds
3. 600 million years ago seafloor organisms that are now extinct show up.
4. There is a lot of diversification of marine organisms; there are the first marine organisms from groups we see today.
5. The first life emerges onto land, spider-like organisms and early plants.
6. Forests and large bodied terrestrial animals are on the land like giant millipedes and land-living vertebrates. The first terrestrial herbivores appear.
7. About 90% of Earth's species go extinct and it seems to have something to do with the carbon cycle.
8. The world is warm, no polar ice caps, a great diversity of animals cohabit with the dinosaurs.
9. An asteroid the size of Denver crashes into Yucatan Peninsula and causes extinction of all large animals.
10. The modern world of life.
11. About 8 million years ago in the savannahs of Africa.
12. About 13,000 years ago.
13. fossils

Review

1. How does a single fossil or set of fossils help geologists to decipher the geological history of an area?
2. How is an index fossil used to identify a time period?
3. Why are the fossils of marine organisms sometimes found in rock units at the tops of high mountains? What evidence would you look for to determine if this reason is plausible?

Review Answers

1. A fossil will tell us about the environment that existed at the time the organism lived. A set of fossils will tell about the ecosystem of the region.
2. An index fossil is from a specific period of time. It is widespread, but lived briefly. It can be used as an indicator of that time period.
3. The mountains must have been uplifted slowly from the sea. The indication of this besides the fossils would be faults and other evidence that the mountains rose.

1.4 Principles of Relative Dating

- Steno's laws are used to determine the order in which geological events took place.

Relative ages.

In most families a person's age fits into his or her generation: Siblings are around the same age as are first cousins. But in some families, multiple marriages, delayed childbearing, extended childbearing or other variations mixes up generations so that Aunt Julia may be five years younger than her nephew. In a family like this it's hard to tell how people are related simply by age. With rock units we use certain principles to tell their ages relative to each other.

Relative Age Dating

Early geologists had no way to determine the absolute age of a geological material. If they didn't see it form, they couldn't know if a rock was one hundred years or 100 million years old. What they could do was determine the ages of materials relative to each other. Using sensible principles they could say whether one rock was older than another and when a process occurred relative to those rocks.

Steno's Laws

Remember Nicholas Steno, who determined that fossils represented parts of once-living organisms? Steno also noticed that fossil seashells could be found in rocks and mountains far from any ocean. He wanted to explain how that could occur. Steno proposed that if a rock contained the fossils of marine animals, the rock formed from sediments that were deposited on the seafloor. These rocks were then uplifted to become mountains.

This scenario led him to develop the principles that are discussed below. They are known as Steno's laws. Steno's laws are illustrated in **Figure** 1.11.

- **Original horizontality**: Sediments are deposited in fairly flat, horizontal layers. If a sedimentary rock is found tilted, the layer was tilted after it was formed.
- **Lateral continuity**: Sediments are deposited in continuous sheets that span the body of water that they are deposited in. When a valley cuts through sedimentary layers, it is assumed that the rocks on either side of the valley were originally continuous.
- **Superposition**: Sedimentary rocks are deposited one on top of another. The youngest layers are found at the top of the sequence, and the oldest layers are found at the bottom.

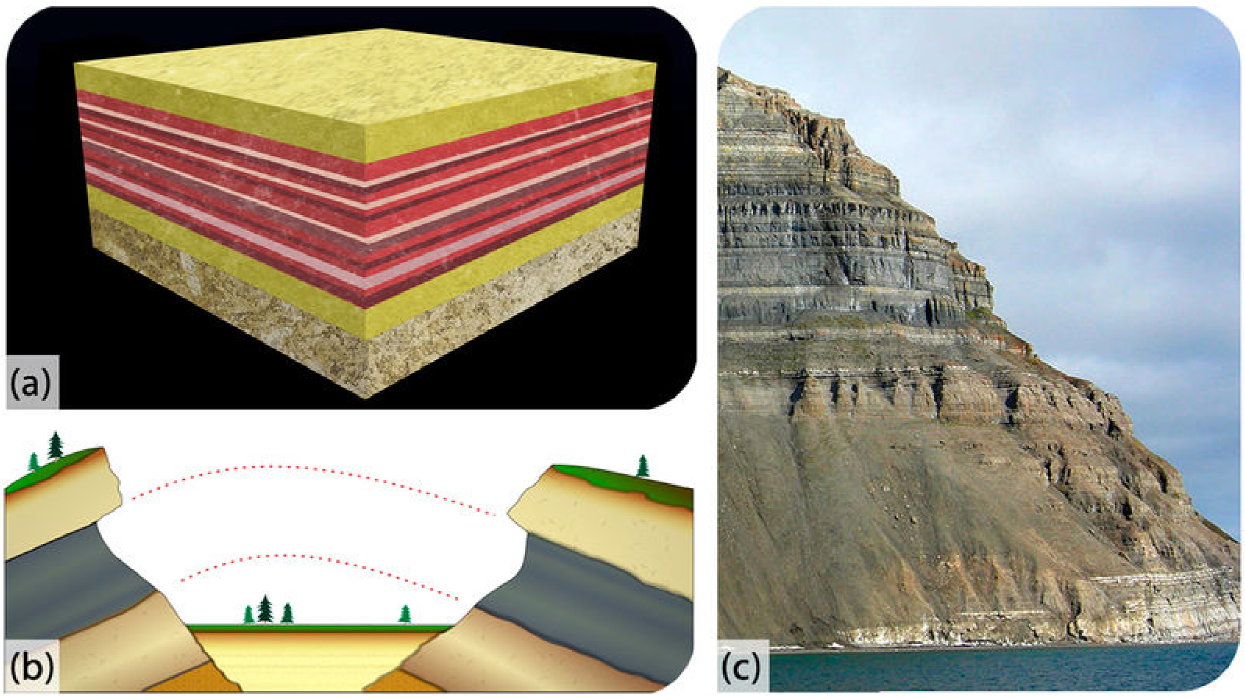


FIGURE 1.11
(a) Original horizontality. (b) Lateral continuity. (c) Superposition.

More Principles of Relative Dating

Other scientists observed rock layers and formulated other principles.

Geologist William Smith (1769-1839) identified the **principle of faunal succession**, which recognizes that:

- Some fossil types are never found with certain other fossil types (e.g. human ancestors are never found with dinosaurs) meaning that fossils in a rock layer represent what lived during the period the rock was deposited.
- Older features are replaced by more modern features in fossil organisms as species change through time; e.g. feathered dinosaurs precede birds in the fossil record.
- Fossil species with features that change distinctly and quickly can be used to determine the age of rock layers quite precisely.

Scottish geologist, James Hutton (1726-1797) recognized the **principle of cross-cutting relationships**. This helps geologists to determine the older and younger of two rock units (**Figure** 1.12).

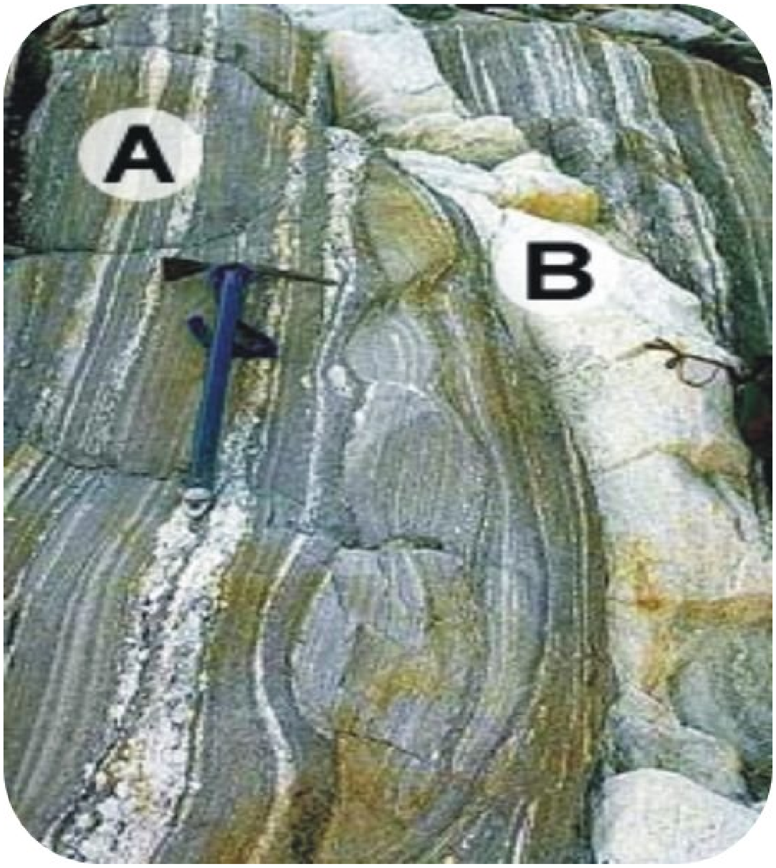


FIGURE 1.12
If an igneous dike (B) cuts a series of metamorphic rocks (A), which is older and which is younger? In this image, A must have existed first for B to cut across it.

The Grand Canyon

The Grand Canyon provides an excellent illustration of the principles above. The many horizontal layers of sedimentary rock illustrate the principle of original horizontality (**Figure** 1.13).

- The youngest rock layers are at the top and the oldest are at the bottom, which is described by the law of superposition.
- Distinctive rock layers, such as the Kaibab Limestone, are matched across the broad expanse of the canyon. These rock layers were once connected, as stated by the rule of lateral continuity.
- The Colorado River cuts through all the layers of rock to form the canyon. Based on the principle of cross-cutting relationships, the river must be younger than all of the rock layers that it cuts through.

Summary

- Sediments are deposited horizontally with the oldest at the bottom. Any difference in this pattern means that the rock units have been altered.
- The principle of faunal succession recognizes that species evolve and these changes can be seen in the rock record.
- The Grand Canyon exhibits many of the principles of relative dating and is a fantastic location for learning about the geology of the southwestern U.S.

FIGURE 1.13
At the Grand Canyon, the Coconino Sandstone appears across canyons. The Coconino is the distinctive white layer; it is a vast expanse of ancient sand dunes.

Practice

Use this resource to answer the questions that follow.

https://www.youtube.com/watch?v=z93fKmQqPW0 Start at 1:23

1. What do you determine when you're doing relative dating? What are you not determining?
2. What is the Law of Superposition? What is the exception?
3. What is the Law of Original Horizontality? If rocks are not horizontal what does that mean?
4. What is the Law of Cross-Cutting Relationships?
5. What is the Law of Inclusions?
6. What is an unconformity? What can cause an unconformity?
7. What does an angular unconformity look like? What does this indicate?
8. What happened during an unconformity and how do we know that?
9. How do you know where there is a disconformity?
10. What happened to create an nonconformity? What can you look for to identify a nonconformity?

Practice Answers

1. Determining which of two things is older or younger. You're not determining the actual age of the thing.
2. In a horizontal sequence of sedimentary rocks the oldest are on the bottom and the youngest are on the top. If the rock is flipped over it will be reverse.
3. Layers of sediment are generally deposited in a horizontal position. If they are no longer horizontal something must have happened to them.
4. For something to cut across rock layers the rocks must have been there first so they are older.
5. Rock fragments found in another rock, like a conglomerate, must be older than the whole rock.
6. A break in the rock record caused by erosion or non-deposition.
7. The rocks below the unconformity are tilted relative to the rocks above. The rocks below are tilted due to deformation. The unconformity indicates erosion and/or lack of deposition.
8. We don't know what happened because there is no rock record of that time period.
9. There may be an erosional surface at the disconformity, but there is definitely a gap in rock ages.
10. An older igneous or metamorphic rock experienced erosion and then sediments were deposited on top of it. There would not be a baked zone on the sedimentary rocks.

Review

1. How do Steno's laws help geologists to decipher the geological history of a region?
2. What is the principle of faunal succession?
3. Why does just about every geology textbook use the Grand Canyon as the example in the sections on geological history?

Review Answers

1. Steno's laws indicate how rocks should appear and how to interpret what it means when rocks do or do not appear that way. They are used to indicate the relative ages of rocks.
2. Fossils change over time and these changes can be used to determine the relative age of rocks and even the time period of rocks precisely.
3. It is the best place on Earth for seeing exposed rock layers that expose a tremendous amount of Earth history. Plus its a beautiful place!

1.5 Determining Relative Ages

- Be able to determine the relative ages of a set of rocks and the processes that have altered them.

Clues can tell you a person's age.

There are ways to tell the ages of people relative to each other. For children we use height, for adults we might use gray hair and wrinkles. There are also ways to tell the relative ages of rocks. We'll practice in this concept.

Determining the Relative Ages of Rocks

Steno's and Smith's principles are essential for determining the relative ages of rocks and rock layers. In the process of relative dating, scientists do not determine the exact age of a fossil or rock but look at a sequence of rocks to try to decipher the times that an event occurred relative to the other events represented in that sequence. The **relative age** of a rock then is its age in comparison with other rocks. If you know the relative ages of two rock layers, (1) Do you know which is older and which is younger? (2) Do you know how old the layers are in years?

An interactive website on relative ages and geologic time is found here: http://www.ucmp.berkeley.edu/education/explorations/tours/geotime/gtpage1.html .

In some cases, it is very tricky to determine the sequence of events that leads to a certain formation. Can you figure out what happened in what order in (**Figure** 1.14)? Write it down and then check the following paragraphs.

The principle of cross-cutting relationships states that a fault or intrusion is younger than the rocks that it cuts through. The fault cuts through all three sedimentary rock layers (A, B, and C) and also the intrusion (D). So the fault must be the youngest feature. The intrusion (D) cuts through the three sedimentary rock layers, so it must be younger than those layers. By the law of superposition, C is the oldest sedimentary rock, B is younger and A is still younger.

The full sequence of events is:

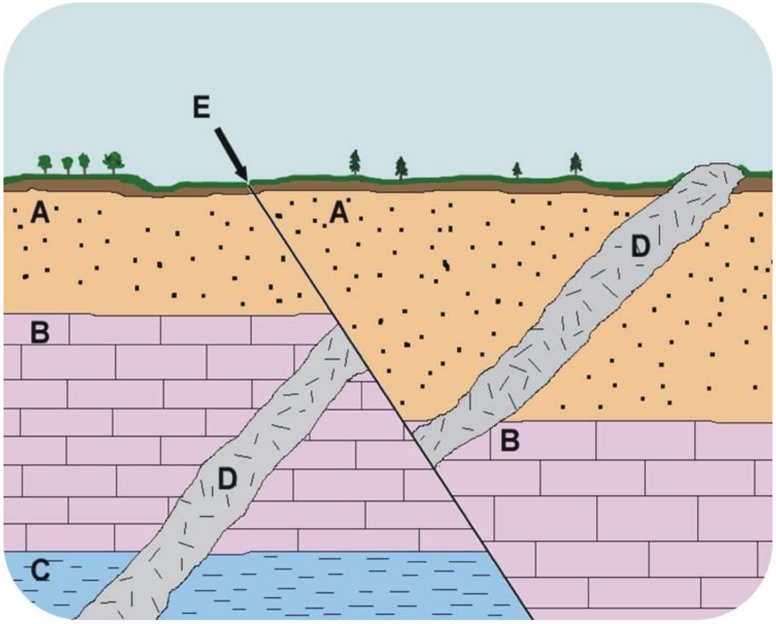


FIGURE 1.14
A geologic cross section: Sedimentary rocks (A-C), igneous intrusion (D), fault (E).

1. Layer C formed.
2. Layer B formed.
3. Layer A formed.
4. After layers A-B-C were present, intrusion D cut across all three.
5. Fault E formed, shifting rocks A through C and intrusion D.
6. Weathering and erosion created a layer of soil on top of layer A.

Summary

- The oldest rock units lie beneath the younger ones.
- By the principle of cross-cutting relationships (and common sense) we know that something must exist before something else can cut across it.
- The history of a section of rocks can be deciphered using the principles outlined in this Concept.

Practice

Use the resource below to answer the questions that follow.

https://www.youtube.com/watch?v=5UFXxap7g9I

1. What does relative dating give you? What doesn't it give you?
2. What is the order of rock layers and events in the first rock section shown?
3. What is the order of rock layers and events in the second rock section shown?
4. What is the order of rock layers and events in the third rock section shown?
5. What is the order of rock layers and events in the fourth rock section shown?
6. What is the order of rock layers and events in the fifth rock section shown?
7. What is the order of rock layers and events in the sixth rock section shown?

Practice Answers

1. It tells you the order in which things occur but not the date it happened or even the number of years different they are.
2. The lowermost rock layer, a shale, is the oldest. Next came the second lowest, then the third lowest, and the top layer is the youngest.
3. The lowest layer, the conglomerate, is oldest. Then the 2nd, 3rd and 4th layers come above that. These layers are tilted, then there was erosion to create an angular unconformity. The top layer was laid down next and is the youngest layer.
4. The oldest is the rock layer in the middle, then the three above it are 2, 3 and 4. They are all folded, which came next. After the deformation came the unconformity and then the two rock layers above it. The igneous intrusion is youngest because it cuts everything.
5. The igneous rock is causing metamorphism so the schist had to be there first. The intrusion is cutting across both layers.
6. The green gneiss is oldest and it was intruded by the granite, which shows some metamorphism of the gneiss around it. There is an angular unconformity, then the yellow sandstone was deposited on top of it. The basalt intrusion cuts into the gneiss, the unconformity and the sandstone so it is next. However, we can't tell if it's older or younger than the rock layer on top since they have no interactions.
7. The three rocks in order are limestone, clay, and then gravel. The fault then cuts them. There is an unconformity and then the final siltstone is deposited on top.

