

Chapter 17

Glaciers

Chapter Outline

1 Glaciers: Moving Ice

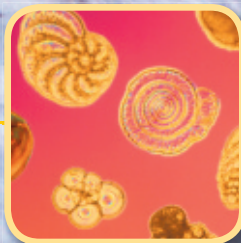
- Formation of Glaciers
- Types of Glaciers
- Movement of Glaciers
- Features of Glaciers

2 Glacial Erosion and Deposition

- Glacial Erosion
- Glacial Deposition
- Glacial Lakes

3 Ice Ages

- Glacial and Interglacial Periods
- Causes of Glaciation



Why It Matters

Glaciers—huge masses of slowly moving ice—reshape Earth's surface by carving valleys, forming lakes, and moving sediment. Glaciers provide information about past and present climates, and they are key indicators of current climate changes.

Inquiry Lab

 20 min

Iceberg in a Glass



Find the volume of an **ice cube**. Place your “iceberg” in a **glass** that is two-thirds full of **water**. Determine the volume of the ice that is floating above the water and the volume of the ice that is below the water. Without disturbing the glass, observe what happens as the ice melts. Record your observations.

Fill another **glass** two-thirds full of water. Add **salt**, stirring until no more salt dissolves. Find the volume of a new **ice cube**. Place your new “iceberg” in the glass with the salt water. Determine the volume of the ice above and below the water. Record your observations as the ice melts.

Calculate the percentage of the iceberg that is above the water in each glass.

Questions to Get You Started

1. If a rectangular iceberg with a volume of $60,000 \text{ m}^3$ is floating in the ocean, what volume of ice is above the surface of the water? Explain your answer.
2. Describe what happened as the ice melted in each glass. What accounts for any differences between the two glasses?



Word Families

Glacier In this chapter, you will learn many two-word terms, including *alpine glacier* and *glacial drift*, that contain the word *glacier* or *glacial*. Both *glacier* and *glacial* come from the Latin word *glacies*, meaning “ice.”

Your Turn As you read this chapter, make a table like the one below. In the first column, write all the terms that include either *glacier* or *glacial*. In the second column, define the other word in each term. Then write your own definition of the whole two-word term.

Term	Definition of second word	Definition of whole two-word term
alpine glacier	alpine = of or like mountains	
continental glacier	continent =	
glacial drift	drift =	
glacial period	period =	

Classification

Classifying Glacial Depositions

Classification is a tool for organizing objects and ideas by grouping them into categories. The categories are based on defining characteristics of the objects and ideas. For example, the following table shows how landforms produced by glacial erosion can be classified by their shape and location.

Landform produced by glacial erosion	Shape	Location
cirque	bowl-shaped depression	floor of a valley
arête	sharp, jagged ridge	between cirques

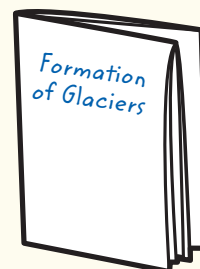
Your Turn As you read Section 2, create a table like the one above to show how glacial depositions can be classified by their composition and by where and how they are deposited.

FoldNotes

Booklet FoldNote A booklet is a useful tool for taking notes as you read a chapter. Each page of the booklet can be used to record details about one of the main topics in the chapter.

Your Turn Create a booklet FoldNote as described in Appendix A. On each page of the booklet, write one of the main topics in Sections 1 and 2: Formation of Glaciers, Types of Glaciers, Movement of Glaciers,

Features of Glaciers, Glacial Erosion, Glacial Deposition, and Glacial Lakes. As you read, take notes about each main topic on the appropriate page of your booklet.



For more information on how to use these and other tools, see **Appendix A**.

Glaciers: Moving Ice

Key Ideas

- Describe how glaciers form.
- Compare two main kinds of glaciers.
- Explain two processes by which glaciers move.
- Describe three features of glaciers.

Key Terms

glacier
alpine glacier
continental glacier
basal slip
internal plastic flow
crevasse

Why It Matters

Because the size of glaciers depends on climate, glaciers are also an indicator of climate change. Understanding how glaciers form and move can help us make predictions about climate.

A single snowflake is lighter than a feather. However, if you squeeze a handful of snow, you make a firm snowball. In a process similar to making a snowball, natural forces compact snow to make a large mass of moving ice called a **glacier**.

Formation of Glaciers

At high elevations and in polar regions, snow may remain on the ground all year and form an almost motionless mass of permanent snow and ice called a *snowfield*. Snowfields form as ice and snow accumulate above the snowline. The *snowline* is the elevation above which ice and snow remain throughout the year, as shown in **Figure 1**.

Average temperatures at high elevations and in polar regions are always near or below the freezing point of water. So, snow that falls there accumulates year after year. Cycles of partial melting and refreezing change the snow into grainy ice called *firn*.

In deep layers of snow and firn, the pressure of the overlying layers flattens the ice grains and squeezes the air from between the grains. The continued buildup of snow and firn forms a glacier that moves downslope or outward under its own weight.

The size of a glacier depends on the amount of snowfall received and the amount of ice lost. When new snow is added faster than ice and snow melt, the glacier gets bigger. When the ice melts faster than snow is added, the glacier gets smaller. Small differences in average yearly temperatures and snowfall may upset the balance between snowfall and ice loss. Thus, changes in the size of a glacier may indicate climatic change.

Figure 1 The snowline on the Grand Teton Mountains at Grand Teton National Park, Wyoming, is more than 3,000 m above sea level.

glacier a large mass of moving ice

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Figure 2 An alpine glacier (above) descends through Thompson Pass in Alaska. A continental glacier (right) covers much of the land surface in Greenland.



alpine glacier a narrow, wedge-shaped mass of ice that forms in a mountainous region and that is confined to a small area by surrounding topography

continental glacier a massive sheet of ice that may cover millions of square kilometers, that may be thousands of meters thick, and that is not confined by surrounding topography

READING TOOLBOX

Classification

As you read this page, create a classification table like the one at the beginning of this chapter. List the two main types of glaciers, describe their characteristics, and give examples.

Types of Glaciers

The two main categories used to classify glaciers are alpine and continental. An **alpine glacier** is a narrow, wedge-shaped mass of ice that forms in a mountainous region and that is confined to a small area by surrounding topography, as shown in **Figure 2**. Alpine glaciers are located in Alaska, the Himalaya Mountains, the Andes, the Alps, and New Zealand.

Continental glaciers are massive sheets of ice that may cover millions of square kilometers, that may be thousands of meters thick, and that are not confined by surrounding topography, as shown in **Figure 2**. Today, continental glaciers, also called *ice sheets*, exist only in Greenland and Antarctica. The Antarctic ice sheet covers an area of more than 13 million km² and is more than 4,000 m thick in some places. The Greenland ice sheet covers 1.7 million km² of land, and its maximum thickness is more than 3,000 m. If these ice sheets melted, the water they contain would raise the worldwide sea level by more than 50 m.

Reading Check Where can you find continental glaciers today? (See Appendix G for answers to Reading Checks.)

Movement of Glaciers

Glaciers are sometimes called “rivers of ice.” Gravity causes both glaciers and rivers to flow downward. However, glaciers and rivers move in different ways. Unlike water in a river, glacial ice cannot move rapidly or flow easily around barriers. In a year, some glaciers may travel only a few centimeters, while others may move a kilometer or more. Glaciers move by two basic processes—basal slip and internal plastic flow.

Basal Slip

One way that glaciers move is by slipping over a thin layer of water and sediment that lies between the ice and the ground. The weight of the ice in a glacier exerts pressure that lowers the melting point of ice. As a result, the ice melts where the glacier touches the ground. The water mixes with sediment at the base of the glacier. This mixture acts as a lubricant between the ice and the underlying surface. The process that lubricates a glacier's base and causes the glacier to slide forward is called **basal slip**.

Basal slip also allows a glacier to work its way over small barriers in its path by melting and then refreezing. For example, if the ice pushes against a rock barrier, the pressure causes some of the ice to melt. The water from the melted ice travels around the barrier and freezes again as the pressure is removed.

Internal Plastic Flow

Glaciers also move by a process called **internal plastic flow**. In this process, pressure deforms grains of ice under a glacier. As the grains deform, they slide over each other and cause the glacier to flow slowly. However, the rate of internal plastic flow varies for different parts of a glacier, as shown in **Figure 3**. The slope of the ground and the thickness and temperature of the ice determine the rate at which ice flows at a given point. The edges of a glacier move more slowly than the center because of friction with underlying rock. For this same reason, a glacier moves more quickly near its surface than near its base.

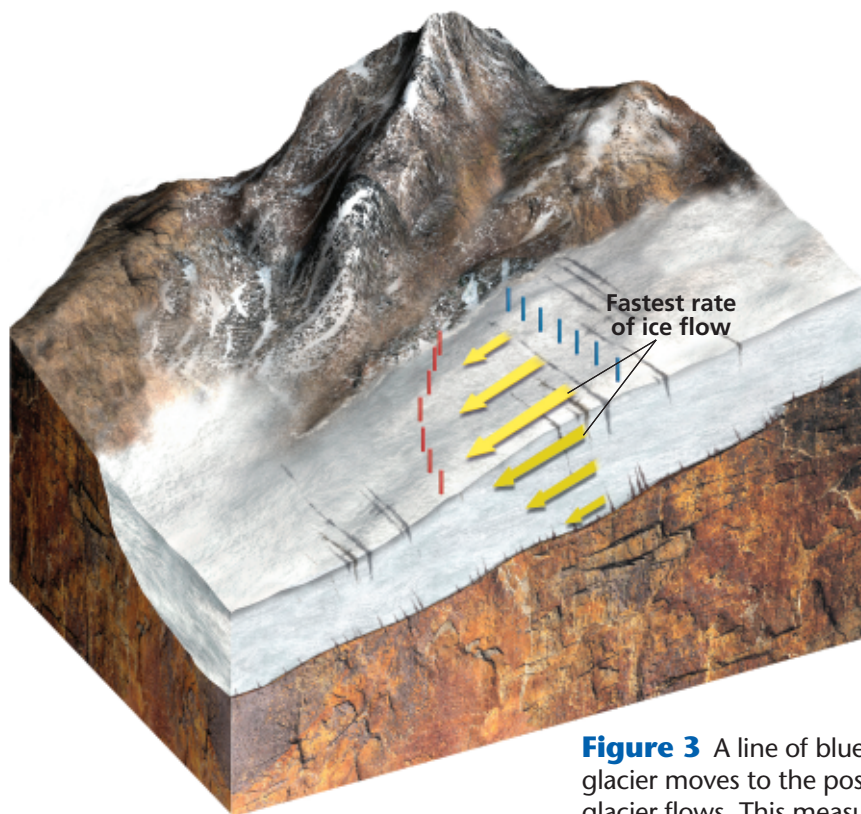


Figure 3 A line of blue stakes driven into an alpine glacier moves to the position of the red stakes as the glacier flows. This measurement shows that the central part of the glacier moves faster than its edges.

basal slip the process that causes the ice at the base of a glacier to melt and the glacier to slide

internal plastic flow the process by which glaciers flow slowly as grains of ice deform under pressure and slide over each other

Quick Lab

15 min

Slipping Ice



Procedure

- 1 Squeeze flat a handful of **snow** or **shaved ice** until you notice a change in the particles.
- 2 Place the squeezed ice on a **tray**. Place a **heavy weight** on the squeezed ice.
- 3 Lift one end of the tray to a 30° incline, and record your observations.

Analysis

1. What does squeezing do to the particles of snow or ice?
2. How is squeezing the snow or ice similar to the formation of a glacier?
3. What did you observe when you placed the squeezed ice on the tray? What glacial movement process is modeled here?

Figure 4 Crevasses (right) are large cracks in a glacier. The composite image below shows what an iceberg might look like if you could see the entire iceberg.



crevasse in a glacier, a large crack or fissure that results from ice movement



Features of Glaciers

While the interior of a glacier moves by internal plastic flow and the entire glacier moves by basal slip, the low pressure on the surface ice causes the surface ice to remain brittle. The glacier flows unevenly beneath the surface, and regions of tension and compression build under the brittle surface. As a result, large cracks, called **crevasses** (kruh VAS uhz), form on the surface, as shown in **Figure 4**. Some crevasses may be as deep as 50 m!

Continental glaciers move outward in all directions from their centers toward the edges of their landmasses. Some parts of the ice sheets may move out over the ocean and form *ice shelves*. When the tides rise and fall, large blocks of ice, called *icebergs*, may break from the ice shelves and drift into the ocean. Because most of an iceberg is below the surface of the water, as shown in Figure 4, icebergs pose a hazard to ships. The area above water of one of the largest icebergs ever observed in the Antarctic was twice the size of Connecticut! 🌿

Section 1 Review

Key Ideas

1. **Identify** two regions in which snow accumulates year after year.
2. **Describe** the process by which glaciers form.
3. **Compare** an alpine glacier and a continental glacier.
4. **Explain** how internal plastic flow and basal slip move glaciers.
5. **Describe** two features of glaciers.
6. **Compare** a glacier and a snowfield.
7. **Explain** how a crevasse forms.

Critical Thinking

8. **Making Inferences** If glaciers could move only by internal plastic flow, what might happen to the rate at which glaciers move? Explain your answer.
9. **Identifying Relationships** How can changes in the size of a glacier indicate climate change?
10. **Analyzing Ideas** If icebergs are visible at sea level, why do they pose a hazard to ships?

Concept Mapping

11. Use the following terms to create a concept map: *glacier, firn, snowline, snowfield, alpine glacier, continental glacier, basal slip, internal plastic flow, ice shelf, iceberg, and crevasse*.

SECTION 2

Glacial Erosion and Deposition

Key Ideas	Key Terms	Why It Matters
- Describe the landscape features that are produced by glacial erosion. - Name and describe five features formed by glacial deposition. - Explain how glacial lakes form.	cirque till arête moraine horn kettle erratic esker glacial drift	While glaciers have only affected the surface of the northern part of the United States, they are responsible for many of our nation's natural wonders.

Many of the landforms in Canada and in the northern United States were created by glaciers. Large lakes, solitary boulders on flat plains, and jagged ridges are just a few examples of landforms created by glaciers. Glaciers created these landforms through the processes of erosion and deposition.

Glacial Erosion

Like rivers, glaciers are agents of erosion. Both a river and a glacier can pick up and carry rock and sediment. However, because of the size and density of glaciers, landforms that result from glacial action are very different from those that rivers form. For example, deep depressions in rock form when a moving glacier loosens and dislodges, or plucks, a rock from the bedrock at the base or side of the glacier. The rock plucked by the glacier is then dragged across the bedrock and causes abrasions. As shown in **Figure 1**, long parallel grooves in the bedrock are left behind and show the direction of the glacier's movement.

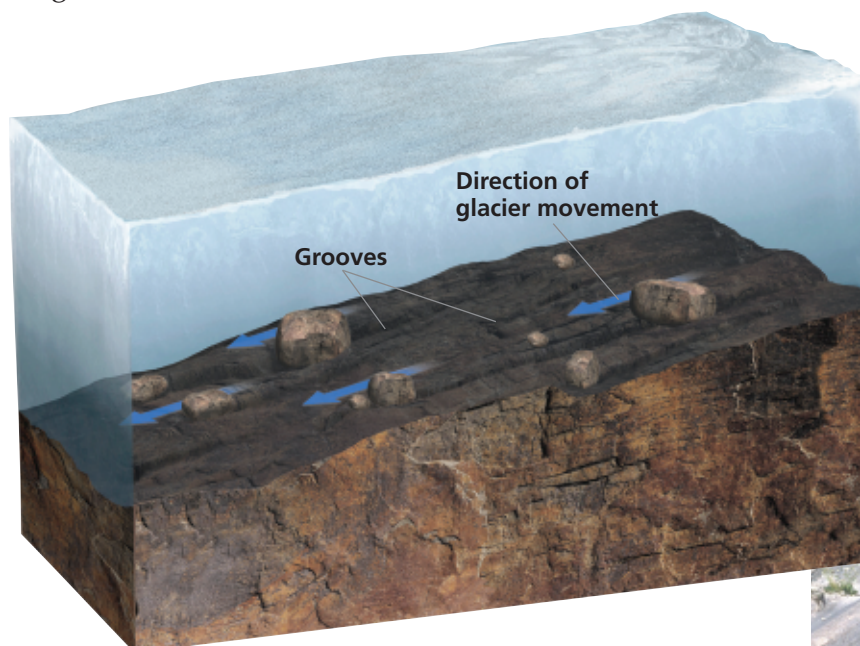


Figure 1 As a glacier moves, it picks up and carries rocks from the bedrock. These grooves at Kelly's Island in Ohio were carved by a glacier 35,000 years ago.