Review

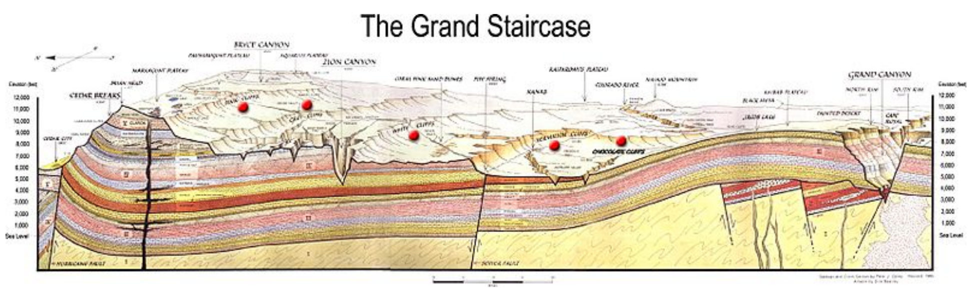
1. What is relative age? How does it differ from absolute age?
2. Why do the principles of relative dating not indicate the absolute age of a rock unit?
3. Under what circumstances would a rock unit with an older fossil be above a rock until with a younger fossil?

Review Answers

1. Relative age is the age of something relative to other things. It does not give an age in years like absolute age does.
2. Relative dating has no basis on which to make a determination of absolute age.
3. If the older fossil eroded out of another rock and then was deposited in a younger rock.

1.6 Correlation Using Relative Ages

- Rock units can be correlated over vast distances if they are distinctive, or contain index fossils or a key bed.



Rock matching.

If we want to understand the geological history of a location we need to look at the rocks in that location. But if we want to understand a region, we need to correlate the rocks between different locations so that we can meld the individual histories of the different locations into one regional history.

Matching Up Rock Layers

Superposition and cross-cutting are helpful when rocks are touching one another and lateral continuity helps match up rock layers that are nearby. To match up rocks that are further apart we need the process of **correlation**. How do geologists correlate rock layers that are separated by greater distances? There are three kinds of clues:

Distinctive Rock Formations

1. Distinctive rock formations may be recognizable across large regions (**Figure** 1.15).

Index Fossils

2. Two separated rock units with the same index fossil are of very similar age. What traits do you think an index fossil should have? To become an index fossil the organism must have (1) been widespread so that it is useful for identifying rock layers over large areas and (2) existed for a relatively brief period of time so that the approximate age of the rock layer is immediately known.

Many fossils may qualify as index fossils (**Figure** 1.16). Ammonites, trilobites, and graptolites are often used as index fossils.

Microfossils, which are fossils of microscopic organisms, are also useful index fossils. Fossils of animals that drifted in the upper layers of the ocean are particularly useful as index fossils, since they may be distributed over very large areas.

A biostratigraphic unit, or **biozone**, is a geological rock layer that is defined by a single index fossil or a fossil assemblage. A biozone can also be used to identify rock layers across distances.

FIGURE 1.15
The famous White Cliffs of Dover in southwest England can be matched to similar white cliffs in Denmark and Germany.

Key Beds

3. A **key bed** can be used like an index fossil since a key bed is a distinctive layer of rock that can be recognized across a large area. A volcanic ash unit could be a good key bed. One famous key bed is the clay layer at the boundary between the Cretaceous Period and the Tertiary Period, the time that the dinosaurs went extinct (**Figure** 1.17). This widespread thin clay contains a high concentration of iridium, an element that is rare on Earth but common in asteroids. In 1980, the father-son team of Luis and Walter Alvarez proposed that a huge asteroid struck Earth 66 million years ago and caused the mass extinction.

Summary

- A single rock unit contains the story of the geology of that location. To understand the geology of a region, scientists use correlation.
- To correlate rock units, something distinctive must be present in each. This can include an index fossil, a unique rock type, a key bed, or a unique sequence of rocks.
- A key bed can be global. An example is the iridium layer that was deposited at the time of the Cretaceous-Tertiary extinctions.

Practice

Use the resource below to answer the questions that follow.

https://www.youtube.com/watch?v=M4aL96AKKbY To see where these two canyons are in the geology of this potion of southern Utah shown see in the drawing of the Grand Staircase at the top of this concept.

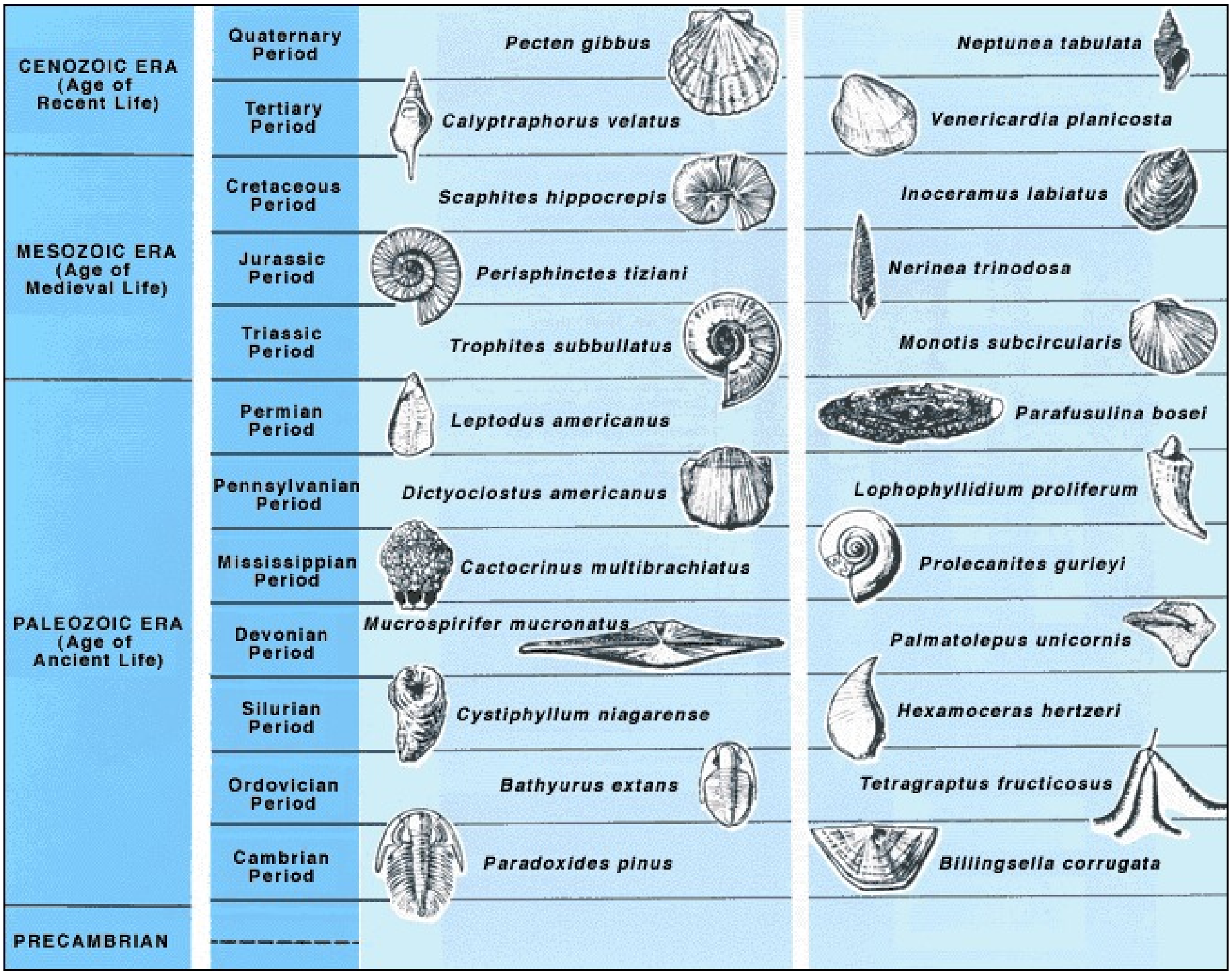


FIGURE 1.16

Several examples of index fossils are shown here. Mucrospirifer mucronatus is an index fossil that indicates that a rock was laid down from 416 to 359 million years ago.

1. What does the rock that forms the hoodoos of Bryce Canyon tell geologists about the environment at the time the sediments were deposited?
2. Why are the rocks at Bryce Canyon orange?
3. What happened when the Colorado Plateau rose?
4. How were the hoodoos created for the most part?
5. What is the rock that creates the white cliffs at Zion? Why are the sands at angles?
6. When was that portion of Utah a giant sand dune? Why are there dunes stacked on top of dunes?

Practice Answers

1. The region was a basin containing lakes with water flowing in but not out. Sediments were deposited in the bottom of the lakes and kept building up.
2. Iron settled out in the lake system and entered the limestone.

FIGURE 1.17
The white clay is a key bed that marks the Cretaceous-Tertiary Boundary.

3. The lake got lifted and the water drained. The sediments lithified and became rock.
4. Ice wedging: The freezing and thawing of water in the rock. It expands and gets hard as it freezes.
5. The Navajo Sandstone is ancient sand dunes.
6. About 200 million years ago; because the winds changed direction.

Review

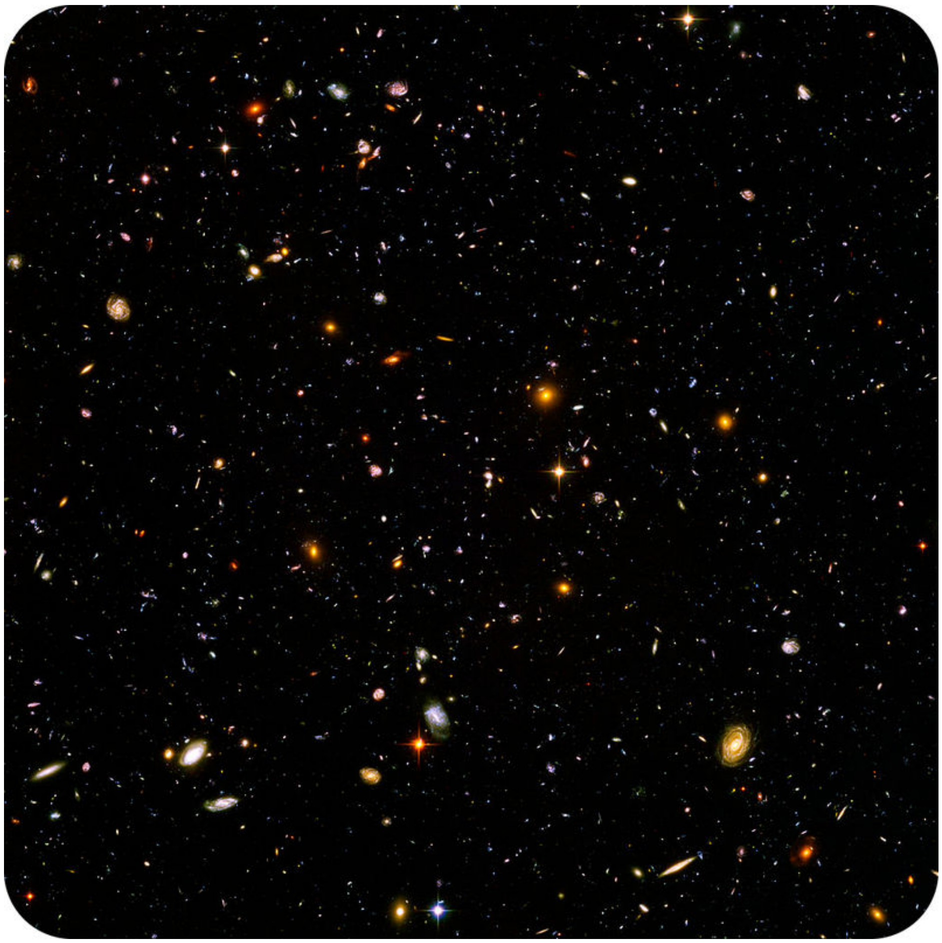
1. What features must the iridium layer that dates to around 66 million years ago have to be a key bed?
2. Why are microfossils especially useful as index fossils?
3. What is the process of correlation?

Review Answers

1. It must be widespread, very distinctive and have been deposited in a short period of time.
2. Tiny marine organisms drift through the upper layers of a sea so they are widespread.
3. Geologists look for the same rock unit in different places or the same microfossils or the same key beds to see try to expand what they know about the geology of an area to the entire region.

1.7 Geologic Time Scale

- The geologic time scale allows scientists to refer to events in Earth history in relevant units.



To infinity and beyond!

We can picture deep space, but what does deep time look like? If you divided up the 4.6 billion years of Earth history into one calendar year, as is done at the end of this concept, you might get an idea.

The Geologic Time Scale

To be able to discuss Earth history, scientists needed some way to refer to the time periods in which events happened and organisms lived. With the information they collected from fossil evidence and using Steno's principles, they created a listing of rock layers from oldest to youngest. Then they divided Earth's history into blocks of time with each block separated by important events, such as the disappearance of a species of fossil from the rock record. Since many of the scientists who first assigned names to times in Earth's history were from Europe, they named the blocks of time from towns or other local places where the rock layers that represented that time were found.

From these blocks of time the scientists created the **geologic time scale** (**Figure** 1.18). In the geologic time scale the youngest ages are on the top and the oldest on the bottom. Why do you think that the more recent time periods are divided more finely? Do you think the divisions in the scale below are proportional to the amount of time each time period represented in Earth history?

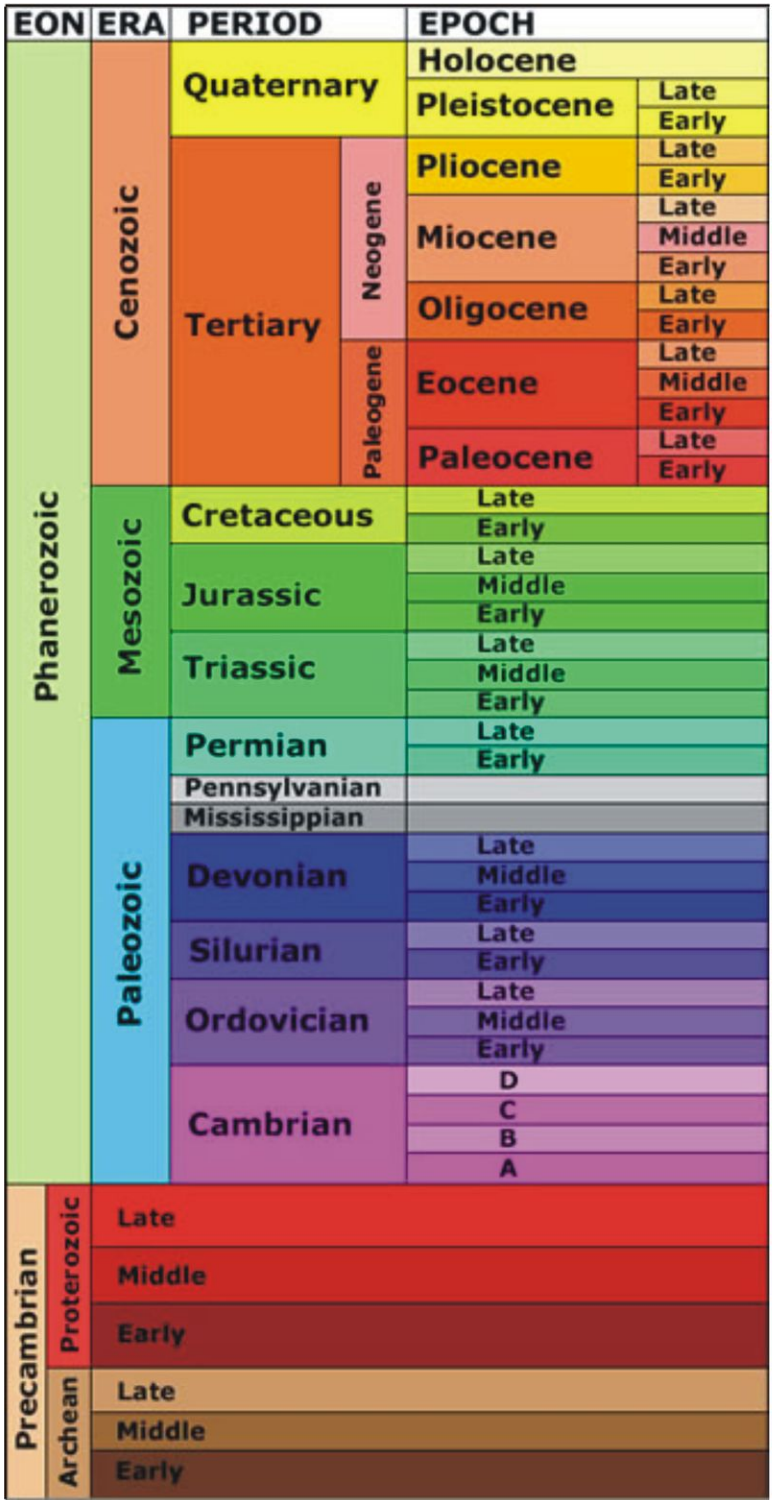


FIGURE 1.18
The geologic time scale is based on relative ages. No actual ages were placed on the original time scale.

In what eon, era, period and epoch do we now live? We live in the Holocene (sometimes called Recent) epoch, Quaternary period, Cenozoic era, and Phanerozoic eon.

Geologic Time Condensed to One Year

It's always fun to think about geologic time in a framework that we can more readily understand. Here are when some major events in Earth history would have occurred if all of earth history was condensed down to one calendar year.