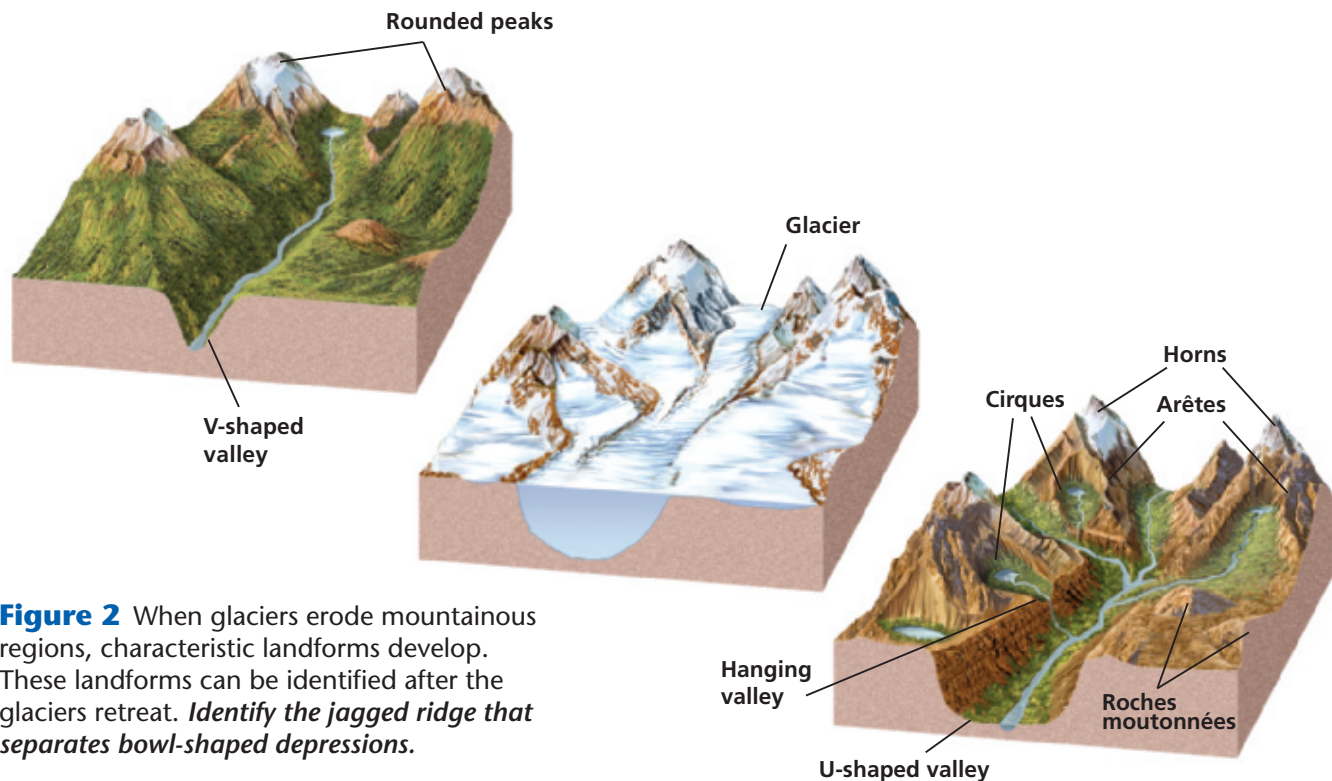


Figure 2 When glaciers erode mountainous regions, characteristic landforms develop. These landforms can be identified after the glaciers retreat. *Identify the jagged ridge that separates bowl-shaped depressions.*

cirque a deep and steep bowl-like depression produced by glacial erosion

arête a sharp, jagged ridge that forms between cirques

horn a sharp, pyramid-like peak that forms because of the erosion of cirques

Academic Vocabulary

projection (proh JEK shuhn) an extension or a structural outgrowth

Landforms Created by Glacial Erosion

Glaciers have shaped many mountain ranges and have created unique landforms by erosive processes. The glacial processes that change the shape of mountains begin in the upper end of the valley where an alpine glacier forms. As a glacier moves through a narrow, V-shaped river valley, rock from the valley walls breaks off and the walls become steeper. The moving glacier also pulls blocks of rock from the floor of the valley. These actions create a bowl-shaped depression called a **cirque** (SUHRK). A sharp, jagged ridge called an **arête** (uh RAYT) forms between cirques. When several arêtes join, they form a sharp, pyramid-like peak called a **horn**, as shown in **Figure 2**.

As the glacier flows down through an existing valley, the glacier picks up large amounts of rock. These rock fragments, which range in size from microscopic particles to large boulders, become embedded in the ice.

Rock particles embedded in the ice may polish solid rock as the ice moves over the rock. Large rocks carried by the ice may gouge deep grooves in the bedrock. Glaciers may also round large rock projections. These rounded projections usually have a smooth, gently sloping side facing the direction from which the glacier came. The other side is steep and jagged because rock is pulled away as the ice passes. The resulting rounded knobs of rock are called *roches moutonnées* (ROHSH moo tuh NAY), which means “sheep rocks” in French.

Reading Check How does a glacier form a cirque?

U-Shaped Valleys

A stream forms the V shape of a valley. As a glacier scrapes away a valley's walls and floor, this original V shape becomes a U shape, as shown in **Figure 3**. Because glacial erosion is the only way by which U-shaped valleys form, scientists can use this feature to determine whether a valley has been glaciated in the past.

Small tributary glaciers in adjacent valleys may flow into a main alpine glacier. Because a small tributary glacier has less ice and less cutting power than the main alpine glacier does, the small glacier's U-shaped valley is not cut as deeply into the mountains. When the ice melts, the tributary valley is suspended high above the main valley floor and is called a *hanging valley*. When a stream flows from a hanging valley, a waterfall forms.



Figure 3 Jollie Valley, a U-shaped glaciated valley, is located in the Southern Alps of New Zealand.

Erosion by Continental Glaciers

The landscape eroded by continental glaciers differs from the sharp, rugged features eroded by alpine glaciers. Continental glaciers erode by leveling landforms to produce a smooth, rounded landscape. Continental glaciers smooth and round exposed rock surfaces in a way similar to the way that bulldozers flatten landscapes. Rock surfaces are also scratched and grooved by rocks carried at the base of the ice sheet. These scratches and grooves are parallel to the direction of glacial movement.

Quick Lab

Glacial Erosion




25 min

Procedure

- 1 Put a **mixture of sand, gravel, and rock** in the bottom of a **15 cm × 10 cm × 5 cm plastic container**. Fill the container with **water** to a depth of about 4 cm. Freeze the container until the water is solid. Remove the **ice block** from the container.
- 2 Use a **rolling pin or large dowel** to flatten some **modeling clay** into a rectangle about 20 cm × 10 cm × 1 cm.
- 3 Grasp the ice block firmly with a **hand towel**. Place the block with the gravel-and-rock side down at one end of the clay. Press down on the ice block, and push it along the length of the flat clay surface.
- 4 Sketch the pattern made in the clay by the ice block.
- 5 Next, press a 2 cm layer of **damp sand** into the bottom of a **shallow, rectangular box**. As in step 3, push the ice block along the surface of the sand, but press down lightly.



- 6 Repeat steps 3 and 4, but use a **soft, wooden board** in place of the clay.

Analysis

1. Describe the effects of the ice block on the clay, on the sand, and on the wood.
2. Did any clay, sand, or wood become mixed with material from the ice block? Did the ice deposit material on any surface?
3. What glacial land features are represented by the features of the clay model? the sand model? the wood model?

Glacial Deposition

Glaciers are also agents of deposition. Deposition occurs when a glacier melts. A glacier will melt if it reaches low, warm elevations or if the climate becomes warmer. As the glacier melts, it deposits all of the material that it has accumulated, which may range in size from fine sediment to large rocks.

Large rocks that a glacier transports from a distant source are called **erratics**. Because a glacier carries an erratic a long distance, the composition of an erratic usually differs from that of the bedrock over which the erratic lies.

Various other landforms develop as glaciers melt and deposit sediment, as shown in **Figure 4**. The general term for all sediments deposited by a glacier is **glacial drift**. Unsorted glacial drift that is deposited directly from a melting glacier is called **till**. Till is composed of sediments from the base of the glacier and is commonly left behind when glacial ice melts. Another type of glacial drift is *stratified drift*. Stratified drift is material that has been sorted and deposited in layers by streams flowing from the melted ice, or *meltwater*.

erratic a large rock transported from a distant source by a glacier

glacial drift rock material carried and deposited by glaciers

till unsorted rock material that is deposited directly by a melting glacier

Figure 4 Moraines, glacial lakes, drumlins, meltwater streams, and outwash plains are some examples of landforms created by glacial deposition.



Till Deposits

Landforms that result when a glacier deposits till are called *moraines*. **Moraines** are ridges of unsorted sediment on the ground or on the glacier itself. There are several types of moraines, as shown in **Figure 4**. A *lateral moraine* is a moraine that is deposited along the sides of an alpine glacier, usually as a long ridge. When two or more alpine glaciers join, their adjacent lateral moraines combine to form a *medial moraine*.

The unsorted material left beneath the glacier when the ice melts is the *ground moraine*. The soil of a ground moraine is commonly very rocky. An ice sheet may mold ground moraine into clusters of *drumlins*. *Drumlins* are long, low, tear-shaped mounds of till. The long axes of the drumlins are parallel to the direction of glacial movement.

Terminal moraines are small ridges of till that are deposited at the leading edge of a melting glacier. These moraines have many depressions that may contain lakes or ponds. Large terminal moraines, some of which are more than 100 km long, can be seen across the Midwest, especially south of the Great Lakes.

Reading Check Which glacial deposit is a tear-shaped mound of sediment?

moraine a landform that is made from unsorted sediments deposited by a glacier

READING TOOLBOX

Word Families

Many two-word terms on this page include the key term *moraine*. Make a table for this family of words, similar to the one at the beginning of this chapter. Use a dictionary to find definitions for the words *lateral*, *medial*, *ground*, and *terminal*. Then, write your own definition of each two-word term.

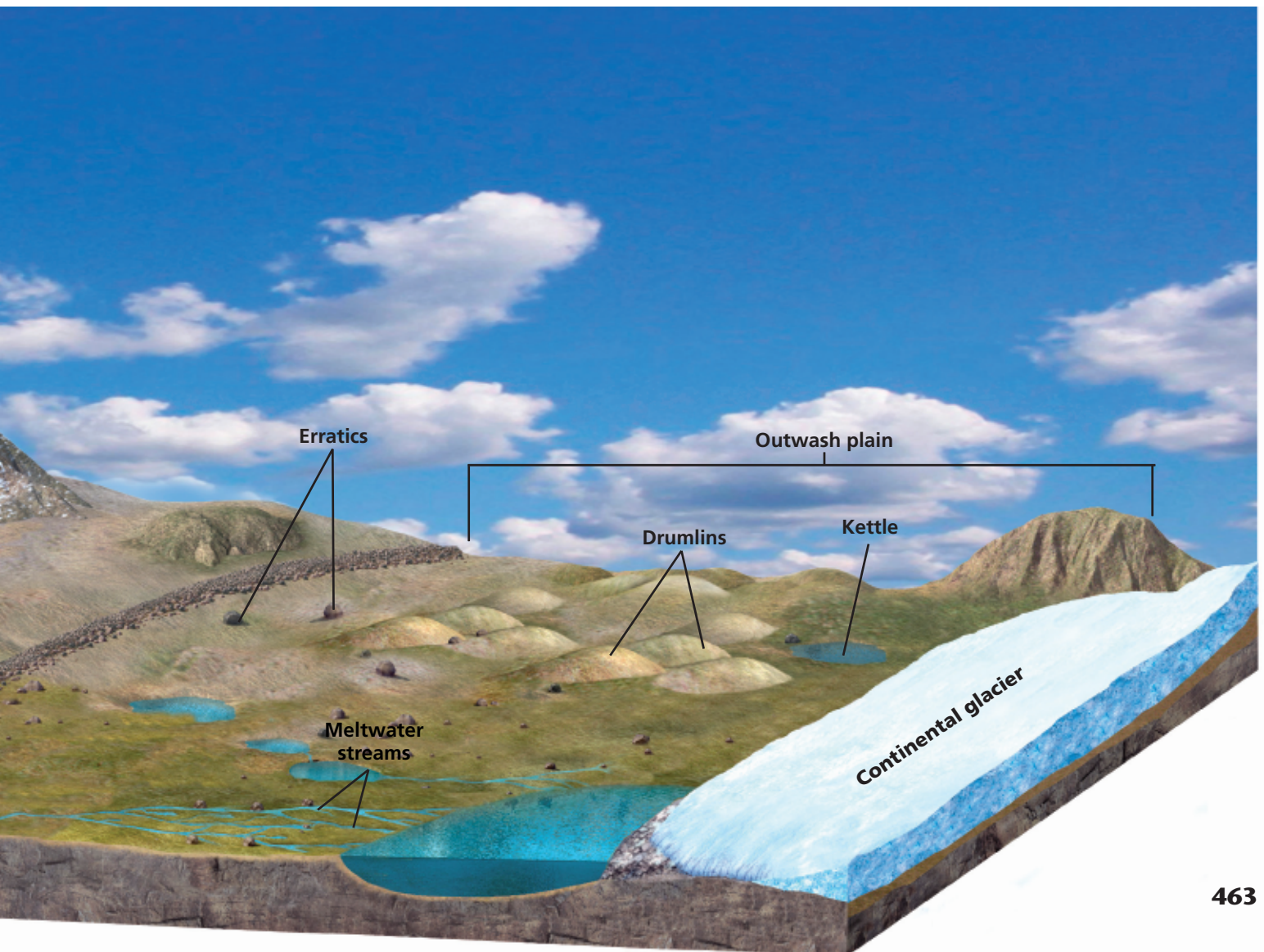




Figure 5 This kettle lake in Saskatchewan, Canada, formed as a result of glacial deposition.

kettle a bowl-shaped depression in a glacial drift deposit

esker a long, winding ridge of gravel and coarse sand deposited by glacial meltwater streams

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Code: HQX0676

Outwash Plains

When a glacier melts, streams of meltwater flow from the edges, the surface, and beneath the glacier. Glacial meltwater may have beautiful colors, such as milky white, emerald green, or turquoise blue, because it carries very fine sediment. The meltwater carries drift as well as rock particles and deposits them in front of the glacier as a large outwash plain. An *outwash plain* is a deposit of stratified drift that lies in front of a terminal moraine and is crossed by many meltwater streams.

Kettles

Most outwash plains are pitted with depressions called **kettles**. A kettle forms when a chunk of glacial ice is buried in drift. As the ice melts, a cavity forms in the drift. The drift collapses into the cavity and produces a depression. Kettles commonly fill with water to form kettle lakes, such as the one shown in **Figure 5**.

Eskers

When continental glaciers recede, **eskers** (ES kuhrz)—long, winding ridges of gravel and sand—may be left behind. These ridges consist of stratified drift deposited by streams of meltwater that flow through ice tunnels within the glaciers. Eskers may extend for tens of kilometers, like raised, winding roadways.

 **Reading Check** How do eskers form?

Glacial Lakes

Lake basins commonly form where glaciers erode surfaces and leave depressions in the bedrock. Thousands of lake basins in Canada and the northern United States were gouged from solid rock by a continental glacier. Thousands of other glacial lakes form as a result of deposition rather than as a result of erosion. Many lakes form in the uneven surface of ground moraine deposited by glaciers. These lakes exist in many areas of North America and Europe.

Long, narrow *finger lakes*, such as those in western New York, form where terminal and lateral moraines block existing streams. The area south of the Great Lakes, from Minnesota to Ohio, has belts of moraines and lakes. Minnesota, also called the “Land of 10,000 Lakes,” was completely glaciated and has evidence of all types of glacial lakes.

Formation of Salt Lakes

Many lakes existed during the last glacial advance. But because of topographic and climatic changes, outlet streams no longer leave these lakes. Water leaves the lakes only by evaporation. When the water evaporates, salt that was dissolved in the water is left behind, which makes the water increasingly salty. Salt lakes, such as the one shown in **Figure 6**, commonly form in dry climates, where evaporation is rapid and precipitation is low.



Figure 6 Many streams and rivers carry dissolved minerals to the Great Salt Lake in Utah. However, because there is no outlet, the lake becomes concentrated with these minerals as continual evaporation removes water.

Why It Matters

Can You Drink a Glacier?

Over 7 billion gallons of bottled water are sold each year in the United States. Companies that bottle water from glacial streams claim that their water is purer than other bottled water because it has been trapped in ice for centuries. Some companies use images of glaciers on their bottles, even if their water does not actually come from glaciers.

Companies that bottle water from glacial streams want you to think that they sell nature’s purest water. Is this true? Atmospheric pollutants—including radioactive waste—can be found in glacial lakes and in ice cores.

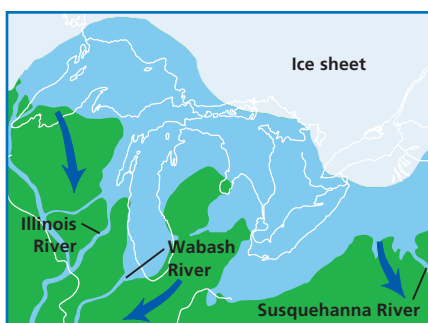


Water companies often use beautiful images of natural landscapes, but producing, transporting and disposing of plastic bottles causes environmental harm. Over 3 million water bottles are thrown out each day in California alone.

YOUR TURN

CRITICAL THINKING

Why do you think many people believe bottled water is healthier than tap water?



Early Ice Retreat The ice sheet that covered much of North America formed enormous lakes.



Late Ice Retreat As the ice sheet retreated, the lakes became smaller and the drainage pattern changed.



Today's Great Lakes Uplifting of the land reduced the Great Lakes to their present sizes.

Figure 7 The Great Lakes in the northern United States were formed by a massive continental glacier.

History of the Great Lakes

The Great Lakes of North America formed as a result of erosion and deposition by a continental glacier, as shown in **Figure 7**. Glacial erosion widened and deepened existing river valleys. Moraines to the south blocked off the ends of these valleys. As the ice sheet melted, the meltwater was trapped in the valleys by the moraines, and lakes formed.

In their early stages, the lakes emptied to the south into the Wabash and Illinois Rivers, which flowed into the Mississippi River. Later, the lakes grew larger and also drained into the Atlantic Ocean through the Susquehanna, Mohawk, and Hudson River valleys.

After the glacial period, the crust rose as the weight of the ice was removed. The lake beds uplifted and shrank. The uplift of the land caused the lakes to drain to the northeast through the St. Lawrence River. As a result of this northeasterly flow, Niagara Falls formed between Lake Erie and Lake Ontario.

Section 2 Review

Key Ideas

- 1. Describe** the following landscape features: a cirque, an arête, and a horn.
- 2. List** five features that form by glacial deposition.
- 3. Explain** how terminal and lateral moraines can form glacial lakes.
- 4. Compare** the process of glacial deposition with the process of glacial erosion.
- 5. Describe** how a kettle forms.
- 6. Explain** how an alpine glacier can change the topography of a mountainous area.
- 7. Compare** the process of erosion by glaciers with the process of erosion by rivers.

Critical Thinking

- 8. Making Comparisons** Compare the processes that form ground moraines with the processes that form eskers.
- 9. Analyzing Predictions** On a field trip, you find rock that has long, parallel grooves. Form a hypothesis that explains this feature. What other landforms would you try to find to test this hypothesis?
- 10. Making Comparisons** Compare glacial sediment deposited directly by glacial ice with the sediment deposited by glacial meltwater.

Concept Mapping

- 11.** Use the following terms to create a concept map: *cirque*, *stratified drift*, *roches moutonnées*, *moraine*, *till*, *glacial drift*, *kettle*, *outwash plains*, and *glacier*.

Key Ideas

- Describe glacial and interglacial periods within an ice age.
- Summarize the theory that best accounts for the ice ages.

Key Terms

ice age
Milankovitch theory

Why It Matters

Given global warming, an advance of glaciation seems remote, but it's only a matter of time.