January 1 12 am: Earth forms from the planetary nebula –4600 million years ago

February 25, 12:30 pm: The origin of life; the first cells –3900 million years ago

March 4, 3:39 pm: Oldest dated rocks –3800 million years ago

March 20, 1:33 pm: First stromatolite fossils –3600 million years ago

July 17, 9:54 pm: first fossil evidence of cells with nuclei –2100 million years ago

November 18, 5:11 pm: Cambrian Explosion –544 million years ago

December 1, 8:49 am: first insects –385 million years ago

December 2, 3:54 am: first land animals, amphibians –375 million years ago

December 5, 5:50 pm: first reptiles –330 million years ago

December 12, 12:09 pm: Permo-Triassic Extinction –245 million years ago

December 13, 8:37 pm: first dinosaurs –228 million years ago

December 14, 9:59 am: first mammals – 220 million years ago

December 22, 8:24 pm: first flowering plants –115 million years ago

December 26, 7:52 pm: Cretaceous-Tertiary Extinction –66 million years ago

December 26, 9:47 pm: first ancestors of dogs –64 million years ago

December 27, 5:25 am: widespread grasses –60 million years ago

December 27, 11:09 am: first ancestors of pigs and deer –57 million years ago

December 28, 9:31 pm: first monkeys –39 million years ago

December 31, 5:18 pm: oldest hominid –4 million years ago

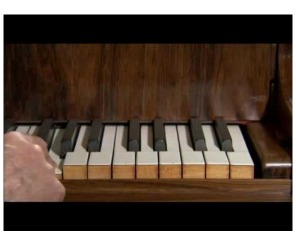
December 31, 11:02 pm: oldest direct human ancestor –1 million years ago

December 31, 11:48 pm: first modern human –200,000 years ago

December 31, 11:59 pm: Revolutionary War –235 years ago

Source: http://www.timetoast.com/timelines/63215

See the video below for another analogy of geologic time:



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Summary

- The geologic time scale divides earth history into named units that are separated by major events in earth or life history.
- Naming time periods makes it easier to talk about them.
- Humans have been around for a miniscule portion of earth history.

Practice

Use this resource to answer the questions that follow.

Geologic Time - Introduction

https://www.youtube.com/watch?v=ZNM59d-nD_Y Please note that he mispronounces the names routinely.

1. What are the break-downs of chunks of time on the geologic time scale in order from longest to shortest?
2. What is the one supereon? Why does it get its own category?
3. What are the three eons in the supereon?
4. What are the Paleozoic, Mesozoic and Cenozoic Eras part of?
5. What are the periods within the Paleozoic Era?
6. What are the periods within the Mesozoic Era?
7. What are the periods within the Cenozoic Era?

Practice Answers

1. eon, era, period, epoch.
2. The Precambrian is the only supereon because it represents a tremendous amount of time.
3. Hadeon, Archaeon, Proterozoic
4. The Phanerozoic Eon
5. Cambrian, Ordovician, Silurian, Devonian, Carboniferous, Permian
6. Triassic, Jurassic, Cretaceous
7. Tertiary, Quaternary

Review

1. Why do earth scientists need a geologic time scale?
2. Why are some units of the geologic time scale longer and some shorter?
3. How does the section that condenses all of geologic time into one year make you feel?

Review Answers

1. It helps them to refer to time periods by something easier to use than a date; plus it gives a sense of what was happening in the bigger picture at that time.
2. The units are divided by events and events do not happen in evenly spaced time chunks. Also, we know more about more recent history so those blocks are divided more finely.
3. Answers will vary.

1.8 Tree Rings, Ice Cores, and Varves

- Learn three ways that scientists can get an absolute age, tree rings, ice cores and varves.

How can scientists tell the oldest possible age of this painting?

The Netherlandish paintings, which were painted in the low-lying countries of and near the Netherlands, were painted on solid wood panels, usually oak. The wood was split radially so that tree rings are visible and dates for the paintings date, which are from the 15th and 16th centuries, can be determined. Why does this give the oldest possible age?

Tree Ring Dating

In locations where summers are warm and winters are cool, trees have a distinctive growth pattern. Tree trunks display alternating bands of light-colored, low density summer growth and dark, high density winter growth. Each light-dark band represents one year. By counting **tree rings** it is possible to find the number of years the tree lived (**Figure** 1.19).

The width of these growth rings varies with the conditions present that year. A summer drought may make the tree grow more slowly than normal and so its light band will be relatively small. These tree-ring variations appear in all trees in a region. The same distinctive pattern can be found in all the trees in an area for the same time period.

Scientists have created continuous records of tree rings going back over the past 2,000 years. Wood fragments from old buildings and ancient ruins can be age dated by matching up the pattern of tree rings in the wood fragment in question and the scale created by scientists. The outermost ring indicates when the tree stopped growing; that is, when it died. The tree-ring record is extremely useful for finding the age of ancient structures.

FIGURE 1.19
Cross-section showing growth rings.

An example of how tree-ring dating is used to date houses in the United Kingdom is found in this article: http://www.periodproperty.co.uk/ppuk_discovering_article_013.shtml .

Ice Cores

Besides tree rings, other processes create distinct yearly layers that can be used for dating. On a glacier, snow falls in winter but in summer dust accumulates. This leads to a snow-dust annual pattern that goes down into the ice (**Figure** 1.20). Scientists drill deep into ice sheets, producing **ice cores** hundreds of meters long. The information scientists gather allows them to determine how the environment has changed as the glacier has stayed in its position. Analyses of the ice tell how concentrations of atmospheric gases changed, which can yield clues about climate. The longest cores allow scientists to create a record of polar climate stretching back hundreds of thousands of years.

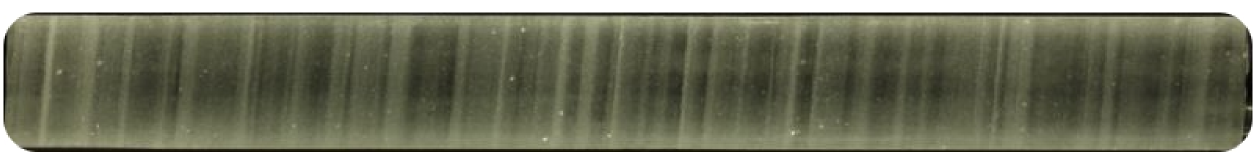

FIGURE 1.20
Ice core section showing annual layers.

Varves

Lake sediments, especially in lakes that are located at the end of glaciers, also have an annual pattern. In the summer, the glacier melts rapidly, producing a thick deposit of sediment. These alternate with thin, clay-rich layers deposited in the winter. The resulting layers, called **varves**, give scientists clues about past climate conditions (**Figure** 1.21). A warm summer might result in a very thick sediment layer while a cooler summer might yield a thinner layer.

FIGURE 1.21
Ancient varve sediments in a rock outcrop.

Summary

- Where conditions vary seasonally, trees develop distinctive rings, ice contains more or less dust, and lake sediments show more or less clay.
- Tree rings, ice cores and varves indicate the environmental conditions at the time they were made.
- The distinctive patterns of tree rings, ice cores and varves going back thousands of years can be used to determine the time they were made.

Practice

Use the resources below to answer the questions that follow.

- **Lord of the Tree Rings** at http://www.youtube.com/watch?&v=FAOYkx8E-Gc (2:29)

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Click image to the left for use the URL below.
URL: http://gamma.ck12.org/flx/render/embeddedobject/4805

1. What do annual tree rings tell scientists?
2. What can be learned from tree rings?
3. What do tree rings indicate about the lost colony of Roanoke, Virginia?
4. What type of trees do scientists look for? Why?

- **Ice Core Secrets Could Reveal Answers to Global Warming** at http://www.youtube.com/watch?v=NENZ6TSc1fo (4:59)

MEDIA

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5. What is trapped in the ice cores and when it it from?
6. How long have ice cores been studied?
7. What can be learned from ice cores?
8. What circumstances make the best ice cores? What is a good location to obtain cores like this?
9. How much would sea level rise if the Greenland ice sheet melted?

Practice Answers

1. Annual tree rings reveal the environmental history of a year, including whether it was wet or dry, or whether there were droughts or fires.
2. The climate history of a region can be learned from tree rings.
3. The tree rings indicate that there was a major drought at the same time the colony disappeared.
4. Scientists look for old-growth trees to use because they have the least imprint of human activity.
5. Trapped inside the ice cores are bubbles of gas that represent the atmosphere at the time the snow fell.
6. 40 years
7. Ice cores can indicate levels of carbon dioxide and methane in the atmosphere.
8. Steady and heavy snowfall leads to good ice cores; Greenland is one good location.
9. about 20 feet

Review

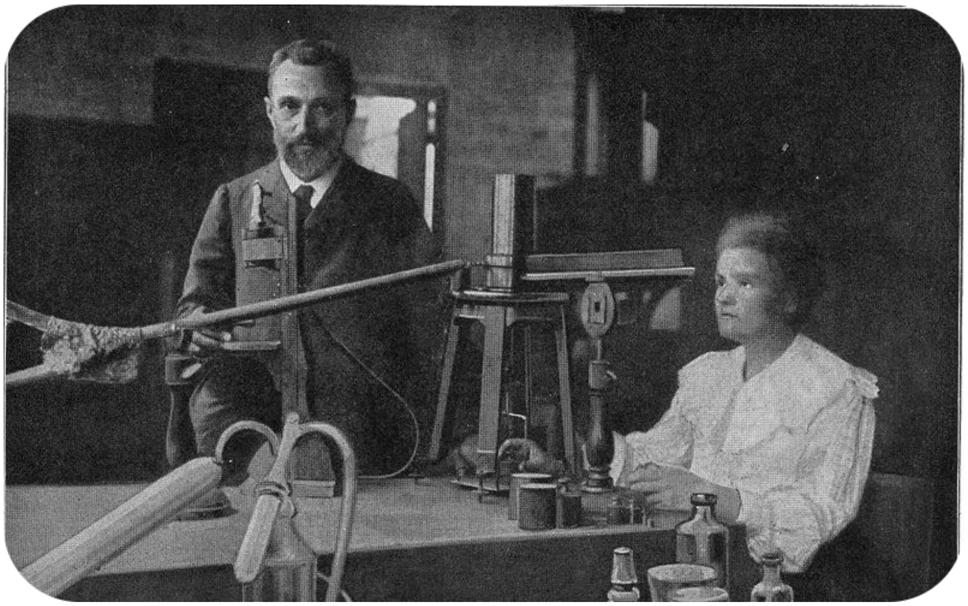
1. What is dendrochronology?
2. How do tree rings, ice cores and varves indicate the time at which they were made?
3. How do tree rings, ice cores and varves indicate environmental conditions at the time they formed?

Review Answers

1. Dendrochronology is tree ring dating. When trees grow they produce summer and winter growth bands that are different based on the conditions that year. This rings can be matched to master lists to determine the age the tree died.
2. The patterns of tree ring sizes or ice core snow-dust patterns or varve sediment-clay patterns can tell the absolute age of the tree died, the ice core was deposited or the varve was deposited.
3. The sizes of the different layers indicate climate and other environmental factors. Large growth rings in a tree, for example, indicate good conditions.

1.9 Radioactive Decay as a Measure of Age

- Radioactive decay gives a way to determine the age of some types of rocks.



Why did this couple win the Nobel Prize?

Pierre and Marie Curie, a husband and wife team of physicists, discovered the spontaneous emission of particles from certain elements. They called this phenomenon "radioactivity." Together they won three Nobel prizes, and the element curium was named in their honor.

Radioactive Decay

Radioactivity is the tendency of certain atoms to decay into lighter atoms, a process that emits energy. Radioactivity also provides a way to find the absolute age of a rock. First, we need to know about radioactive decay.

Radioactive Isotopes

Some isotopes are radioactive; **radioactive isotopes** are unstable and spontaneously change by gaining or losing particles. Two types of radioactive decay are relevant to dating Earth materials (**Table** 1.1):

TABLE 1.1: **Types of Radioactive Decay**

Particle	Composition	Effect on Nucleus
Alpha	2 protons, 2 neutrons	The nucleus contains two fewer protons and two fewer neutrons.
Beta	1 electron	One neutron decays to form a proton and an electron. The electron is emitted.

The radioactive decay of a **parent isotope** (the original element) leads to the formation of stable **daughter product**, also known as daughter isotope. As time passes, the number of parent isotopes decreases and the number of daughter isotopes increases (**Figure** 1.22).

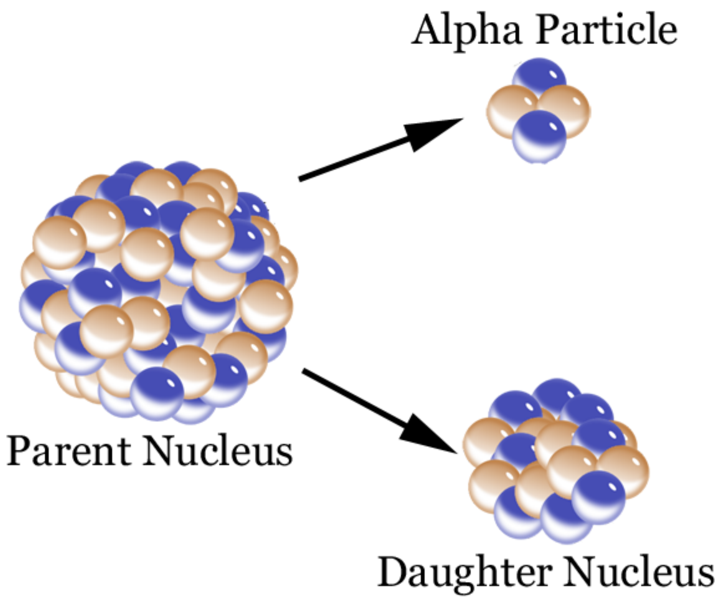


FIGURE 1.22
A parent emits an alpha particle to create a daughter.

An animation of radioactive decay: http://lectureonline.cl.msu.edu/~mmp/applist/decay/decay.htm .

Half-Lives

Radioactive materials decay at known rates, measured as a unit called **half-life**. The half-life of a radioactive substance is the amount of time it takes for half of the parent atoms to decay. This is how the material decays over time (see **Table** 1.2).

TABLE 1.2: Radioactive Decay

No. of half lives passed	Percent parent remaining	Percent daughter produced
0	100	0
1	50	50
2	25	75
3	12.5	87.5
4	6.25	93.75
5	3.125	96.875
6	1.563	98.437
7	0.781	99.219
8	0.391	99.609

Pretend you find a rock with 3.125% parent atoms and 96.875% daughter atoms. How many half lives have passed? If the half-life of the parent isotope is 1 year, then how old is the rock? The decay of radioactive materials can be shown with a graph (**Figure** 1.23).

An animation of half-life: http://einstein.byu.edu/~masong/htmstuff/Radioactive2.html .

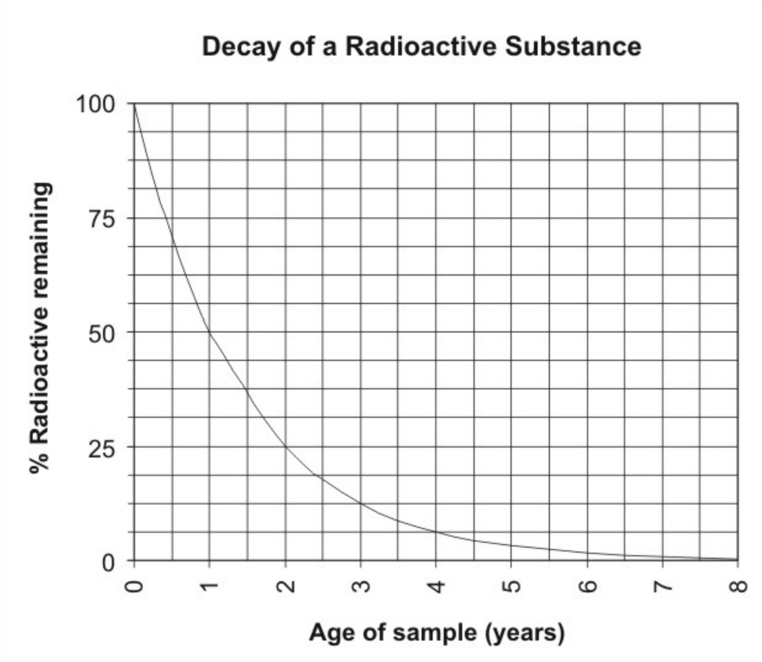
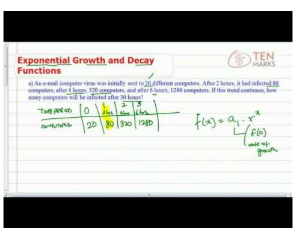


FIGURE 1.23
Decay of an imaginary radioactive substance with a half-life of one year.

Notice how it doesn't take too many half lives before there is very little parent remaining and most of the isotopes are daughter isotopes. This limits how many half lives can pass before a radioactive element is no longer useful for dating materials. Fortunately, different isotopes have very different half lives.

Radiometric decay is exponential. Learn how exponential growth and decay can be described mathematically in this video: http://www.youtube.com/watch?v=UbwMW7Q6F3E (4:46).



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Summary

- A half life is the time it takes for half of the parent isotopes of an element to change to daughter isotopes.
- With alpha decay, the nucleus loses two protons and two neutrons; with beta decay only one electron is lost.
- Radiometric decay is exponential.

Practice

Use this resource to answer the questions that follow.

https://www.youtube.com/watch?v=oFdR_yMKOCw

1. What is radiation?
2. How is radiation detected?

3. What happens to the ratio between protons and neutrons between smaller atoms and larger atoms?
4. Why does a large nucleus lose neutrons?
5. What is alpha decay and what charge and mass does it have?
6. What is beta decay and what charge and mass does it have?
7. What is gamma radiation and what charge and mass does it have?
8. What type of radiation does U-238 undergo? What does it lose?
9. Why does U-238 become Th-234?
10. Why does Cs-137 become Ba-137?
11. Why does Na-11 become Ne-12?