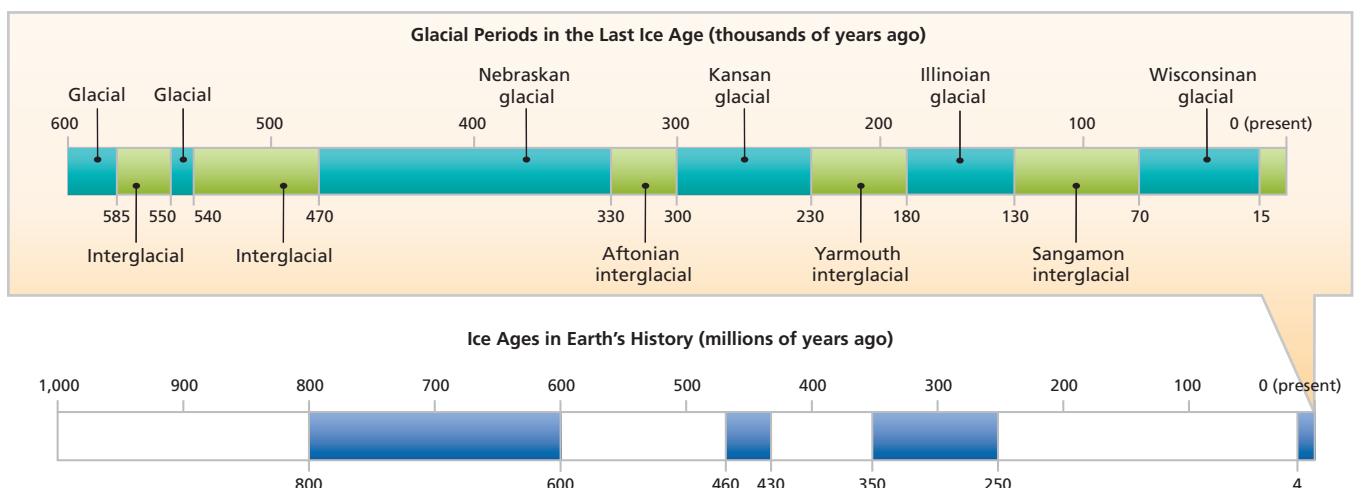
Today, continental glaciers are located mainly in latitudes near the North and South Poles. However, thousands of years ago, ice sheets covered much more of Earth's surface. An **ice age** is a long period of climatic cooling during which the continents are glaciated repeatedly. Several major ice ages have occurred during Earth's geologic history, as shown in **Figure 1**. The earliest known ice age began about 800 million years ago. The most recent ice age began about 4 million years ago. The last advance of this ice age's massive ice sheets reached its peak about 18,000 years ago. Ice ages probably begin with a long, slow decrease in Earth's average temperatures. A drop in average global temperature of only about 5 °C may be enough to start an ice age.

Glacial and Interglacial Periods

Continental glaciers advance and retreat several times during an ice age. The ice sheets advance during colder periods and retreat during warmer periods. A period of cooler climate that is characterized by the advancement of glaciers is called a *glacial period*. A period of warmer climate that is characterized by the retreat of glaciers is called an *interglacial period*. Currently, Earth is in an interglacial period of the most recent ice age.

ice age a long period of climatic cooling during which the continents are glaciated repeatedly

Figure 1 Glacial and Interglacial Periods



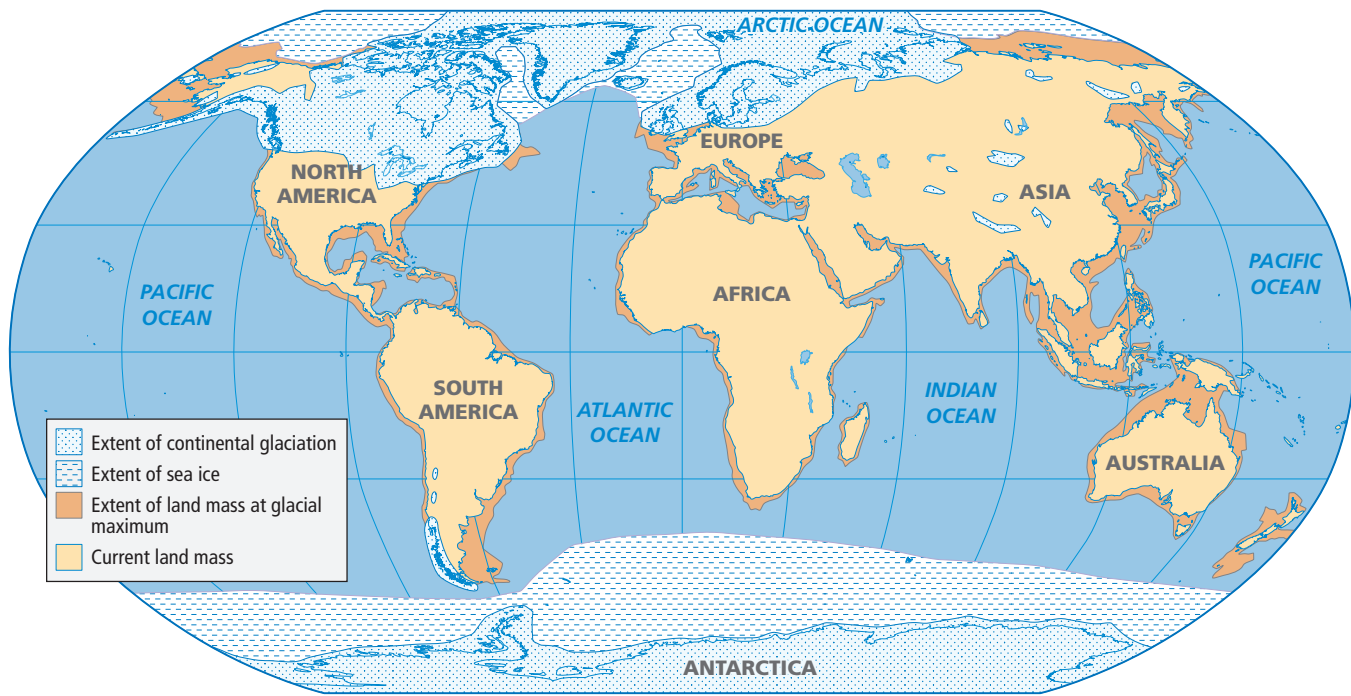


Figure 2 During the last glacial period, about 30% of Earth's surface was covered with ice.

Academic Vocabulary

period (PIR ee uhd) an interval or unit

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Topic: Ice Ages
Code: HQX0781

Glaciation in North America

Glaciers covered about one-third of Earth's surface during the last glacial period. Most glaciation took place in North America and Eurasia. In some parts of North America, the ice was several kilometers thick. So much water was locked in ice during the last glacial period that sea level was as much as 140 m lower than it is today. As a result, the coastlines of the continents extended farther than they do today, as shown in **Figure 2**.

Canada and the mountainous regions of Alaska were buried under ice. In the mountains of the western United States, numerous small alpine glaciers joined to form larger glaciers. These large glaciers flowed outward from the Rocky Mountains and the Cascade and Sierra Nevada Ranges. A great continental ice sheet that was centered on what is now the Hudson Bay region of Canada spread as far south as the Missouri and Ohio Rivers.

Reading Check How did glaciation in the last glacial period affect the sea level?

Glaciation in Eurasia and the Southern Hemisphere

In Europe, a continental ice sheet that was centered on what is now the Baltic Sea spread south over Germany, Belgium, and the Netherlands and west over Great Britain and Ireland. It flowed eastward over Poland and Russia. Long alpine glaciers formed in the Alps and the Himalayas. A continental ice sheet formed in Siberia. In the Southern Hemisphere, the Andes Mountains in South America and much of New Zealand were covered by mountainous ice fields and alpine glaciers. Many land features that formed during the last glacial period are still recognizable.

READING TOOLBOX

Booklet FoldNote

Make a Booklet FoldNote to record your notes for Section 3. Use one page for each main topic in the section, and take notes to create an outline.

Causes of Glaciation

The repeated glaciation of Earth's surface is caused by a variety of complex factors. These factors range from very rapid events to very slow processes. For example, the movement of tectonic plates happens very slowly but can cause changes in global circulation patterns of air and ocean water. These changes may lead to ice ages. Scientists have also proposed a number of ideas to explain glacial and interglacial periods. The leading explanation is the Milankovitch theory.

The Milankovitch Theory

A Serbian scientist named Milutin Milankovitch proposed a theory to explain the cause of glacial periods. Milankovitch noticed that climate change occurs in cycles. He thought that these cycles could be linked to cycles in Earth's movement relative to the sun. The **Milankovitch theory** is the theory that cyclical changes in Earth's orbit and in the tilt of Earth's axis occur over thousands of years and cause climatic changes.

Three periodic changes occur in the way that Earth moves around the sun, as **Figure 3** shows. First, the shape of Earth's orbit, or *eccentricity*, changes from nearly circular to elongated and back to nearly circular every 100,000 years. The second change occurs in the tilt of Earth's axis. Every 41,000 years, the tilt of Earth's axis varies between about 22.2° and 24.5° . A third periodic change is caused by the circular motion, or *precession*, of Earth's axis. Precession causes the axis to change its position, which is often described as a wobble. The axis of Earth traces a complete circle every 25,700 years.