Practice Answers

1. Parts of atoms or energy that are given off by radioactive atoms.
2. With a Geiger Counter?
3. Small atoms have the same number of protons and neutrons, but large atoms have many more neutrons than protons.
4. The protons and neutrons are held together by the strong nuclear force. There is a perfect number of neutrons for the number of protons, but large atoms may not have the perfect number of neutrons to hold the nucleus together. This makes the nucleus unstable so it might lose protons or neutrons.
5. Alpha decay is two protons and two neutrons so it has a positive charge and the mass of a helium nucleus.
6. Beta decay is an electron so it has a negative charge and virtually no mass.
7. Gamma radiation is when the strong nuclear forces that hold the nucleus together wiggle and that energy is gamma radiation. It has no mass.
8. It undergoes alpha decay and it loses 2 protons and 2 neutrons, a helium nucleus.
9. Because the U=238 loses two protons and two neutrons. The loss of protons changes the element that the atom is and the loss of two protons makes that element thorium.
10. An electron was lost and one of the neutrons became a proton.
11. The Na loses a positron so it loses a proton and becomes neon.

Review

1. Describe the two types of radioactive decay that are relevant to dating earth materials.
2. For how many half lives is a set of parent and daughter isotopes useful as a system of dating?
3. What does it mean that radioactive decay is exponential?

Review Answers

1. Alpha decay, in which 2 protons and 2 neutrons are lost, and beta decay, in which 1 electron is lost.
2. After about 7 or 8 half lives there is very little of the parent isotope left.
3. The growth rate is proportional to the functions current value; the amount of parent always decreases by half.

1.10 Radiometric Dating

- Radiometric dating uses radioactive isotopes to get the absolute ages of rocks and other materials.

How do you date a rock (and who would want to)?

How you date a rock depends on what type of rock it is and how old it might be. Different radioactive isotopes have different half lives and so they are useful for dating different types and ages of rocks. Who would want to? Why, geologists, of course!

Radiometric Dating of Rocks

Radiometric dating is the process of using the concentrations of radioactive substances and daughter products to estimate the age of a material. Different isotopes are used to date materials of different ages. Using more than one isotope helps scientists to check the accuracy of the ages that they calculate.

Radiocarbon Dating

Radiocarbon dating is used to find the age of once-living materials between 100 and 50,000 years old. This range is especially useful for determining ages of human fossils and habitation sites (**Figure** 1.24).

The atmosphere contains three isotopes of carbon: carbon-12, carbon-13 and carbon-14. Only carbon-14 is radioactive; it has a half-life of 5,730 years. The amount of carbon-14 in the atmosphere is tiny and has been relatively stable through time.

Plants remove all three isotopes of carbon from the atmosphere during photosynthesis. Animals consume this carbon when they eat plants or other animals that have eaten plants. After the organism's death, the carbon-14 decays to stable nitrogen-14 by releasing a beta particle. The nitrogen atoms are lost to the atmosphere, but the amount of carbon-14 that has decayed can be estimated by measuring the proportion of radioactive carbon-14 to stable carbon-12. As time passes, the amount of carbon-14 decreases relative to the amount of carbon-12.

FIGURE 1.24
Carbon isotopes from the black material in these cave paintings places their creating at about 26,000 to 27,000 years BP (before present).

A video of carbon-14 decay is seen here: http://www.youtube.com/watch?v=81dWTeregEA ; a longer explanation is here: http://www.youtube.com/watch?v=udkQwW6aLik .

Potassium-Argon Dating

Potassium-40 decays to argon-40 with a half-life of 1.26 billion years. Argon is a gas so it can escape from molten magma, meaning that any argon that is found in an igneous crystal probably formed as a result of the decay of potassium-40. Measuring the ratio of potassium-40 to argon-40 yields a good estimate of the age of that crystal.

Potassium is common in many minerals, such as feldspar, mica, and amphibole. With its half-life, the technique is used to date rocks from 100,000 years to over a billion years old. The technique has been useful for dating fairly young geological materials and deposits containing the bones of human ancestors.

Uranium-Lead Dating

Two uranium isotopes are used for radiometric dating.

- Uranium-238 decays to lead-206 with a half-life of 4.47 billion years.
- Uranium-235 decays to form lead-207 with a half-life of 704 million years.

Uranium-lead dating is usually performed on zircon crystals (**Figure** 1.25). When zircon forms in an igneous rock, the crystals readily accept atoms of uranium but reject atoms of lead. If any lead is found in a zircon crystal, it can be assumed that it was produced from the decay of uranium.

Uranium-lead dating is useful for dating igneous rocks from 1 million years to around 4.6 billion years old. Zircon crystals from Australia are 4.4 billion years old, among the oldest rocks on the planet.

FIGURE 1.25
Zircon crystal.

Limitations of Radiometric Dating

Radiometric dating is a very useful tool for dating geological materials but it does have limits:

1. The material being dated must have measurable amounts of the parent and/or the daughter isotopes. Ideally, different radiometric techniques are used to date the same sample; if the calculated ages agree, they are thought to be accurate.
2. Radiometric dating is not very useful for determining the age of sedimentary rocks. To estimate the age of a sedimentary rock, geologists find nearby igneous rocks that can be dated and use relative dating to constrain the age of the sedimentary rock.

Using Radiometric Ages to Date Other Materials

As you've learned, radiometric dating can only be done on certain materials. But these important numbers can still be used to get the ages of other materials! How would you do this? One way is to constrain a material that cannot be dated by one or more that can. For example, if sedimentary rock A is below volcanic rock B and the age of volcanic rock B is 2.0 million years, then you know that sedimentary rock A is older than 2.0 million years. If sedimentary rock A is above volcanic rock C and it's age is 2.5 million years then you know that sedimentary rock A is between 2.0 and 2.5 million years. In this way, geologists can figure out the approximate ages of many different rock formations.

Summary

- Radiocarbon is useful for relatively young, carbon-based materials; other longer-lived isotopes are good for older rocks and minerals.
- Different isotope pairs are useful for certain materials of certain ages.
- Radiometric dating cannot be used if parent or daughter are not measurable or if one or the other has been lost from the system.

Practice

Use this resource to answer the questions that follow.

https://www.youtube.com/watch?v=2io5opwhQMQ

1. What is radiocarbon dating?
2. What are the three isotopes of carbon and how many protons and neutrons do they each have? Which isotope of carbon is not stable?
3. How does carbon-14 form?
4. Why is carbon-14 used for radiocarbon dating?
5. How does carbon get into a living thing? How does carbon-14 get into a living thing?
6. How much carbon-14 is in your body when you are alive? What happens to the carbon-14 in your body after you die?
7. What is the half life of carbon-14?
8. What's the greatest age that a thing can be to be able to be dated by carbon-14?
9. How do we know that carbon-14 dating is accurate?
10. Why can't you use radiocarbon dating on an object from 1965??

Practice Answers

1. A way to use the amount of carbon-14 left in an object to determine how old it is.
2. Carbon-12 has 6 protons and 6 neutrons; carbon-13 has 6 protons and 7 neutrons; carbon-14 has 6 protons and 8 neutrons, which is not stable.
3. Nitrogen in the atmosphere is ht by cosmic rays and it forms carbon-14.
4. Carbon-14 gives off beta particles and turns back into nitrogen. The amount of carbon-14 in something tells us how old it is.
5. The carbon is taken up by plants during photosynthesis and an animal eats it as food; sometimes that carbon is carbon-14
6. The amount in the atmosphere and the amount in the body is the same when the person is alive, but it decays after the person die.
7. 5730 years
8. about 60,000 years ago
9. Ages determined by carbon-14 match dating of objects we know the ages of.
10. Nuclear weapons testing added addition carbon-14 into the atmosphere.

Review

1. How would you determine which isotope pair to use for a particular material?
2. How does potassium-argon dating work and on what materials does it work best on?
3. What types of rocks are best for radiometric dating and why?

Review Answers

1. You need to use an isotope pair that is found in the material you want to date. For example, radiocarbon dating needs an organic substance to work. You also need to find something that is effective for the time frame the material is from. For example, radiocarbon can't be used on things that are more than about 60,000 years old because there is not enough carbon-14 left to count.
2. Potassium-40 decays to arbon-40 with a half-life of 1.26 billion years. Since argon is a gas, the technique must be used on a crystal that has been stable and not lost the gas over time. It must also be used on materials that are the right age, about 100,000 years to more than 1 billion years.
3. The best rocks for radiometric dating are igneous because the crystals do not break apart as easily so they store the parent and the daughter well. For radiocarbon the material must be organic.

1.11 Age of Earth

- Know how scientists arrived at the conclusion that Earth is 4.6 billion years old.

How old is Earth and how do scientists know?

4.6 billion years old. Arriving at this number wasn't easy but there are many lines of evidence that have allowed scientists to reach that conclusion.

Indirect Estimates

During the 18th and 19th centuries, geologists tried to estimate the age of Earth with indirect techniques. What methods can you think of for doing this? One example is that by measuring how much sediment a stream deposited in a year, a geologist might try to determine how long it took for a stream to deposit an ancient sediment layer. Not surprisingly, these methods resulted in wildly different estimates. A relatively good estimate was produced by the British geologist Charles Lyell, who thought that 240 million years had passed since the appearance of the first animals with shells. Today scientists know that this event occurred about 530 million years ago.

In 1892, William Thomson (later known as Lord Kelvin) calculated that the Earth was 100 million years old. He did this systematically assuming that the planet started off as a molten ball and calculating the time it would take for it to cool to its current temperature. This estimate was a blow to geologists and supporters of Charles Darwin's theory of evolution, which required an older Earth to provide time for geological and evolutionary processes to take place.

Thomson's calculations were soon shown to be flawed when radioactivity was discovered in 1896. What Thomson didn't know is that radioactive decay of elements inside Earth's interior provides a steady source of heat. Thomson had grossly underestimated Earth's age.

More Quantitatively

Radioactivity turned out to be useful for dating Earth materials and for coming up with a quantitative age for Earth. Scientists not only date ancient rocks from Earth's crust, they also date meteorites that formed at the same time Earth and the rest of the solar system were forming. Moon rocks also have been radiometrically dated.

Using a combination of radiometric dating, index fossils, and superposition, geologists have constructed a well-defined timeline of Earth history. With information gathered from all over the world, estimates of rock and fossil ages have become increasingly accurate. This is the modern geologic time scale with all of the ages.

All of this evidence comes together to pinpoint the age of Earth at 4.6 billion years. A video discussing the evidence for this is found here: http://www.youtube.com/watch?v=w5369-OobM4 .

The age of Earth is also discussed in this video: http://www.youtube.com/watch?v=lplcRdNDcps .

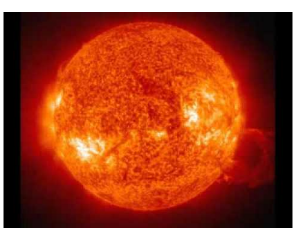
Summary

- Early geologists estimated Earth's age in a variety of inaccurate ways like the amount of time it might take for a sediment layer to be deposited.
- Estimates of how long it would take for a molten Earth to cool were also too young since scientists didn't know about radioactivity.
- Radiometric dating of meteorites and Moon rocks indicate that Earth is 4.6 billion years old.

Practice

Use this resource to answer the questions that follow.

http://www.youtube.com/watch?v=w5369-OobM4



MEDIA

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URL: http://gamma.ck12.org/flx/render/embeddedobject/4810

1. How does comparative dating indicate that Earth is old?
2. How does dendrochronology show that Earth is older than 6,000 years?
3. How does carbon dating show Earth is older than 6,000 years?
4. How do we know that carbon dating works?
5. Why aren't coal and diamonds dated using the C-14 method?
6. Where does DNA dating lead human ancestors to?
7. What is paleomagnetic dating?
8. What is potassium-argon dating useful for?
9. What has been found with radiometric dating?

10. What do creation scientists need to do to show that Earth is actually young?

Practice Answers

1. By determining the relative ages of rocks and using correlation, geologists can put together a set of rocks and their ages.
2. If tree rings are matched up so that there is a continuous scale, the ages go back beyond 6,000 years.
3. Carbon-14 to other carbon isotopes is stable in living things, but C-14 decays in dead organisms. The rate of decay is known so objects can be dated by determining the amount of C-14 left in an object.
4. It can be checked by dating objects of known age, it can be dated in different labs, objects can be dated in order.
5. C-14 levels are high near rocks that have uranium.
6. DNA changes show that humans came from Africa around 50,000 years ago.
7. Earth's magnetic fields flip throughout Earth history, which can be dated.
8. It has a half life of 1.3 billion years so it is useful for older materials and ones that can trap argon gas.
9. The solar system and other locations all confirm the same ages.
10. They need to devise a scientific dating system that shows that the rocks scientists date radiometrically are old are actually young using scientific method.

Review

1. How do scientists know that Earth is 4.6 billion years old?
2. Why was Lord Kelvin's estimate of Earth's age too young?
3. How does the modern geologic time scale differ from the original?

Review Answers

1. That age comes from radiometric dating of meteorites and lunar rocks. Other evidence points to an old age, but doesn't quite get there; e.g. there are no rocks on Earth that are that old.
2. Lord Kelvin didn't know about radioactivity, which add heat, so he just thought Earth was cooling without ever getting added heat.
3. The original was a relative scale and had no absolute ages. The addition of absolute ages from radiometric methods has made the scale more detailed.

1.12 Formation of the Sun and Planets

- Sun and planets formed from a solar nebula about 4.6 billion years ago.

Do scientists just make this stuff up?

No! Although our Solar System formed nearly 5 billion years ago, we can see stars forming elsewhere in the galaxy, such as in the Large Magellanic cloud 160,000 light years away. Although we can't know for sure, astronomers think that our early solar system looked very much like this.

Formation of the Solar System

The most widely accepted explanation of how the solar system formed is called the **nebular hypothesis**. According to this hypothesis, the Sun and the planets of our solar system formed about 4.6 billion years ago from the collapse of a giant cloud of gas and dust, called a **nebula**.

The nebula was drawn together by gravity, which released gravitational potential energy. As small particles of dust and gas smashed together to create larger ones, they released kinetic energy. As the nebula collapsed, the gravity at the center increased and the cloud started to spin because of its angular momentum. As it collapsed further, the spinning got faster, much as an ice skater spins faster when he pulls his arms to his sides during a spin.

Much of the cloud's mass migrated to its center but the rest of the material flattened out in an enormous disk. The disk contained hydrogen and helium, along with heavier elements and even simple organic molecules.

Formation of the Sun and Planets

As gravity pulled matter into the center of the disk, the density and pressure at the center became intense. When the pressure in the center of the disk was high enough, nuclear fusion began. A star was born—the Sun. The burning star stopped the disk from collapsing further.

Meanwhile, the outer parts of the disk were cooling off. Matter condensed from the cloud and small pieces of dust started clumping together. These clumps collided and combined with other clumps. Larger clumps, called planetesimals, attracted smaller clumps with their gravity. Gravity at the center of the disk attracted heavier particles,

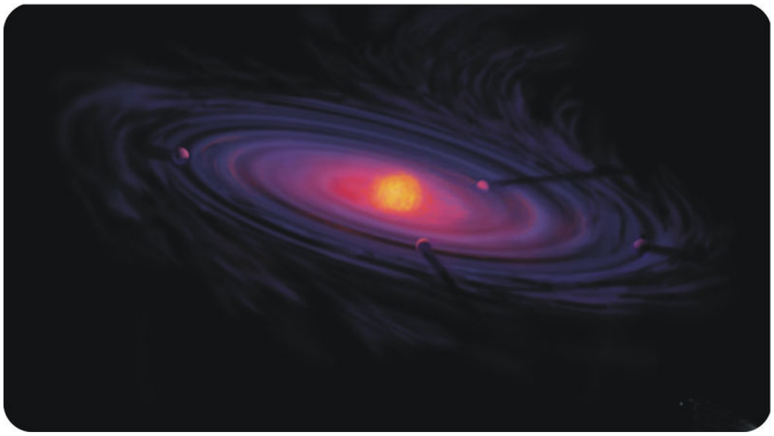


FIGURE 1.26
An artist's painting of a protoplanetary disk.

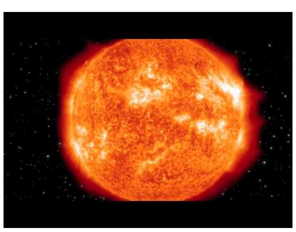
such as rock and metal and lighter particles remained further out in the disk. Eventually, the planetesimals formed protoplanets, which grew to become the planets and moons that we find in our solar system today.

Because of the gravitational sorting of material, the inner planets —Mercury, Venus, Earth, and Mars —formed from dense rock and metal. The outer planets —Jupiter, Saturn, Uranus and Neptune —condensed farther from the Sun from lighter materials such as hydrogen, helium, water, ammonia, and methane. Out by Jupiter and beyond, where it's very cold, these materials form solid particles.

The nebular hypothesis was designed to explain some of the basic features of the solar system:

- The orbits of the planets lie in nearly the same plane with the Sun at the center
- The planets revolve in the same direction
- The planets mostly rotate in the same direction
- The axes of rotation of the planets are mostly nearly perpendicular to the orbital plane
- The oldest moon rocks are 4.5 billion years

This video, from the ESA, discusses the Sun, planets, and other bodies in the Solar System and how they formed **(1a, 1d)**. The first part of the video explores the evolution of our view of the solar system starting with the early Greeks who reasoned that since some points of light - which they called planets - moved faster than the stars, they must be closer: http://www.youtube.com/watch?v=-NxfBOhQ1CY (8:34).



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Summary

- A giant cloud of dust and gas, called a nebula, collapsed to form the solar system; this is the nebular hypothesis.
- The nebular hypothesis explains many of the features of the solar system like the orbital plane, the revolution and rotation of the planets, the relationship of the axes of rotation and the orbital plane and the age of moon rocks.
- Planets nearer the Sun are similar because they formed of denser metal and rocks, but planets further out are lighter and gaseous.