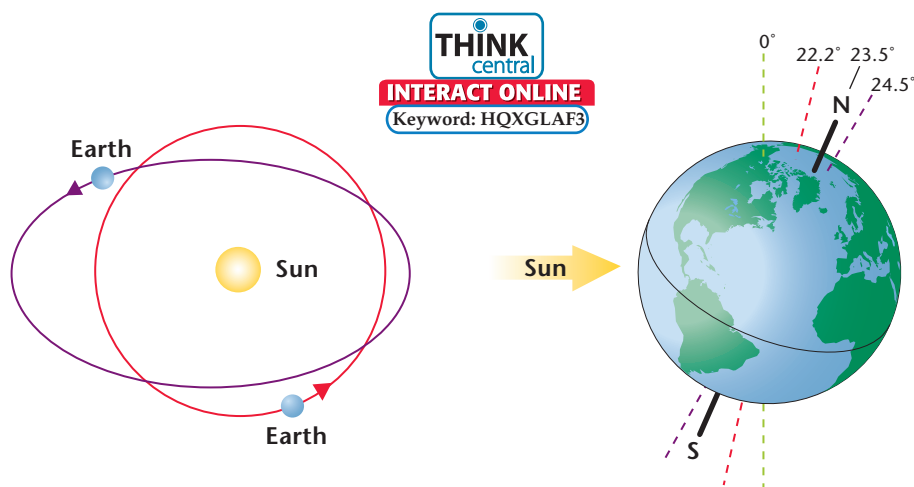
Milankovitch calculated how these three factors may affect the distribution of solar energy that reaches Earth's surface. Changes in the distribution of solar energy affects global temperatures, which may cause periods of glacial advance and retreat.

Math Skills

Earth's Tilt The current angle of Earth's tilt is 23.5° . That angle is decreasing. If the tilt moves from 24.5° to 22.2° over 41,000 years, estimate how many years will pass before Earth's current tilt reaches 22.2° .

Milankovitch theory the theory that cyclical changes in Earth's orbit and in the tilt of Earth's axis occur over thousands of years and cause climatic changes

Figure 3 According to the Milankovitch theory, the distribution of solar radiation that Earth receives varies because of three kinds of changes in Earth's position relative to the sun.



Eccentricity Changes in orbital eccentricity cause an increase in seasonality in one hemisphere and reduce seasonality in the other hemisphere.

Tilt Over a period of 41,000 years, the tilt of Earth's axis varies between 22.2° and 24.5° . The poles receive more solar energy when the tilt angle is greater.

Precession A gradual change, or "wobble," in the orientation of Earth's axis affects the relationship between Earth's tilt and eccentricity.

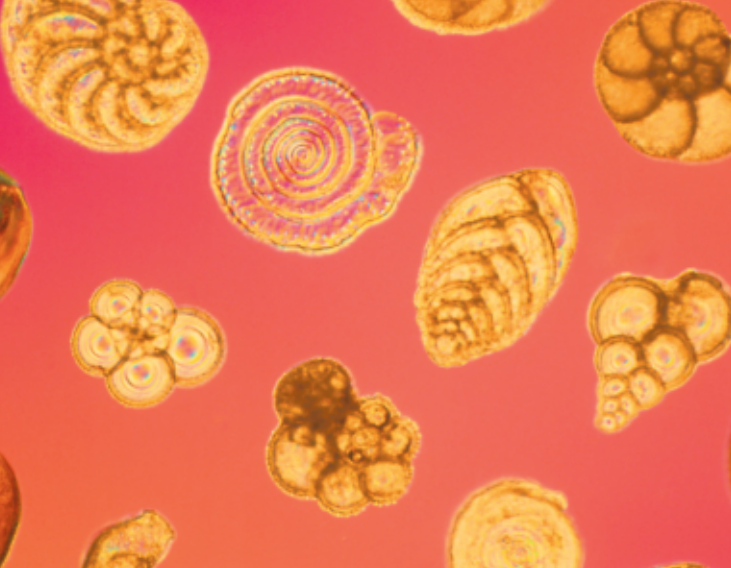


Figure 4 The microscopic shells of organisms from the order Foraminifera give clues to climate change.

Biological Evidence of Glaciation

Evidence for past glaciation has been discovered in the shells of dead marine animals found on the ocean floor. The formation of the shells of organisms from the order Foraminifera, shown in **Figure 4**, is affected by the temperature of the ocean water. Temperature of the ocean water affects the amount of oxygen that the water dissolves. The amount of oxygen in turn affects how these organisms form their shells. In addition, organisms that lived in ocean waters that were warmer than 8°C coiled their shells to the right. Organisms that lived in ocean waters that were much cooler coiled their shells to the left.

By studying Foraminifera shells in the layers of sediment on the ocean floor, scientists have discovered evidence of different glacial periods. Scientists have found that the record of changes in marine sediments closely follows the cycle of cooling and warming predicted by the Milankovitch theory.

Other Explanations for Glaciation

Other explanations for the causes of glacial periods have been suggested. Most of these explanations indicate that the glacial periods were caused by changes in the amount of solar energy that reached Earth's surface that were not caused by changes in Earth's position relative to the sun. Some scientists propose that changes in solar energy are caused by varying amounts of energy produced by the sun. Other scientists suggest that glacial periods start when volcanic dust blocks the sun's rays. Volcanic dust in Earth's atmosphere prevents solar radiation from reaching Earth's surface. As a result, Earth's average global temperature drops. 🌿

Section 3 Review

Key Ideas

1. **Describe** glacial periods and interglacial periods.
2. **Explain** what happens to global sea level during a glacial period.
3. **Identify** the areas of Earth's surface that were covered by ice during the last glacial period.
4. **Summarize** the Milankovitch theory.
5. **Explain** how fossils of marine animals provide evidence of past glaciation.
6. **Describe** two explanations for glacial periods other than the Milankovitch theory.

Critical Thinking

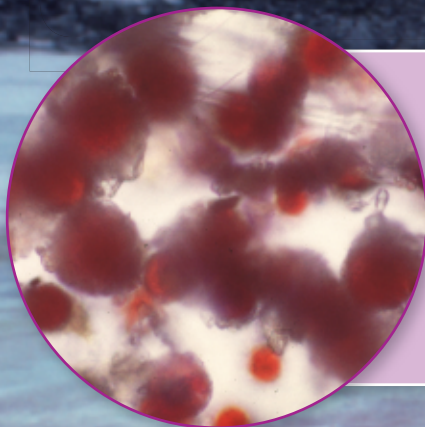
7. **Evaluating Hypotheses** Use the information that you learned about glacial periods within an ice age to explain why volcanic eruptions may not be the cause of ice ages.
8. **Predicting Consequences** If Earth's orbit were always circular, would Earth be more likely to experience ice ages or less likely to experience ice ages? Explain your answer.

Concept Mapping

9. Use the following terms to create a concept map: *ice age, glacial period, interglacial period, Milankovitch theory, eccentricity, tilt, volcanic eruption, and precession.*

Watermelon Ice

Believe it or not, glacial ice is home to hundreds of different organisms, including over 60 different species of snow algae in the United States. One type of red snow algae forms the base of the glacial food web. These algae cause pink snow, known as “watermelon ice.” When a person walks on the pink snow, the crushed algae release a compound that smells like watermelon!



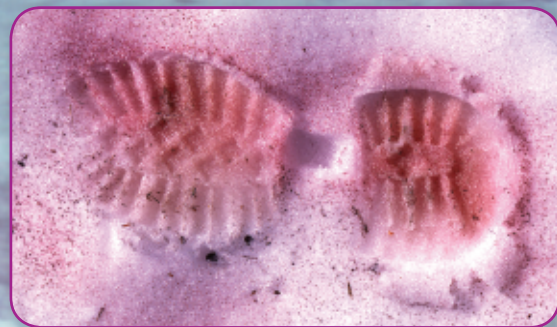
These red snow algae contain carotene—the pigment found in carrots, oranges, flowers, and flamingoes. Carotene helps another pigment, chlorophyll, in the process of photosynthesis and protects the organism from intense exposure to the sun.



Ice worms come out by the millions at night. They eat snow algae and other microscopic organisms.



Snow fleas are less than 1 mm long. They eat snow algae and wind-blown pollen. Birds, in turn, eat the snow fleas and ice worms.



Walking on watermelon ice can stain the soles of a person's shoes.

YOUR TURN

UNDERSTANDING CONCEPTS

How does the color of red snow algae help them survive the glacial environment?

ONLINE RESEARCH

Use the Internet to find out more about one of the organisms described above. Write a one-page summary to describe your findings.

What You'll Do

- **Model** the melting of an ice sheet.
- **Analyze** the effects of melting ice on sea level.

What You'll Need

block, ice,
 5 cm × 5 cm × 5 cm
 block, wooden,
 5 cm × 5 cm × 5 cm
 pan,
 30 cm × 40 cm × 10 cm
 pebbles (1 kg)
 ruler, metric
 sand (1 kg)
 water

Safety



Glaciers and Sea-Level Change

Today, glaciers hold only about 2% of Earth's water. But if the polar ice sheets melted, the coastal areas of many countries would flood. Many major cities, such as New York, New Orleans, Houston, and Los Angeles, would flood if the sea level rose only a few meters. In this lab, you will construct a model to simulate what would happen if the Antarctic ice sheet melted.

Procedure

- ➊ Calculate and record the approximate surface area of the bottom of the pan. Area (A) is equal to length (l) times width (w), or $A = l \times w$, and is expressed in square units.
- ➋ Calculate and record the overall volume of the ice block and the area of one side of the ice block. Volume (V) is equal to length (l) times width (w) times height (h), or $V = l \times w \times h$, and is expressed in cubic units.
- ➌ Add the sand and small pebbles to one end of the pan so that they cover about half of the area of the pan and slope toward the middle of the pan. Use the wooden block to elevate the end of the pan containing the sand and pebbles.
- ➍ Slowly add water to the opposite end of the pan. Be sure that the water does not cover the sand and pebbles and touches only the edge of the sand.

Step 3



- 5 Measure and record the depth of the water at the deepest point.
- 6 Measure and record the distance from the end of the pan covered with sand to the point where the sand touches the water.
- 7 Place the block of ice in the pan on top of the sand. Calculate and record the percentage of the total area of the pan that is covered by ice.
- 8 As the ice begins to melt, pick up the ice block. Note the appearance of the bottom of the ice block and the appearance of the sand under the ice block. Record what is happening to the ice block and what is happening to the sand under the ice block. Place the ice block back on the sand.
- 9 While the ice is melting, calculate the expected rise in the pan's water level by using the following formula:

$$\text{rise in water level} = \frac{\text{volume of water in ice block}}{\text{area of pan covered by water}}$$

- 10 When the ice is completely melted, measure and record the depth of water at the deepest point.
- 11 Measure and record the distance from the end of the pan covered with sand to the point where the sand touches the water.



Step 4

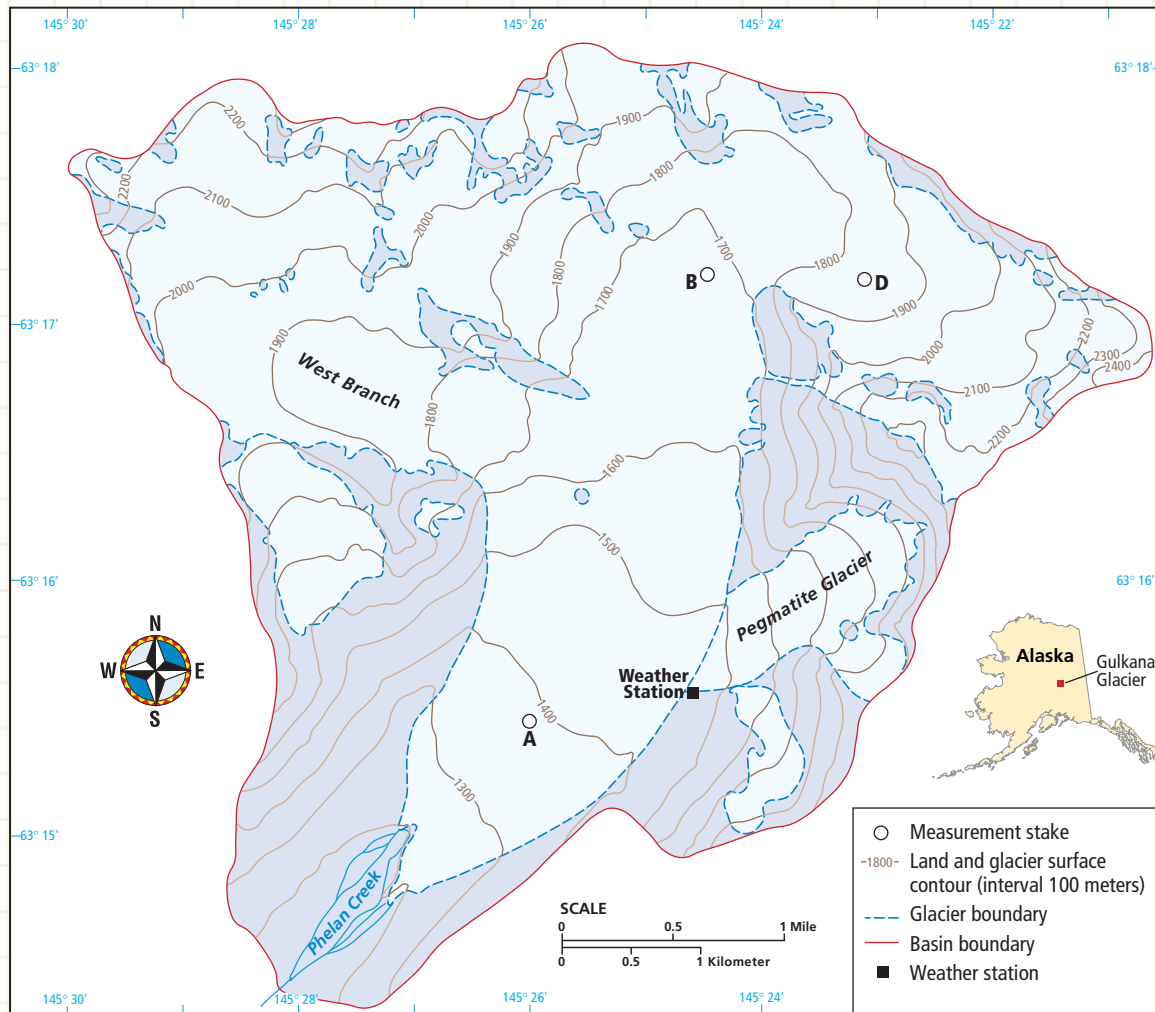
Analysis

1. **Making Comparisons** Compare the depth of the water at the beginning of the lab with the depth at the end of the lab. Explain any differences.
2. **Analyzing Results** How did the distance from the end of the pan covered with sand to the point where the sand touches the water change? Explain your answer.
3. **Compare and Contrast** How does the ice-block model differ from a glacier on Earth?
4. **Drawing Conclusions** How does the ice-block model represent what would happen on Earth if the Antarctic polar ice sheet melted?

Extension

Evaluating Models In this lab, you used a physical model to simulate an occurrence in nature. In what other ways do scientists use models? What kinds of errors can occur when models are used?

Gulkana Glacier



Map Skills Activity

This contour map shows the elevation and boundaries of the Gulkana Glacier located in Alaska. Use the map to answer the questions below.

- Using a Key** Estimate the length of the Gulkana Glacier from its northernmost point to its southernmost point.
- Analyzing Data** Estimate the latitude and longitude of the glacier's highest point.
- Identifying Trends** In which direction do you think Gulkana Glacier is moving at measurement stake D?
- Identifying Trends** In which direction do you think Gulkana Glacier is moving at measurement stake A?
- Predicting Consequences** Why might you think that the glacier moves in different directions at measurement stake A and measurement stake B?
- Analyzing Data** What do you think the scientists are measuring at the measurement stakes?

Section 1**Key Ideas****Glaciers: Moving Ice**

- Glaciers form at high elevations and in polar regions as layers of snow and ice build up.
- The two main types of glaciers are alpine glaciers, which form in mountainous areas and are relatively small, and continental glaciers, which are massive ice sheets that cover millions of square kilometers.
- Glaciers move by basal slip, sliding over the thin layer of water and sediment that separates the ice from the ground, and internal plastic flow, the process by which grains of ice deform under pressure and slide over each other.
- Three features of glaciers are large cracks called crevasses, ice sheets that extend out over the ocean called ice shelves, and large pieces of ice that break off into the ocean called icebergs.

Key Terms

glacier, p. 455
alpine glacier, p. 456
continental glacier,
p. 456
basal slip, p. 457
internal plastic flow,
p. 457
crevasse, p. 458

Section 2**Glacial Erosion and Deposition**

- Features produced by glacial erosion include U-shaped valleys, hanging valleys, bowl-shaped depressions called cirques, sharp ridges called arêtes, pointed peaks called horns, and rounded rocks called roches moutonnées.
- Features formed by glacial deposition include large transported rocks called erratics, depressions called kettles, ridges called eskers, mounds of till called drumlins, and ridges of sediment called moraines.
- Glaciers may form lake basins by eroding the land or by depositing sediments.

cirque, p. 460
arête, p. 460
horn, p. 460
erratic, p. 462
glacial drift, p. 462
till, p. 462
moraine, p. 463
kettle, p. 464
esker, p. 464

Section 3**Ice Ages**

- During an ice age, cooler glacial periods, characterized by the advancement of glaciers, alternate with warmer interglacial periods, characterized by the retreat of glaciers.
- The Milankovitch theory best accounts for the ice ages. It suggests that glacial periods are caused by changes in the distribution of solar energy Earth receives. These changes are caused by regular changes in the eccentricity of Earth's orbit, the tilt of Earth's axis, and precession.

ice age, p. 467
Milankovitch theory,
p. 469

- 1. Classification** Make a three-column table to classify the two main ways that glaciers move. Label the first column “Type of movement,” the second column “Where movement occurs on glacier,” and the third column “Description of movement.” Fill in your table with details about basal slip and internal plastic flow.

READING TOOLBOX**USING KEY TERMS**

Use each of the following terms in a separate sentence.

2. *glacier*
3. *crevasse*
4. *ice age*

For each pair of terms, explain how the meanings of the terms differ.

5. *alpine glacier* and *continental glacier*
6. *till* and *moraine*
7. *basal slip* and *internal plastic flow*
8. *cirque* and *arête*
9. *glacial period* and *interglacial period*

UNDERSTANDING KEY IDEAS

10. Glaciers that form in mountainous areas are called
 - a. continental glaciers.
 - b. alpine glaciers.
 - c. icebergs.
 - d. ice shelves.
11. A glacier will move by sliding when the base of the ice and the underlying rock are separated by a thin layer of
 - a. water and sediment.
 - b. snow.
 - c. pebbles.
 - d. drift.