Practice

Use this resource to answer the questions that follow.

https://www.youtube.com/watch?v=Uhy1fucSRQI

1. How old is the story of our solar system?
2. Why does the story of our solar system start with an exploding star?
3. What was the early Earth made of and how did it come together?
4. What was happening at the heart of the nebula?
5. What happened when the sun ignited?
6. Where and what names are the huge gas planets?
7. What are the inner planets and what are they made of?
8. How long will the sun burn in all?

Practice Answers

1. 6 billion years
2. That star made any of the materials that we have in our solar system, like nitrogen, oxygen, iron, silica and all the other stuff needed for Earth.
3. stardust and gravity
4. Fusion was beginning to create our sun.
5. A big blast of solar wind blew all the rest of the debris out of the solar system.
6. The huge gas planets are in the outer reaches of the solar system. They are Jupiter, Saturn, Uranus and Neptune.
7. Mercury, Venus, Earth and Mars are in the inner solar system and they are rocky.
8. About 8 billion years.

Review

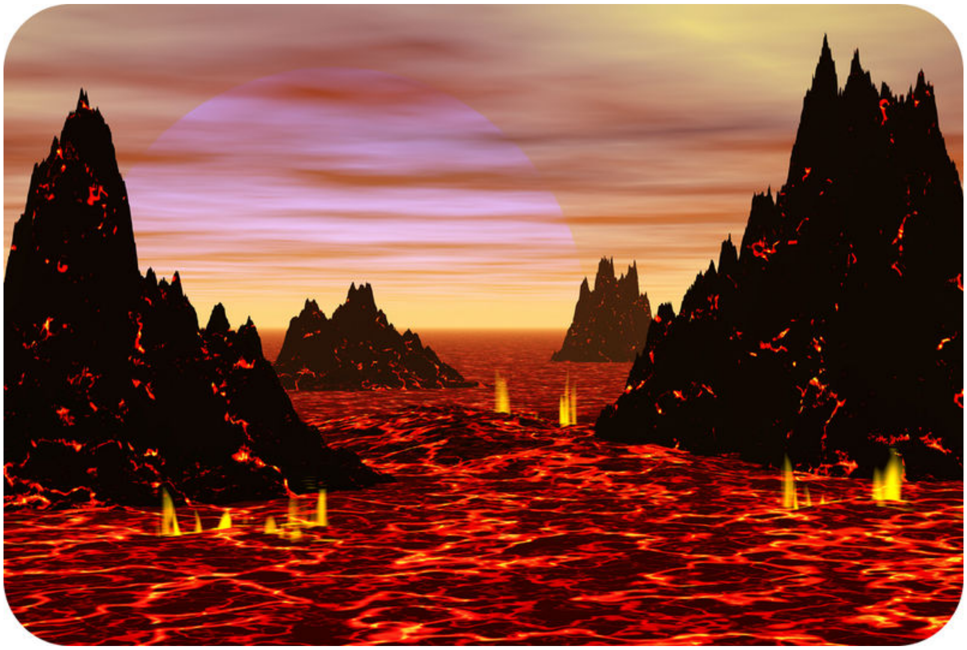
1. What is the nebular hypothesis?
2. Why did the solar system form two very different groups of planets, the inner and outer planets?
3. How does the nebular hypothesis account for the observable features of the solar system?

Review Answers

1. The hypothesis that the solar system formed from a spinning cloud of gas and dust, a nebula.
2. Gravity pulled the heavy material inward in the solar nebula. The rocky and metallic materials were closer in to the sun so they formed the inner planets and the gases and ices were further out and they formed the outer planets.
3. The nebular hypothesis explains: the orbits of the planets are on nearly the same plane; the planets revolve in the same direction; the axes of rotation of the planets are nearly perpendicular to the orbital plane; the oldest moon rocks are 4.5 billion years old.

1.13 Formation of Earth

- Earth formed with the rest of the solar system and differentiated into layers.



What was early Earth like?

Earth was not always the moderate and habitable planet it is today. In its earliest days, Earth was scorching hot and without an atmosphere or water. If life originated early on, it was wiped out by the terrible conditions.

Formation of Earth

Earth formed at the same time as the other planets. The history of Earth is part of the history of the Solar System.

Planets Form

Earth came together (accreted) from the cloud of dust and gas known as the solar nebula nearly 4.6 billion years ago, the same time the Sun and the rest of the solar system formed. Gravity caused small bodies of rock and metal orbiting the proto-Sun to smash together to create larger bodies. Over time, the planetoids got larger and larger until they became planets.

Molten Earth

When Earth first came together it was really hot, hot enough to melt the metal elements that it contained. Earth was so hot for three reasons:

- Gravitational contraction: As small bodies of rock and metal accreted, the planet grew larger and more massive. Gravity within such an enormous body squeezes the material in its interior so hard that the pressure swells. As Earth's internal pressure grew, its temperature also rose.

- Radioactive decay: Radioactive decay releases heat, and early in the planet's history there were many radioactive elements with short half lives. These elements long ago decayed into stable materials, but they were responsible for the release of enormous amounts of heat in the beginning.
- Bombardment: Ancient impact craters found on the Moon and inner planets indicate that asteroid impacts were common in the early solar system. Earth was struck so much in its first 500 million years that the heat was intense. Very few large objects have struck the planet in the past many hundreds of millions of year.

Differentiation

When Earth was entirely molten, gravity drew denser elements to the center and lighter elements rose to the surface. The separation of Earth into layers based on density is known as **differentiation**. The densest material moved to the center to create the planet's dense metallic core. Materials that are intermediate in density became part of the mantle (**Figure** 1.27).

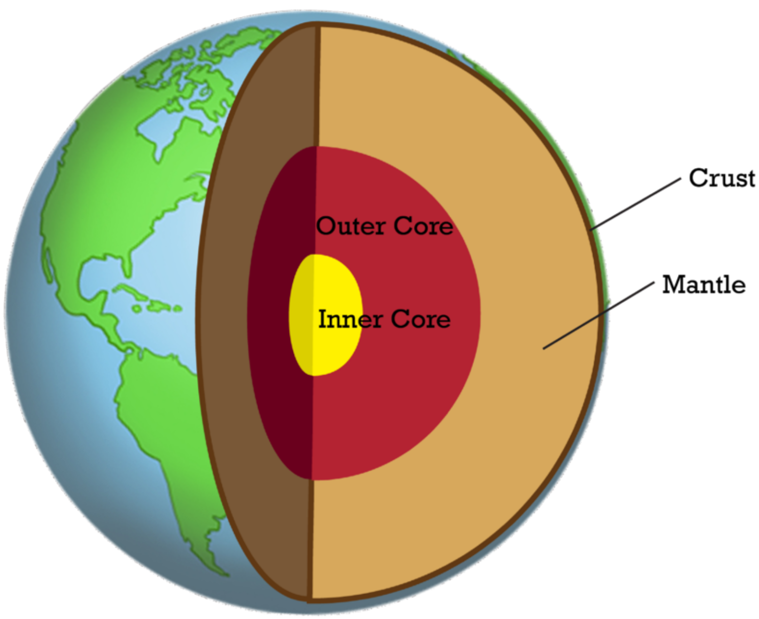


FIGURE 1.27
Earth's interior: Inner core, outer core, mantle, and crust.

First Crust

Lighter materials accumulated at the surface of the mantle to become the earliest crust. The first crust was probably basaltic, like the oceanic crust is today. Intense heat from the early core drove rapid and vigorous mantle convection so that crust quickly recycled into the mantle. The recycling of basaltic crust was so effective that no remnants of it are found today.

Early Solar System Materials

There is not much material to let us know about the earliest days of our planet Earth. What there is comes from three sources: (1) zircon crystals, the oldest materials found on Earth, which show that the age of the earliest crust formed at least 4.4 billion years ago; (2) meteorites that date from the beginning of the solar system, to nearly 4.6 billion years ago (**Figure** 1.28); and (3) lunar rocks, which represent the early days of the Earth-Moon system as far back as 4.5 billion years ago.

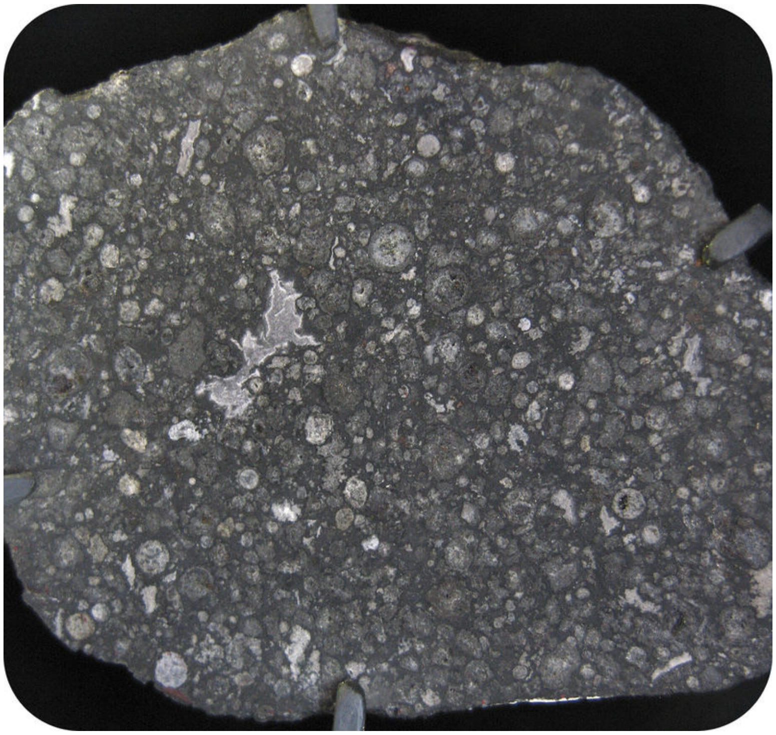


FIGURE 1.28
The Allende Meteorite is a carbonaceous chondrite that struck Earth in 1969. The calcium-aluminum-rich inclusions are fragments of the earliest solar system.

Summary

- In the beginning, Earth was exceedingly hot due to gravitational contraction, the radioactive decay of short-lived isotopes, and bombardment from meteorites.
- The molten Earth separated into layers by density in a process known as differentiation.
- We know about the early Earth from zircon crystals, meteorites that originated elsewhere in the solar system, and moon rocks.

Practice

Use this resource to answer the questions that follow.

https://www.youtube.com/watch?v=VbNXh0GaLYo End at 7:26.

1. What did the shock wave do to the material that was gathered in our nebula?
2. Why do scientists think that a supernova was necessary for the solar system to form?
3. Why did fusion start in the center?
4. How do seeds of planets form?
5. How did the moon and Earth form?

Practice Answers

1. The shock wave went though the cloud of molecules and it compressed the material so it had critical density to accrete into a star and solar system.
2. Some of the really heavy elements we have in the solar system can only form in the heat of a supernova. The uranium we have on Earth formed about when Earth formed, about 4.5 billion years ago.
3. The density and temperature became high enough.

4. Rocks smash together and gravity pulls things in and they clump together into planetesimals.
5. A very large asteroid about the size of Mars struck Earth and the combined energy melted them and molten material splashed into orbit. Some was captured by Earth and some was in orbit and eventually came together to form the Moon. Earth cooled from the remaining molten material.

Review

1. Radioactive elements inside the planet release heat now, but why was so much more heat released earlier in Earth's history that is released now?
2. Describe how and why Earth material separated into layers.
3. How do zircon crystals indicate when the first crust formed?

Review Answers

1. Many radioactive elements have short half lives so those elements released heat in the early Earth but they are now stable and do not release heat.
2. The planet was molten and gravity pulled in the heaviest materials, the metals, to crate the core. The less heavy materials were left behind to go into the mantle and crust.
3. Zircon is a mineral that forms in granitic rocks. It formed in early granite and then the granite weathered and eroded, but the zircon remained behind and can now be dated.

1.14 Formation of the Moon

- Moon's birth story accounts for its amazing features.

Why is this called the Genesis Rock?

The Genesis Rock was brought from the Moon to Earth by Apollo 15 astronauts. The rock is only 100 million years younger than the solar system and comes from the Moon's original crust.

How the Moon Formed

One of the most unique features of planet Earth is its large Moon. Unlike the only other natural satellites orbiting an inner planet, those of Mars, the Moon is not a captured asteroid. Understanding the Moon's birth and early history reveals a great deal about Earth's early days.

Features of the Moon

To determine how the Moon formed, scientists had to account for several lines of evidence:

- The Moon is large; not much smaller than the smallest planet, Mercury.

- Earth and Moon are very similar in composition.
- Moon's surface is 4.5 billion years old, about the same as the age of the solar system.
- For a body its size and distance from the Sun, the Moon has very little core; Earth has a fairly large core.
- The oxygen isotope ratios of Earth and Moon indicate that they originated in the same part of the solar system.
- Earth has a faster spin than it should have for a planet of its size and distance from the Sun.

Can you devise a "birth story" for the Moon that takes all of these bits of data into account?

Moon's Birth Story

Astronomers have carried out computer simulations that are consistent with these facts and have detailed a birth story for the Moon. A little more than 4.5 billion years ago, roughly 70 million years after Earth formed, planetary bodies were being pummeled by asteroids and planetoids of all kinds. Earth was struck by a Mars-sized asteroid (**Figure** 1.29).

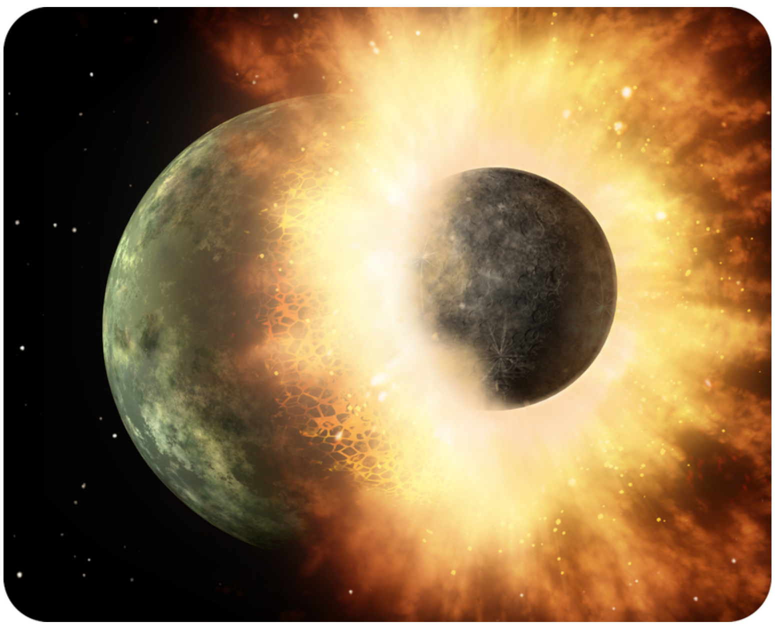


FIGURE 1.29
An artist's depiction of the impact that produced the Moon.

The tremendous energy from the impact melted both bodies. The molten material mixed up. The dense metals remained on Earth but some of the molten, rocky material was flung into an orbit around Earth. It eventually accreted into a single body, the Moon. Since both planetary bodies were molten, material could differentiate out of the magma ocean into core, mantle, and crust as they cooled. Earth's fast spin is from energy imparted to it by the impact.

Moon Rocks

Lunar rocks reveal an enormous amount about Earth's early days. The Genesis Rock, with a date of 4.5 billion years, is only about 100 million years younger than the solar system (see opening image). The rock is a piece of the Moon's anorthosite crust, which was the original crust. Why do you think Moon rocks contain information that is not available from Earth's own materials?

More information about the Genesis Rock from NASA is found here: http://www.nasa.gov/mission_pages/LRO/news/image_release042310.html .

Can you find how all of the evidence presented in the bullet points above is present in the Moon's birth story?

Summary

- The scientific explanation for how the Moon formed must take into account its features, such as its large size, internal structure, chemical composition, and spin.
- Earth was struck by a giant asteroid that melted the planet and asteroid and flung material into orbit where it coalesced and cooled to become the Moon.
- Moon's original crust is anorthosite, a feldspar-rich, light rock.

Practice

Use this resource to answer the questions that follow.

http://www.space.com/9926-moon-life.html

1. What is the mass of the Moon?
2. Why is our Moon unique?
3. What is the Moon made of?
4. What created the Moon?
5. How did the Earth maintain its integrity?
6. Why were the tides important to life on Earth?

Practice Answers

1. About 1% the mass of the Earth.
2. It is very large relative to Earth compared to other planet's Moons to their planet.
3. The same elements arranged the same way as Earth is made of: silicon, oxygen, aluminum and iron in varying proportions.
4. A very large impact 4.5 billion years ago with an asteroid about as big as Mars. Part of the mantles of the planets were vaporized and made a cloud around Earth. Then the Moon accreted.
5. Earth had so much mass and so much gravitational binding energy it stayed together and mostly took in the impactor.
6. Tides are important to life.

Review

1. Relay the story of how the Moon formed. Integrate as many of the Moon's features into the story as possible.
2. Why are Earth and Moon roughly the same age as the rest of the solar system?
3. Why do scientists learn a lot about the early Earth from their studies of the Moon?

Review Answers

1. A large asteroid struck Earth so that both were molten. The dense materials remained on earth but the lighter ones flew off into space. These accreted into the single Moon, which is large because it's not just a captured asteroid like many other moons. The molten bodies differentiated into core mantle and crust and they are very similar in composition because they are from the same two bodies except Moon has relatively less core since the denser materials stayed with Earth. They are both about the same age. Earth's fast spin is the remnants of the impact.

2. Everything formed from the nebula at around the same time.
3. The Moon formed when Earth was young but because it doesn't have plate tectonics or an atmosphere it is largely as it was 4.5 billion years ago so it reflects what was going on in this part of the solar system at that time.

1.15 Early Atmosphere and Oceans

- Earth's early atmosphere formed from volcanic outgassing and meteorites, and the later evolution of photosynthesis released oxygen, allowing more complex life to evolve.

Where did the first atmosphere and oceans come from?

At first, Earth did not have an atmosphere or free water since the planet was too hot for gases and water to collect. The atmosphere and oceans that we see today evolved over time. The gases came from within the planet and from far out in the solar system.

Earth's First Atmosphere

Earth's first atmosphere was made of hydrogen and helium, the gases that were common in this region of the solar system as it was forming. Most of these gases were drawn into the center of the solar nebula to form the Sun. When Earth was new and very small, the solar wind blew off atmospheric gases that collected. If gases did collect, they were vaporized by impacts, especially from the impact that brought about the formation of the Moon.

Eventually things started to settle down and gases began to collect. High heat in Earth's early days meant that there were constant volcanic eruptions, which released gases from the mantle into the atmosphere (see opening image). Just as today, volcanic **outgassing** was a source of water vapor, carbon dioxide, small amounts of nitrogen, and other gases.

Scientists have calculated that the amount of gas that collected to form the early atmosphere could not have come entirely from volcanic eruptions. Frequent impacts by asteroids and comets brought in gases and ices, including water, carbon dioxide, methane, ammonia, nitrogen, and other volatiles from elsewhere in the solar system (**Figure** 1.30).

Calculations also show that asteroids and comets cannot be responsible for all of the gases of the early atmosphere, so both impacts and outgassing were needed.

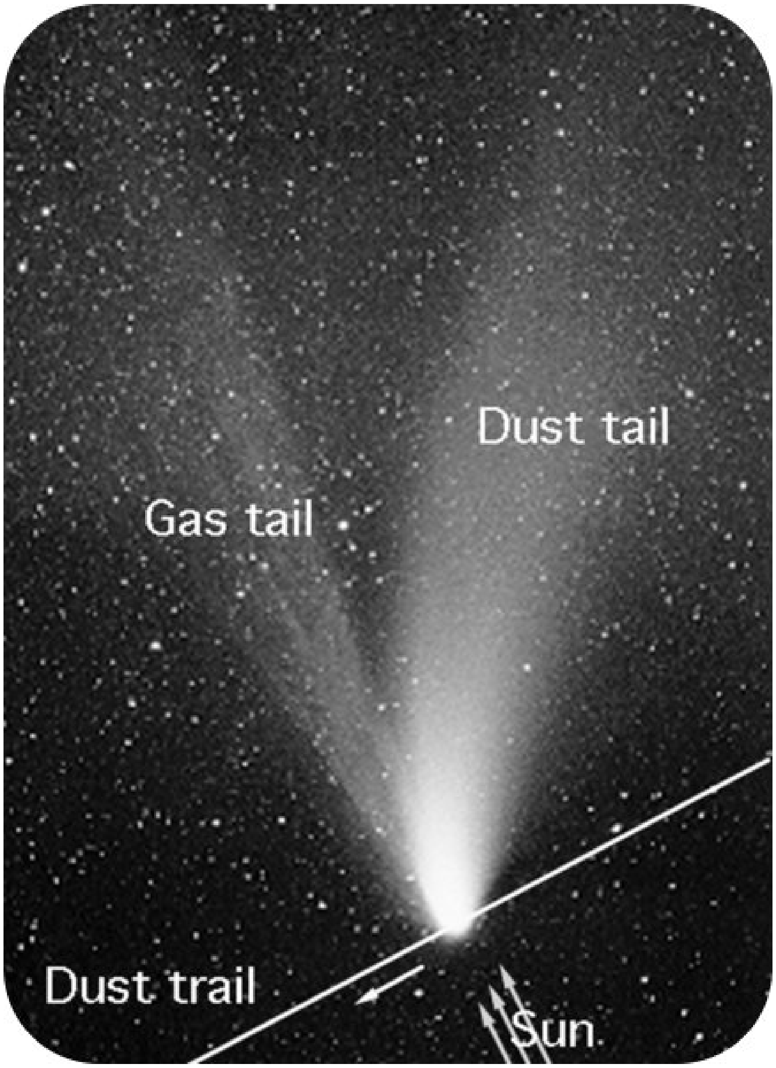


FIGURE 1.30
The gases that create a comet's tail can become part of the atmosphere of a planet.

Earth's Second Atmosphere

The second atmosphere, which was the first to stay with the planet, formed from volcanic outgassing and comet ices. This atmosphere had lots of water vapor, carbon dioxide, nitrogen, and methane but almost no oxygen. Why was there so little oxygen? Plants produce oxygen when they photosynthesize but life had not yet begun or had not yet developed photosynthesis. In the early atmosphere, oxygen only appeared when sunlight split water molecules into hydrogen and oxygen and the oxygen accumulated in the atmosphere.

Without oxygen, life was restricted to tiny simple organisms. Why is oxygen essential for most life on Earth?

1. Oxygen is needed to make ozone, a molecule made of three oxygen ions, O_3. Ozone collects in the atmospheric ozone layer and blocks harmful ultraviolet radiation from the Sun. Without an ozone layer, life in the early Earth was almost impossible.

2. Animals need oxygen to breathe. No animals would have been able to breathe in Earth's early atmosphere.

Early Oceans

The early atmosphere was rich in water vapor from volcanic eruptions and comets. When Earth was cool enough, water vapor condensed and rain began to fall. The water cycle began. Over millions of years enough precipitation collected that the first oceans could have formed as early as 4.2 to 4.4 billion years ago. Dissolved minerals carried by stream runoff made the early oceans salty. What geological evidence could there be for the presence of an early ocean? Marine sedimentary rocks can be dated back about 4 billion years.

By the Archean, the planet was covered with oceans and the atmosphere was full of water vapor, carbon dioxide, nitrogen, and smaller amounts of other gases.

Earth's Third Atmosphere

When photosynthesis evolved and spread around the planet, oxygen was released in abundance. The addition of oxygen is what created Earth's third atmosphere. This event, which occurred about 2.5 billion years ago, is sometimes called the oxygen catastrophe because so many organisms died. Although entire species died out and went extinct, this event is also called the Great Oxygenation Event because it was a great opportunity. The organisms that survived developed a use for oxygen through **cellular respiration**, the process by which cells can obtain energy from organic molecules. This opened up many opportunities for organisms to evolve to fill different niches and many new types of organisms first appeared on Earth.

Banded-Iron Formations

What evidence do scientists have that large quantities of oxygen entered the atmosphere? The iron contained in the rocks combined with the oxygen to form reddish iron oxides. By the beginning of the Proterozoic, banded-iron formations (BIFs) were forming. Banded-iron formations display alternating bands of iron oxide and iron-poor chert that probably represent a seasonal cycle of an aerobic and an anaerobic environment.

The oldest BIFs are 3.7 billion years old, but they are very common during the Great Oxygenation Event 2.4 billion years ago (**Figure** 1.31). By 1.8 billion years ago, the amount of BIF declined. In recent times, the iron in these formations has been mined, and that explains the location of the auto industry in the upper Midwest.

FIGURE 1.31

Banded-iron formation.

UV Protection

With more oxygen in the atmosphere, ultraviolet radiation could create ozone. With the formation of an ozone layer to protect the surface of the Earth from UV radiation, more complex life forms could evolve.

Summary

- Earth's first atmosphere came from outgassing from the planet's interior and from asteroids and comets from elsewhere in the solar system.
- Earth's first and second atmosphere did not contain oxygen so there was no ozone layer to protect life from ultraviolet radiation and no oxygen for animals to breathe.
- Earth's third atmosphere contained oxygen that is a by-product of photosynthesis, allowing the evolution of animals and the formation of an ozone layer.

Practice

Use the resources below to answer the questions that follow.

- **Earth's Early Atmosphere** at http://www.windows2universe.org/earth/geology/earths_primordial_environs.html

1. What was the Earth's early atmosphere like?
2. On the early planet, where might the energy have come from to generate chemical reactions?
3. What did the Miller-Urey experiment show regarding the development of early life on Earth?
4. Why was UV able to reach Earth's surface?

- **More About the Early Atmosphere** at http://www.windows2universe.org/earth/past/earths_primordial_ocean.html

5. What is the Goldilocks theory?
6. What was the source of Earth's secondary atmosphere and what compounds were part of it?
7. Why do scientists believe that nitrogen dominates our current atmosphere?

Practice Answers

1. The first atmosphere was hydrogen based and included compounds like methane, hydrogen gas, and ammonia.
2. Energy could have come from lightning and ultraviolet radiation.
3. The experiment showed that the chemicals that are the foundation of living cells can be produced in a hydrogen-based atmosphere with UV and lightning as an energy source.
4. There was no ozone layer to block the UV.
5. Earth is at a distance from the Sun that is just right—so that it is not too hot and not too cold for water to exist in all three states, including as a liquid.
6. The secondary atmosphere came from Earth's interior through volcanic eruptions and included water, carbon dioxide, sulfur dioxide, hydrogen sulfide, hydrochloric acid, nitrogen, and nitrogen-oxides.
7. Nitrogen doesn't dissolve in water so it is left in the atmosphere.

Review

1. What were the first gases to collect in Earth's atmosphere? Where did they come from and where did they go?

2. What was the source of gases in Earth's first atmosphere that collected? What were those gases?
3. When did oxygen enter the atmosphere in abundance? Where did it come from? What was the effect on life on Earth?
4. What are banded-iron formations and why are they important to Earth historians?

Review Answers

1. The first gases were hydrogen and helium. They were part of the solar nebula. The strong solar wind blew them off into space.
2. Volcanic outgassing contributed water vapor, carbon dioxide, small amounts of nitrogen and other gases. Asteroids and comets brought in gases and ices including water vapor, carbon dioxide, ammonia, nitrogen and other volatiles.
3. Oxygen came from photosynthesis about 2.5 billion years ago. Many species of organisms died out because they couldn't handle the oxygen.
4. Banded-iron formations indicate when large quantities of oxygen entered the atmosphere because the iron oxidized. Once there was oxygen, animals could evolve.

1.16 Precambrian Continents

- Early continents were small and mantle convection was fast.

What did the first crust look like?

These ancient greenstones are metamophosed pillow lavas from much earlier in Earth history. These rocks are found in eastern Canada and similar rocks are found in cratons around the world.

Early Continents

The first crust was made of basaltic rock, like the current ocean crust. Partial melting of the lower portion of the basaltic crust began more than 4 billion years ago. This created the silica-rich crust that became the felsic continents.

Craton

The earliest felsic continental crust is now found in the ancient cores of continents, called the **cratons**. Rapid plate motions meant that cratons experienced many continental collisions. Little is known about the **paleogeography**, or the ancient geography, of the early planet, although smaller continents could have come together and broken up.

Geologists can learn many things about the Pre-Archean by studying the rocks of the cratons.

- Cratons also contain felsic igneous rocks, which are remnants of the first continents.
- Cratonic rocks contain rounded sedimentary grains. Of what importance is this fact? Rounded grains indicate that the minerals eroded from an earlier rock type and that rivers or seas also existed.

- One common rock type in the cratons is **greenstone**, a metamorphosed volcanic rock (**Figure** 1.32). Since greenstones are found today in oceanic trenches, what does the presence of greenstones mean? These ancient greenstones indicate the presence of subduction zones.

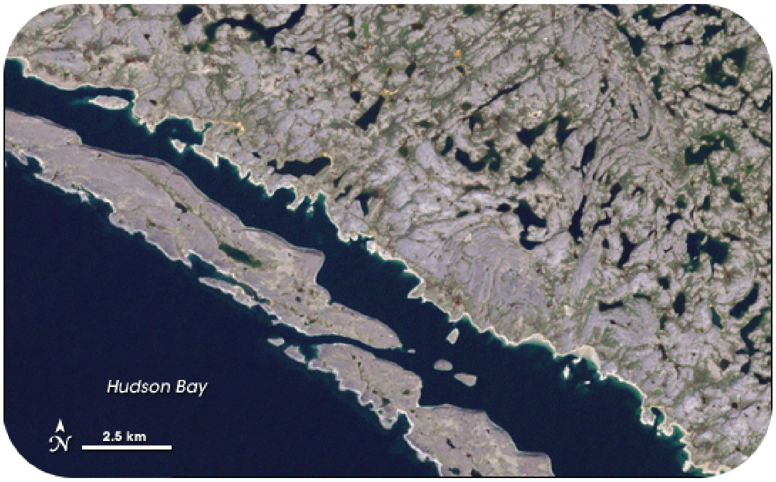


FIGURE 1.32
Ice age glaciers scraped the Canadian Shield down to the 4.28 billion year old greenstone in Northwestern Quebec.

Shield

Places the craton crops out at the surface is known as a **shield**. Cratons date from the Precambrian and are called Precambrian shields. Many Precambrian shields are about 570 million years old (**Figure** 1.33).

FIGURE 1.33
The Canadian Shield is the ancient flat part of Canada that lies around Hudson Bay, the northern parts of Minnesota, Wisconsin and Michigan and much of Greenland.

Platform

In most places the cratons were covered by younger rocks, which together are called a **platform**. Sometimes the younger rocks eroded away to expose the Precambrian craton (**Figure** 1.34).

FIGURE 1.34
The Precambrian craton is exposed in the Grand Canyon where the Colorado River has cut through the younger sedimentary rocks.

Early Convection

During the Pre-Archean and Archean, Earth's interior was warmer than today. Mantle convection was faster and plate tectonics processes were more vigorous. Since subduction zones were more common, the early crustal plates were relatively small.

Since the time that it was completely molten, Earth has been cooling. Still, about half the internal heat that was generated when Earth formed remains in the planet and is the source of the heat in the core and mantle today.

The presence of water on ancient Earth is revealed in a zircon crystal: http://www.youtube.com/watch?v=V21hFmZP5zM (3:13).

MEDIA
Click image to the left for use the URL below.
URL: http://gamma.ck12.org/flx/render/embeddedobject/1515

Summary

- The ancient core of a continent, at and beneath the surface, is its craton.
- The cratonic rock that is seen at the surface is called the shield. Where the shield is covered by younger sediments is the platform.
- Convection on early Earth was faster and so plate tectonics was faster. Since then, Earth has been cooling.

Practice

Use this resource to answer the questions that follow.

http://essayweb.net/geology/quicknotes/continents.shtml

1. What was Yilgarn?
2. What was Vaalbara and when was it formed?
3. When was Ur formed?
4. How was Arctica formed?
5. What was Atlantica composed of?
6. How was Nena formed?
7. When was Columbia formed? When did it begin to break apart?
8. When was Rodinia formed?

Practice Answers

1. A large craton that became the bulk of the Western Australia landmass.
2. Vaalbara was the first supercontinent that existed about 3.3 billion years ago. It was not all that big but there wasn't that much land yet.
3. Ur was an early continent from around 3 billion years old.
4. Atlantica formed about 2 billion years ago and was composed of the ancient cratons of what is now West and Central Africa and Northeastern South America.
5. Nena is short for Northern Europe and North America and it was formed about 1.8 billion years ago.
6. Columbia was the first real supercontinent at around 2 - 1.8 billion years ago. It began to break apart 1.5 billion years ago.
7. Rodinia formed around 1.1 to 1.0 billion years ago.

Review

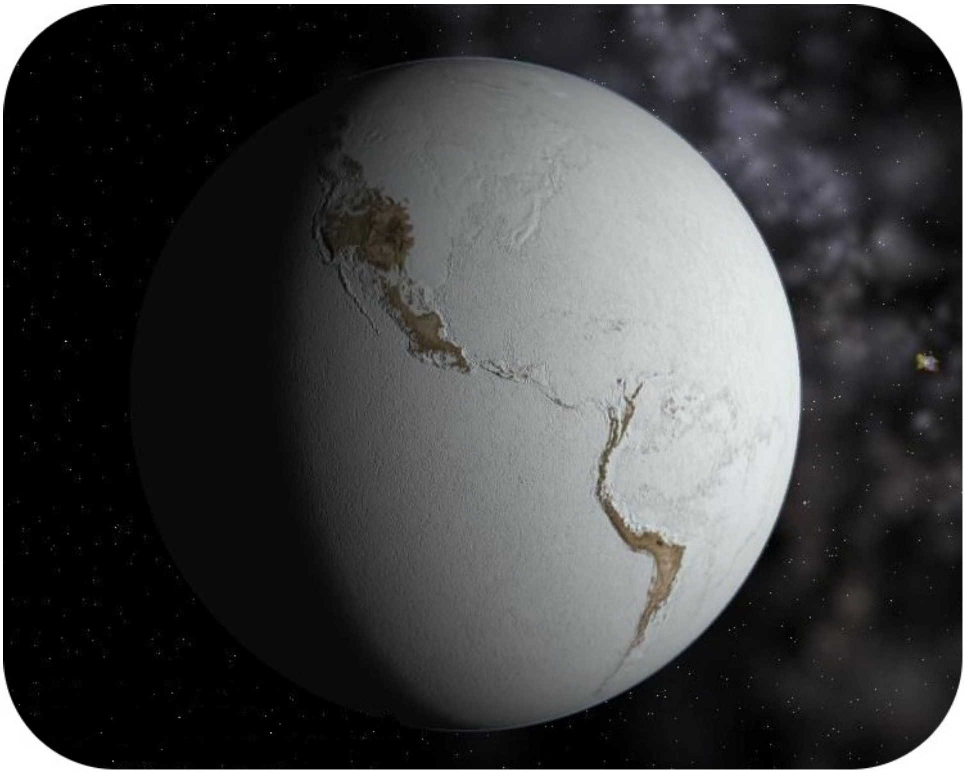
1. Why is it that the felsic continental crust could not be Earth's first crust?
2. What are greenstones and why are they important in understanding early Earth history?
3. Why was plate tectonics more vigorous in the early Earth? What would plate tectonics have been like?