12. What part of a glacier moves fastest when the glacier moves by internal plastic flow?
 - a. The center of the glacier moves fastest.
 - b. The bottom of the glacier moves fastest.
 - c. The edges of the glacier move fastest.
 - d. The whole ice mass moves at the same speed.
13. Icebergs form when ice breaks off of a(n)
 - a. crevasse.
 - b. ice shelf.
 - c. alpine glacier.
 - d. esker.
14. As a glacier moves through a valley, it carves out a(n)
 - a. U shape.
 - b. esker.
 - c. V shape.
 - d. moraine.
15. A deposit of stratified drift is called a(n)
 - a. drumlin.
 - b. outwash plain.
 - c. ground moraine.
 - d. roche moutonnée.
16. One component of the Milankovitch theory is
 - a. the circular motion of Earth’s axis.
 - b. continental drift.
 - c. volcanic activity.
 - d. landslide activity.
17. Which of the following is not a theory for the cause of ice ages?
 - a. volcanic eruptions
 - b. variations in Earth’s orbit
 - c. Foraminifera shell coils
 - d. changes in Earth’s axial orientation

SHORT ANSWER

18. How does climate change during an ice age?
19. What are the four types of moraines, and how are they different from each other?
20. Identify three types of landforms created by alpine glaciers.
21. In what two ways do glacial lakes form?
22. How do the processes of basal slip and internal plastic flow differ?

CRITICAL THINKING

- 23. Identifying Relationships** Why is it important for scientists to monitor and study the continental ice sheets that cover Greenland and Antarctica?
- 24. Applying Concepts** Antarctic explorers need special training to travel safely over the ice sheet. Besides the cold, what structural aspects of the glaciers may be dangerous?
- 25. Evaluating Data** What phenomenon other than decreased temperature and increased snowfall might signal the beginning of a glacial period?

CONCEPT MAPPING

- 26.** Use the following terms to create a concept map: *snowfield, erosion, deposition, glacier, horn, arête, kettle, moraine, basal slip, and internal plastic flow.*

MATH SKILLS

Math Skills

- 27. Using Equations** The area of Earth's surface that is covered with water is 361,000,000 km². The volume of water locked in ice in the Antarctic ice sheet is about 26,384,368 km³. Use the following equation to find the average worldwide rise in sea level, in meters, that would occur if the Antarctic ice sheet melted.

$$\text{rise in water level} = \frac{\text{volume of water in ice sheet}}{\text{area of Earth covered by water}}$$

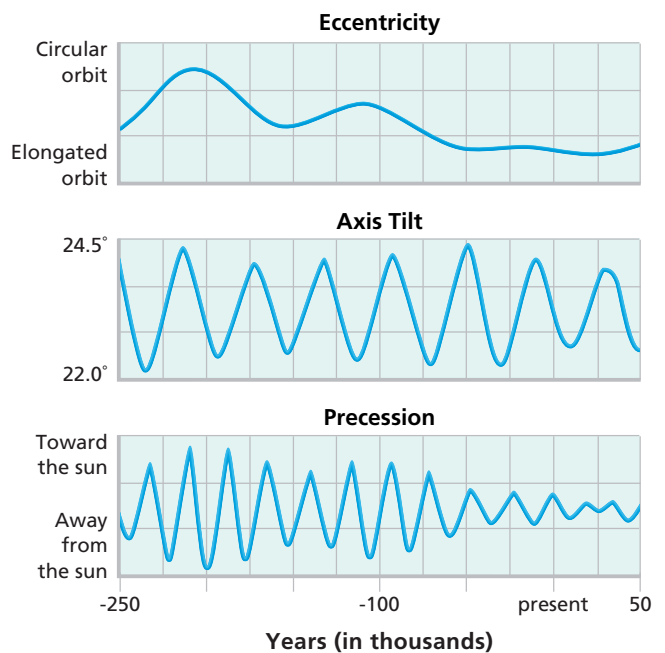
- 28. Evaluating Data** New York City has an average elevation of 27 m above sea level. Although highly unlikely, what would happen to the city if the Antarctic ice sheet suddenly melted and raised the worldwide sea level by 50 m?

WRITING SKILLS

- 29. Writing Persuasively** Write a research proposal to the National Science Foundation that details a plan of action and reasons for studying the ice sheet in Greenland.
- 30. Writing from Research** Research how ocean currents affect the polar icecaps. Write a short essay that describes global ocean currents and explains how they affect the formation and advancement of polar icecaps.

INTERPRETING GRAPHICS

The graph below shows the relationship between cycles of eccentricity, tilt, and precession. Use the graph to answer the questions that follow.



- 31.** What was the angle of Earth's tilt 50,000 years ago?
- 32.** Describe the shape of Earth's orbit 200,000 years ago.
- 33.** How would the seasons 50,000 years from now be different from the seasons 50,000 years ago?

Understanding Concepts

Directions (1–4): For each question, write on a separate sheet of paper the letter of the correct answer.

- Which statement *best* compares the movement of glacial ice to the movement of river water?
 - Glacial ice moves more rapidly than water.
 - Glacial ice cannot easily flow around barriers.
 - Glacial ice moves in response to gravity.
 - Glacial ice moves in the same way as water.
- What landforms created by glaciers have bowl-like shapes?
 - cirques
 - arêtes
 - horns
 - roches moutonnées
- What is the unsorted material left beneath a glacier when the ice melts?
 - lateral moraine
 - ground moraine
 - medial moraine
 - terminal moraine
- Which of the following statements *best* describes how crevasses form on the surface of a glacier?
 - Movement of the glacier's ice from the center toward the edges forms large cracks on the surface of the glacier.
 - As the ice flows unevenly beneath the surface of the glacier, tension and compression on the surface form large cracks.
 - Breakage of large blocks of ice from the edges of ice shelves forms large cracks.
 - Narrow, wedge-shaped masses of ice confined to a small area form large cracks.

Directions (5–6): For each question, write a short response.

- What is the term for all types of sediments deposited by a glacier?
- What is the name of a jagged ridge that is formed between two or more cirques that cut into the same mountain?

Reading Skills

Directions (7–9): Read the passage below. Then, answer the questions.

Glacial and Interglacial Periods

Ice ages are periods during which ice collects in high latitudes and moves toward lower latitudes. During an ice age, there are periods of cold and of warmth. These periods are called *glacial* and *interglacial periods*. During glacial periods, enormous sheets of ice advance, grow bigger, and cover a large area. Because a large amount of sea water is frozen during glacial periods, the sea level around the world drops.

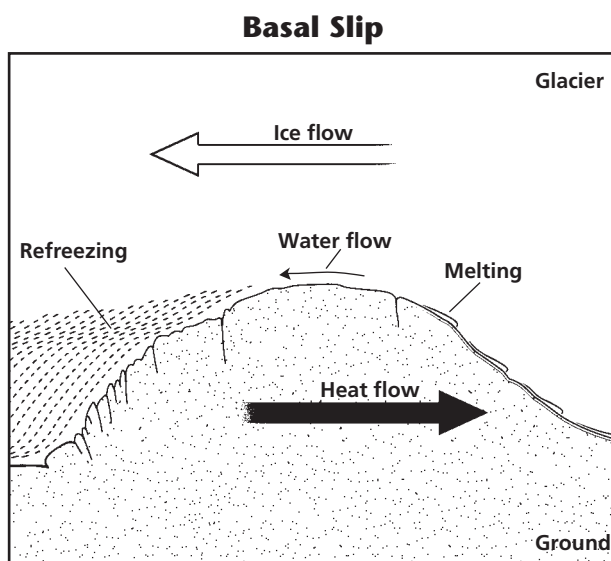
Warmer time periods that occur between glacial periods are known as interglacial periods. During an interglacial period, the large ice sheets begin to melt and the sea levels begin to rise again. Scientists believe that the last interglacial period began approximately 10,000 years ago and is still happening. For nearly 200 years, scientists have been debating what the current interglacial period might mean for humans and the possibility of a future glacial period.

- According to the passage, which of the following statements is true?
 - The last interglacial period began approximately 1,000 years ago.
 - Scientists have been thinking about the next glacial period for two centuries.
 - Ice ages are periods during which ice collects in the lower latitudes and moves toward higher latitudes.
 - During glacial periods, enormous sheets of ice tend to melt, so they become smaller and cover less area.
- Which of the following statements can be inferred from the information in the passage?
 - On average, ice ages occur every 50,000 years and always start with a glacial period.
 - Interglacial periods always last 10,000 years.
 - Glacial periods always last 10,000 years.
 - The current interglacial period will likely be followed by a glacial period.
- If a new glacial period began tomorrow, what might happen to coastal cities?

Interpreting Graphics

Directions (10–13): For each question below, record the correct answer on a separate sheet of paper.

Base your answers to questions 10 and 11 on the diagram below.



10. What causes the ice to melt in the diagram above?

- A. Pressure decreases the melting point of the ice.
- B. Pressure increases the melting point of the ice.
- C. The ground heats the ice until it melts.
- D. Ice at the base of a glacier does not melt.

11. How does meltwater influence basal slip?

Base your answer to question 12 on the table below.

World Cities and Their Elevations

City	Elevation (m)
New York City	27
Kiev, Ukraine	168
Buenos Aires, Argentina	25
Amsterdam, Netherlands	2

12. Although unlikely, what would happen to each of the cities listed in the table if the Antarctic ice sheet were to melt and raise the sea level by 50 m?

13. The movement of a glacier was recorded over a period of 180 days. During that time, the glacier moved a total of 36 m. What was the average speed of the glacier each day?

- F. 0.20 m/day
- G. 0.50 m/day
- H. 2.00 m/day
- I. 5.00 m/day

Test Tip

For a group of questions that refer to a diagram, graph, or table, read all of the questions quickly to determine what information you will need to glean from the graphic.