Review Answers

1. Silica-rich rocks had to form from partial melting of mafic rocks so the felsic continental crust could not have been the first crust.
2. Greenstone is metamorphosed volcanic rock. It indicates teh presence of subduction zones so there was probably plate tectonics.
3. Earth was hotter and mantle convection was faster so the small plates moved around quickly.

1.17 Precambrian Plate Tectonics

- Later Precambrian plate tectonics resembled modern plate tectonics.



Was Earth ever so cold that it was completely encased in ice?

There is a hypothesis that much of the planet was covered by ice at the end of the Precambrian. This hypothesis is called Snowball Earth. One line of evidence is the rapid evolution of life in the Ediacara and Cambrian periods. It is thought that when the ice melted and conditions were favorable, life evolved rapidly.

Precambrian Plate Tectonics

By the end of the Archean, about 2.5 billion years ago, plate tectonics processes were completely recognizable. Small Proterozoic continents known as **microcontinents** collided to create **supercontinents**, which resulted in the uplift of massive mountain ranges.

The history of the North American craton is an example of what generally happened to the cratons during the Precambrian. As the craton drifted, it collided with microcontinents and oceanic island arcs, which were added to the continents. Convergence was especially active between 1.5 and 1.0 billion years ago. These lands came together to create the continent of Laurentia.

About 1.1 billion years ago, Laurentia became part of the supercontinent Rodinia (**Figure** 1.35). Rodinia probably contained all of the landmass at the time, which was about 75% of the continental landmass present today.

Rodinia broke up about 750 million years ago. The geological evidence for this breakup includes large lava flows that are found where continental rifting took place. Seafloor spreading eventually started and created the oceans between the continents.

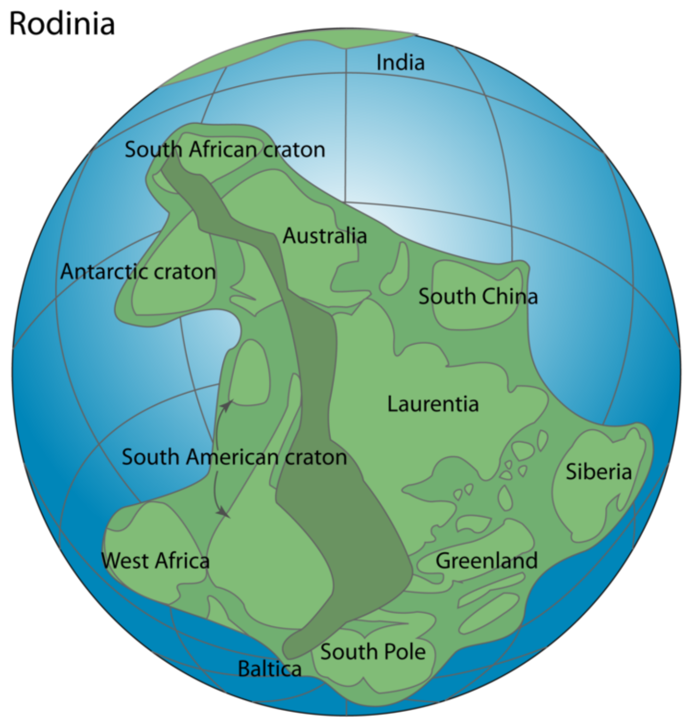
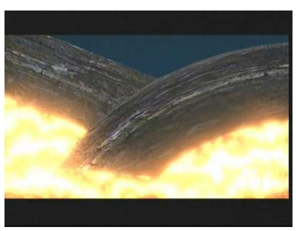


FIGURE 1.35
Rodinia as it came together about 1.1 billion years ago.

The breakup of Rodinia may have triggered Snowball Earth around 700 million years ago.

This video explores the origin of continents and early plate tectonics on the young Earth: http://www.youtube.com/watch?v=QDqskltCixA (5:17).



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Summary

- About 2 billion years after Earth formed, plate tectonics processes were similar to those around today.
- Microcontinents collided together to create larger continents and supercontinents.
- The supercontinent of Rodinia came together about 1.1 billion years ago and broke apart about 750 million years ago.

Practice

Use this resource to answer the questions that follow.

https://www.youtube.com/watch?v=QDqskltCixA

1. What were the landmasses like at 2.5 billion years ago?

2. What formed at 2.0 billion years?
3. What was the next continent to form?
4. What happened 1.8 billion years ago?
5. What continents came together 1 billion years ago to form a supercontinent of what name?
6. What happened after the supercontinent of Rodinia split up?

Practice Answers

1. Cratons and the continent Ur were on the surface.
2. Artica formed.
3. Atlantica
4. Artica collided with what is now eastern Antarctica to form Nena.
5. Nena, Atlantica and Ur collided to form Rodinia.
6. The continents were separate for about 300 million years but came back together to form Pangaea.

Review

1. Why did it take 2 billion years for plate tectonics to be similar to the way it is today?
2. What evidence is there for Snowball Earth? What evidence would you look for to test the hypothesis?
3. How did Rodinia break apart and what is the evidence for that?

Review Answers

1. By 2.5 billion years ago plate Earth was cooler and plate tectonics happened at a rate similar to today. Larger continents and supercontinents formed.
2. The rapid evolution of life in the late Precambrian and Cambrian could have been driven by the melting of ice and the return to more favorable conditions for organisms.
3. Rodinia broke up 750 million years ago by continental rifting that left behind large lav flows. Eventually the continents separated and there was seafloor spreading and the creation of ocean basins.

1.18 Paleozoic Plate Tectonics

- Continental collisions that form supercontinents create mountain ranges by the process of orogeny.

Why were the continents near the South Pole?

During the Paleozoic the continents were joined and they were not in their current latitudes. In the late Cambrian, for example, they were clustered around the south polar region. It's probably just chance that they found their way there. This was hundreds of millions of years before the first human expedition reached the South Pole in 1911.

The Paleozoic

The Paleozoic is the furthest back era of the Phanerozoic and it lasted the longest. But the Paleozoic was relatively recent, beginning only 570 million years ago. Compared with the long expanse of the Precambrian, the Phanerozoic is recent history. Much more geological evidence is available for scientists to study so the Phanerozoic is much better known.

The Paleozoic begins and ends with a supercontinent. At the beginning of the Paleozoic, the supercontinent Rodinia began to split up. At the end, Pangaea came together.

Formation of Pangaea

A mountain-building event is called an **orogeny**. Orogenies take place over tens or hundreds of millions of years. As continents smash into microcontinents and island arcs collided, mountains rise.

Geologists find evidence for the orogenies that took place while Pangaea was forming in many locations. For example, Laurentia collided with the Taconic Island Arc during the Taconic Orogeny (**Figure** 1.36). The remnants of this mountain range make up the Taconic Mountains in New York.

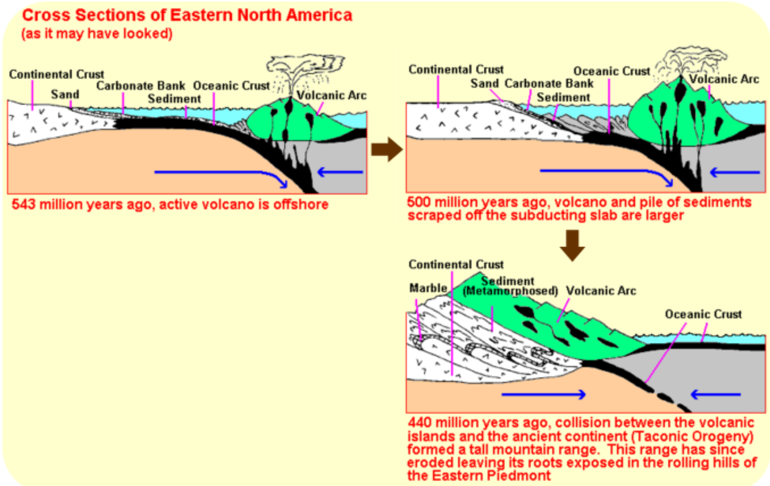


FIGURE 1.36
The Taconic Orogeny is an example of a collision between a continent and a volcanic island arc.

Laurentia experienced other orogenies as it merged with the northern continents. The southern continents came together to form Gondwana. When Laurentia and Gondwana collided to create Pangaea, the Appalachians rose. Geologists think they may once have been higher than the Himalayas are now.

Pangaea

Pangaea was the last supercontinent on Earth. Evidence for the existence of Pangaea was what Alfred Wegener used to create his continental drift hypothesis, which was described in the chapter Plate Tectonics.

As the continents move and the land masses change shape, the shape of the oceans changes too. During the time of Pangaea, about 250 million years ago, most of Earth's water was collected in a huge ocean called Panthalassa (**Figure** 1.37).

Summary

- The Paleozoic began with the supercontinent Rodinia and ended with the supercontinent Pangaea.
- As continents come together, orogenies build up mountain ranges.
- Pangaea was a giant landmass made of all of the continents around 250 million years ago.

Practice

Use this resource to answer the questions that follow.

https://www.youtube.com/watch?v=hrVUDcVI1bc End at 8:44

1. What were the continents like at the beginning of the Mesozoic?
2. How did the area between North/South America and Eurasia/Africa evolve from 200 million years ago to 150 million years ago to 90 million years ago?
3. Why did a desert exist in the region of the Sahara and the United Kingdom 250 million years ago?
4. Why is the Grand Canyon important? What is displayed there from 265 million years ago?
5. What does this video present as the reason for the mass extinction at the end of the Permian?

FIGURE 1.37
Pangaea was the sole landform 250 million years ago, leaving a huge ocean called Panthalassa, along with a few smaller seas.

Practice Answers

1. They were united as Pangaea.
2. At 200 million years ago they were all joined. At 150 million years ago continental rifting was splitting them apart. At 90 million years ago seafloor spreading had created the Atlantic basin and the continents were split apart.
3. 300 million years ago enormous mountains grew on Pangaea. These mountains ran across the center of Pangaea and they caused a wicked rainshadow effect. Rain fell toward the coastline, but the center of the continent had no rain. The center of Pangaea was a super-desert.
4. It displays billions of years of geologic history. The desert was in that region of North America as well.
5. A massive volcanic eruption in Siberia released methane to the atmosphere and caused greenhouse warming that created the desert and killed off most of life.

Review

1. What happens to create an orogeny? How are plate tectonics processes related to orogenies?
2. How did Pangaea come together?
3. How is the creation of Pangaea related to events like the Taconic orogeny?

Review Answers

1. An orogeny is a mountain building event. Two continental plates colliding will cause mountains to rise.
2. There was subduction of the old oceanic crust and then continents merged and created mountain ranges.
3. In the Taconic Orogeny, the Taconic Island Arc collided with the continent. This added land to the continents that is now seen as the Taconic Mountains in New York.

1.19 Paleozoic and Mesozoic Seas

- Six Paleozoic and Mesozoic marine transgressions and regressions were caused by glaciers melting and growing for example.

Do you like the beach? If so, the Paleozoic may be for you!

If we were living right now at the time of a marine transgression, there would be a lot more beach. Of course, it would be hard to find land for all of the people to live on or for all the crops to grow.

Marine Transgressions and Regressions

Some of the most important events of the Paleozoic and Mesozoic were the rising and falling of sea level over the continents. Sea level rises over the land during a **marine transgression**. During a **marine regression**, sea level retreats. During the Paleozoic there were four complete cycles of marine transgressions and regressions. There were two additional cycles during the Mesozoic (**Figure** 1.38).

One of two things must happen for sea level to change in a marine transgression: either the land must sink or the water level must rise. What could cause sea level to rise? When little or no fresh water is tied up in glaciers and ice caps, sea level is high. Sea level also appears to rise if land is down dropped. Sea level rises if an increase in seafloor spreading rate buoys up the ocean crust, causing the ocean basin to become smaller.

What could cause sea level to fall in a marine regression?

Geologists think that the Paleozoic marine transgressions and regressions were the result of the decrease and increase in the size of glaciers covering the lands.

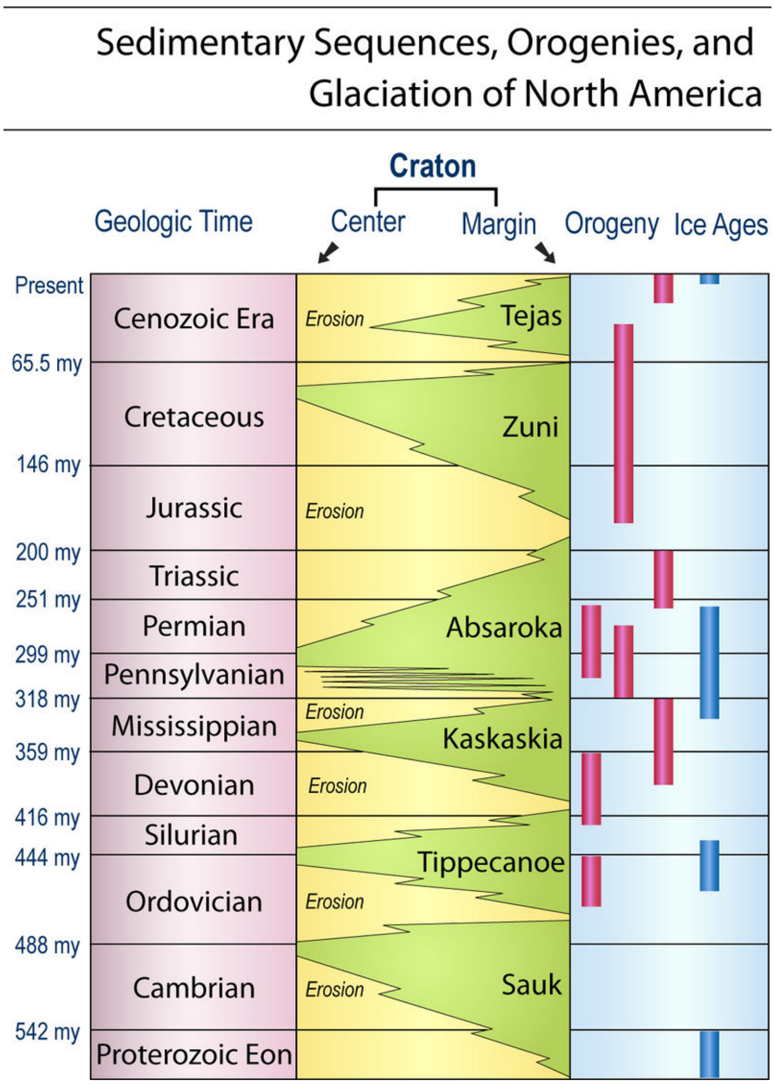


FIGURE 1.38

Six marine transgressions and regressions have occurred during the Phanerozoic.

Rock Facies

Geologists know about marine transgressions and regressions from the sedimentary rock record. These events leave characteristic rock layers known as sedimentary **facies**. On a shoreline, sand and other coarse grained rock fragments are commonly found on the beach where the wave energy is high. Away from the shore in lower energy environments, fine-grained silt that later creates shale is deposited. In deeper, low-energy waters, carbonate mud that later hardens into limestone is deposited.

Grand Canyon

The Paleozoic sedimentary rocks of the Grand Canyon contain evidence of marine transgressions and regressions, but even there the rock record is not complete. Look at the sequence in the **Figure** 1.39 and see if you can determine whether the sea was transgressing or regressing. At the bottom, the Tonto Group represents a marine transgression: sandstone (11), shale (10), and limestone (9) laid down during 30 million years of the Cambrian Period. The Ordovician and Silurian are unknown because of an unconformity. Above that is freshwater limestone (8), which is overlain by limestone (7) and then shale (6), indicating that the sea was regressing. After another unconformity, the rocks of the Supai Group (5) include limestone, siltstone, and sandstone indicative of a regressing sea. Above those rocks are shale (4), sandstone (3), a limestone and sandstone mix (2) showing that the sea regressed and transgressed and finally limestone (1) indicating that the sea had come back in.

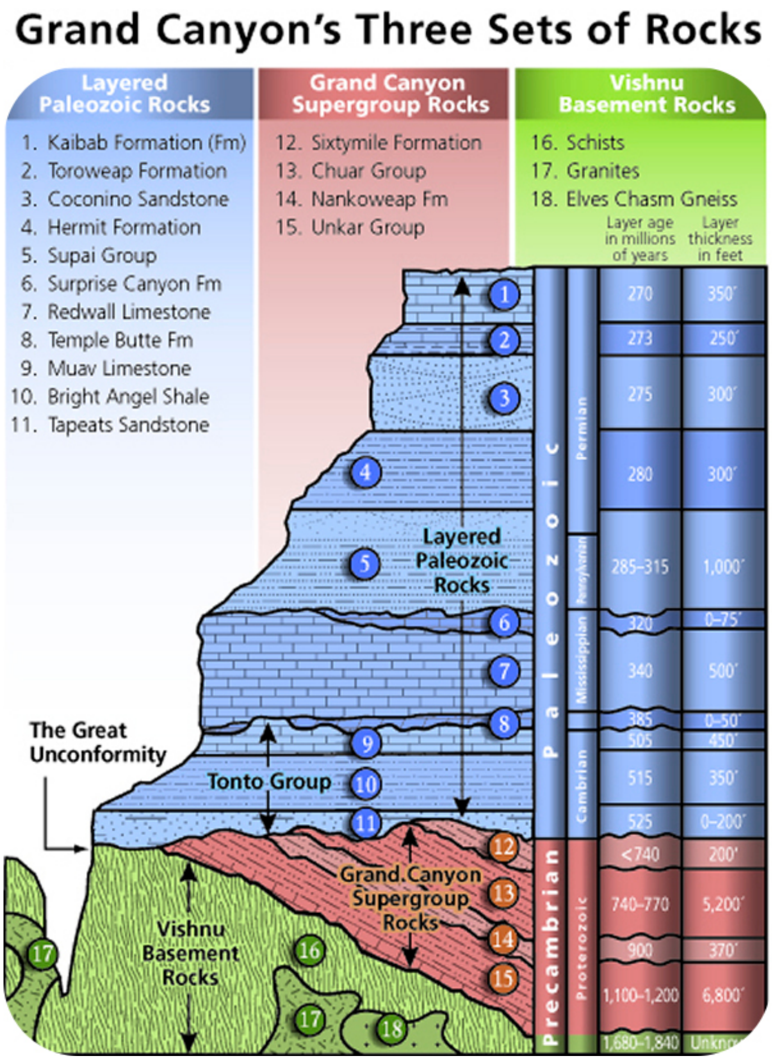


FIGURE 1.39
The Paleozoic sedimentary rocks of the Grand Canyon were deposited during marine transgressions and regressions.

Summary

- Sea level depends on the amount of water tied up in ice and, locally, the position of the land.
- Facies are characteristic rock layers, such as sandstone, shale, limestone for a marine transgression and the reverse for a regression.
- The Grand Canyon has an incomplete record of the four marine transgressions and regression of the Paleozoic.

Explore More

Use the resource below to answer the questions that follow.

- **The Phanerozoic Geological Record in Utah** at http://video.nationalgeographic.com/video/news/history-archaeology-news/utah-dig-missions-wcvin/

1. What are the paleontologists searching for in Utah?
2. How many years ago was there a sea in Utah?
3. How far did the sea extend? How was it related to the geography of North America?
4. What does Tropic Shale contain?
5. How do the scientists date the shale? Is this absolute or relative dating?
6. What do the scientists find?
7. What do they learn from the fossils?

Explore More Answers

1. Paleontologists are looking for marine animals, especially pleisiosaurs.
2. 93 million years ago there was a sea; there were others through time
3. The sea extended from the Gulf of Mexico to the Arctic Ocean and divided North America into two land areas with the sea in the middle.
4. This formation contains fossils of ancient sea life.
5. They use ammonites as guide fossils in this form of relative dating.
6. They find bone fragments, sharks teeth and other fossils.
7. They better understand the life that existed in that part of the sea 93 million years ago.

Review

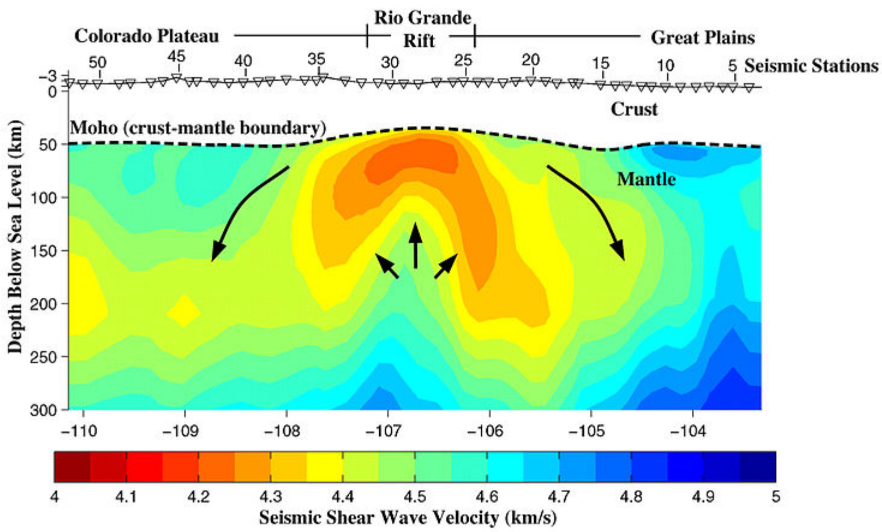
1. How do scientists use sedimentary facies to recognize a marine transgression or regression?
2. What are the possible causes of a marine transgression? What are the possible causes of a marine regression?
3. What must geologists have found to know that there were two more transgressions and regressions in the Mesozoic?

Review Answers

1. These events are characterized by distinctive sequences of rock layers. Since sea level rises during a marine transgression, the same sequence of rock layers will appear in order from oldest to youngest: sandstone, shale and limestone as the sea goes in. For a marine regression, the sequence is reversed: limestone, shale, sandstone as the sea goes out.
2. Sea level will rise relative to the land because the land sinks or sea level increases. The reasons sea level rises includes that there is little fresh water tied up in glaciers or an increase in the rate of seafloor spreading, which buoys up the mid-ocean ridge. A marine regression occurs when land rises or sea level drops. Sea level will drop when more fresh water is tied up in glaciers or when the seafloor spreading rate is low.
3. They must have found two sets of the rock facies that indicate transgressions and regressions.

1.20 Mesozoic Plate Tectonics

- Pangaea split apart, the world ocean fragmented, and the Atlantic Ocean formed.



Why would a supercontinent break up?

A continent is a giant insulating blanket that does not allow mantle heat to escape very effectively. This image is of shear wave velocity beneath New Mexico where hot material is trapped beneath the North American plate. The hot material is causing rifting to begin at the Rio Grande Rift.

Supercontinent Breakup

As heat builds up beneath a supercontinent, continental rifting begins. Basaltic lavas fill in the rift and eventually lead to seafloor spreading and the formation of a new ocean basin. This basalt province is where Africa is splitting apart and generating basalt lava.

The Breakup of Pangaea

At the end of the Paleozoic there was one continent and one ocean. When Pangaea began to break apart about 180 million years ago, the Panthalassa Ocean separated into the individual but interconnected oceans that we see today on Earth.

The Atlantic Ocean basin formed as Pangaea split apart. The seafloor spreading that pushed Africa and South America apart is continuing to enlarge the Atlantic Ocean (**Figure** 1.40).

As the continents moved apart there was an intense period of plate tectonic activity. Seafloor spreading was so vigorous that the mid-ocean ridge buoyed upwards and displaced so much water that there was a marine transgression. Later in the Mesozoic those seas regressed and then transgressed again.

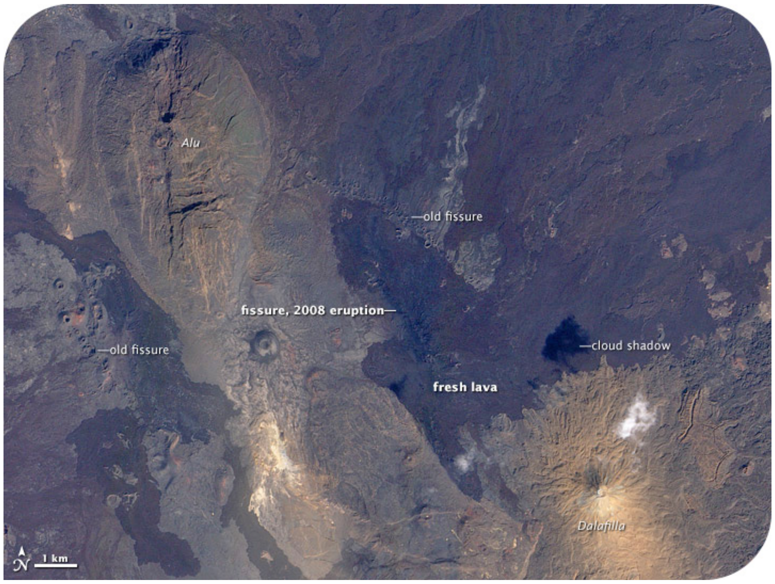


FIGURE 1.40
In the Afar Region of Ethiopia, Africa is splitting apart. Three plates are pulling away from a central point.

Growth of Continents

The moving continents collided with island arcs and microcontinents so that mountain ranges accreted onto the continents' edges. The subduction of the oceanic Farallon plate beneath western North America during the late Jurassic and early Cretaceous produced igneous intrusions and other structures. The intrusions have since been uplifted so that they are exposed in the Sierra Nevada Mountains (**Figure** 1.41).

FIGURE 1.41
The snow-covered Sierra Nevada is seen striking SE to NW across the eastern third of the image. The mountain range is a line of uplifted batholiths from Mesozoic subduction.

Summary

- Continents keep mantle heat from escaping, which may eventually lead to continental rifting.
- Continents grow as microcontinents or igneous activity add continental crust to an existing continent.
- When a supercontinent breaks apart, new seafloor forms between the new continental masses.

Practice

Use this resource to answer the questions that follow. https://www.youtube.com/watch?v=HFQIK_r-BGQ Watch to 6:55.

1. What were the continents doing at the beginning of the Paleozoic?
2. When did Pangaea start breaking apart? What is the first thing that happens?
3. By the end of the Jurassic what was happening to Pangaea? What was the name of the northern continent? What was the name of the southern continent?
4. What did the continents look like in the Cretaceous?
5. What is happening in the rift between North America Eurasia and South America and Africa?
6. Where is India during the Mesozoic? In what direction is it moving?
7. Why did the Andes Mountains and Rocky Mountains form during this time?

Practice Answers

1. They were together as Pangaea.
2. About 200 million years ago continental rifts formed.
3. The northern and southern continents are rifting apart creating Laurasia in the north and Gondwana in the south.
4. They are starting to look like modern continents, although they are not in the exact positions.
5. Seafloor spreading is creating the Atlantic Ocean.
6. It is far in the south but it is moving north toward Eurasia.
7. The Pacific plate was subducting beneath North and South American plates.

Review

1. Would you say that Pangaea is still breaking up? Why or why not?
2. How does the rate of plate tectonics activity affect sea level?
3. What caused the igneous intrusions that make up the Sierra Nevada mountains?

Review Answers

1. The Atlantic Ocean is still growing and the pacific is still shrinking. The continents of Pangaea are still moving away from each other.
2. If seafloor spreading is vigorous the mid-ocean ridge buoys up and displaces sea water causing sea level to rise.
3. The Farallon Plate subducted beneath North America and produce igneous intrusions that have since uplifted to form the Sierra Nevada Mountains.

1.21 Cenozoic Plate Tectonics

- The geology of the Cenozoic is familiar to us.

What defines the beginning of the Quaternary and the Holocene?

The most recent period of the Cenozoic is the Quaternary, which began about 2.6 million years ago. The most recent epoch is the Holocene, which began around 12,000 years ago. Go back to the concept on human evolution in the chapter Life History to figure out what events mark the beginning of these time periods.

Cenozoic

The Cenozoic began around 65.5 million years ago and continues today. Although it accounts for only about 1.5% of the Earth's total history, as the most recent era it is the one scientists know the most about. Much of what has been discussed elsewhere in *CK-12 Earth Science Concepts For High School* describes the geological situation of the Cenozoic. A few highlights are mentioned here.

Plate Tectonics

The paleogeography of the era was very much like it is today. Early in the Cenozoic, blocks of crust uplifted to form the Rocky Mountains, which were later eroded away and then uplifted again. Subduction off of the Pacific Northwest formed the Cascades volcanic arc. The Basin and Range province that centers on Nevada is where crust is being pulled apart.

Evolution of the San Andreas Fault

The San Andreas Fault has grown where the Pacific and North American plates meet. The plate tectonic evolution of that plate boundary is complex and interesting (**Figure** 1.42). The Farallon Plate was subducting beneath the North American Plate 30 Ma. By 20 Ma the Pacific Plate and East Pacific Rise spreading center had started to subduct, splitting the Farallon Plate into two smaller plates. Transform motion where the Pacific and North American plates meet formed the San Andreas Fault. The fault moved inland and at present small sea floor spreading basins along with the transform motion of the San Andreas are splitting Baja California from mainland Mexico.

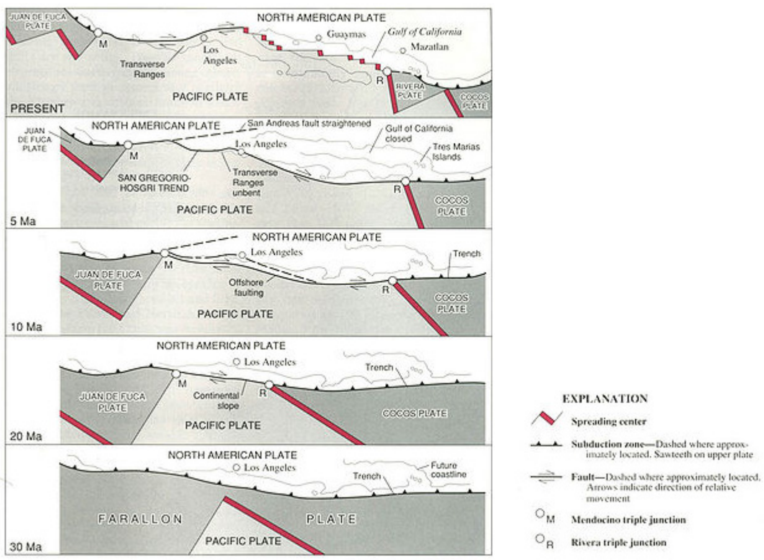


FIGURE 1.42

This figure shows the evolution of the San Andreas Fault zone from 30 million years ago (bottom) to present (top).

Although most plate tectonic activity involves continents moving apart, smaller regions are coming together. Africa collided with Eurasia to create the Alps. India crashed into Asia to form the Himalayas.

Ice Ages

As the continents moved apart, climate began to cool. When Australia and Antarctica separated, the Antarctic Circumpolar Current could then move the frigid water around Antarctica and spread it more widely around the planet.

Antarctica drifted over the south polar region and the continent began to grow a permanent ice cap in the Oligocene. The climate warmed in the early Miocene but then began to cool again in the late Miocene and Pliocene when glaciers began to form. During the Pleistocene ice ages, which began 2.6 million years ago, glaciers advanced and retreated four times (**Figure** 1.43). During the retreats, the climate was often warmer than it is today.

These continental ice sheets were extremely thick, like the Antarctic ice cap is today. The Pleistocene ice ages guided the evolution of life in the Cenozoic, including the evolution of humans.

Summary

- During the Cenozoic, the crust that had once been joined as Pangaea has mostly been moving apart.
- Subduction of the Farallon plate has resulted in the formation of the Rocky Mountains and the San Andreas Fault.
- The Pleistocene was marked by four advances of ice, the remnants of which are found today.

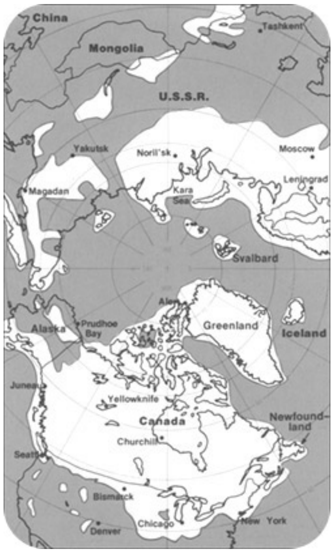


FIGURE 1.43
Glacial ice at its maximum during the Pleistocene.

Practice

Use this resource to answer the questions that follow.

https://www.youtube.com/watch?v=HFQIK_r-BGQ Start at 6:55, end at 9:21

1. What happens with India during the Cenozoic?
2. What are the Asian subcontinents, like North and South Korea, doing?
3. What formed between Australia and Antarctica? What was the result of this?
4. What caused the Red Sea to form?
5. What is happening now?

Practice Answers

1. It keeps moving north until it rams into Eurasia to form the Himalaya Mountains.
2. They are converging with Eurasia to make modern Asia?
3. A new rift formed between those continents causing Australia to break off from Antarctica.
4. A new rift between Africa and Arabia formed.
5. Asia is together; Arabia is coming away from Africa; the Himalaya are forming; Australia has moved to its own place; the Pacific is smaller; the Atlantic is larger

Review

1. Why did the plate boundary that runs up California change from convergent to transform?
2. Which plate tectonics setting is creating each of these: the Rocky Mountains, the Cascades and the Basin and Range?
3. What is the history of the advance and retreat of ice during the Pleistocene? Could we still be in the Pleistocene?

Review Answers

1. The Farallon plate subducted beneath the North American Plate until the East pacific Rise started to subduct. this caused transform motion where the Pacific and North American Plates meet and crated the San Andreas Fault.
2. The Rocky Mountains formed as the Farallon Plate subducted at a low angle. The Cascades are due to subduction off the Pacific Northwest. The Basin and Range is forming due to stretching of the crust.
3. The ice advanced four and retreated four times. It was often warmer in interglacial periods than it is to day so we could be in the Pleistocene still.

Summary

Fossils are remnants of living creatures that can indicate something about the ecosystem and the environmental conditions that were present at the time they lived. Fossils can help geologists decipher the geological history of an area, as can clues from rocks. The principles of relative dating allow geologists to decipher the order of geological events and correlation allows them to determine the geological history of a region. Absolute age dating gives accurate dates for geological events, provided the proper materials are available and the proper techniques are followed. The most accurate and widely used absolute age dating technique is radiometric dating, which uses the ratios of radioactive isotopes to indicate age. Using these techniques, and some from astronomy, scientists have reconstructed a history of Earth and the solar system. The solar system began as a cloud of dust and gas that contracted by gravity until the center ignited to form a star and clumps of matter came together to form the planets. Shortly after Earth formed, a giant asteroid struck the planet, which melted both bodies, and flung material out into Earth's orbit. That material coalesced into the Moon. Earth had to cool before it could support an atmosphere, but when it did precipitation provided the water that filled the ocean basins. Life evolved slowly, and it was not until the evolution of photosynthesis that oxygen could collect in the atmosphere. The presence of oxygen led to the formation of the protective ozone layer and gases for animals to breathe. The early Earth was hot and so convection and plate tectonics were faster than today. From the time of the Archean, plate tectonics processes were similar to today. From then until now, supercontinents formed and broke apart, seas transgressed and regressed, and ice ages came and went.

1.22 References

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