CHAPTER

17

Glaciers and Ice Ages

We often think of glaciers as features of high mountains and the frozen polar regions. Yet anyone who lives in the northern third of the United States is familiar with glacial landscapes. Many low, rounded hills of upper New York State, Wisconsin, and Minnesota are piles of gravel deposited by great ice sheets as they melted. In addition, people in this region swim and fish in lakes that were formed by recent glaciers.

Glaciers have advanced and retreated at least five times during the past 2 million years. Before the most recent major glacial advance, beginning about 100,000 years ago, the world was free of ice except for the polar ice caps of Antarctica and Greenland. Then, in a relatively short time—perhaps only a few thousand years—the Earth's climate cooled by a few degrees. As winter snow failed to melt in summer, the polar ice caps grew and spread into lower latitudes. At the same time, glaciers formed near the summits of high mountains, even near the equator. They flowed down mountain valleys into nearby lowlands. When the glaciers reached their maximum size 18,000 years ago, they covered one third of the Earth's continents. About 15,000 years ago, Earth's climate warmed again and the glaciers melted rapidly.

Although 18,000 years is a long time when compared with a single human lifetime, it is a blink of an eye in geologic time. In fact, humans lived through the most recent glaciation. In southwestern France and northern Spain, humans developed sophisticated spearheads and carved body ornaments between 40,000 and 30,000 years ago. People first began experimenting with agriculture about 10,000 years ago.

Alpine glaciers sculpt mountain landscapes, Bugaboo Mountains, British Columbia.

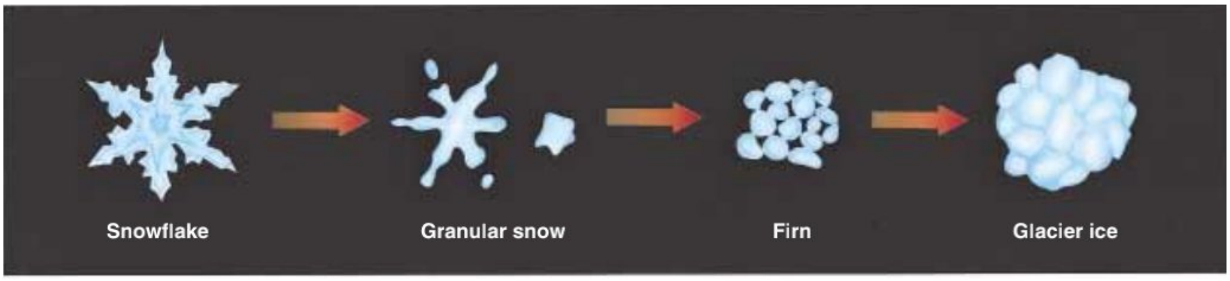

Figure 17–1 The change of newly fallen snow through several stages to form glacier ice.

17.1 FORMATION OF GLACIERS

In most temperate regions, winter snow melts in spring and summer. However, in certain cold, wet environments, only a portion of the winter snow melts and the remainder accumulates year after year. During summer, snow crystals become rounded as the snowpack is compressed and alternately warmed during daytime and cooled at night. Temperature changes and compaction make the snow denser. If snow survives through one summer, it converts to rounded ice grains called **firn** (Fig. 17–1). Mountaineers like firn because the sharp points of their ice axes and crampons sink into it easily and hold firmly. If firn is buried deeper in the snowpack, it converts to closely packed ice crystals.

A **glacier** is a massive, long-lasting, moving mass of compacted snow and ice. Glaciers form only on land, wherever the amount of snow that falls in winter exceeds the amount that melts in summer. Glaciers in mountain regions flow downhill. Glaciers on level land flow outward under their own weight, just as cold honey poured onto a tabletop spreads outward.

Glaciers form in two environments. Alpine glaciers form at all latitudes on high, snowy mountains. Continental ice sheets form at all elevations in the cold polar regions.

ALPINE GLACIERS

Mountains are generally colder and wetter than adjacent lowlands. Near the mountain summits, winter snowfall is deep and summers are short and cool. These conditions create **alpine glaciers** (Fig. 17–2). Alpine glaciers exist on every continent—in the Arctic and Antarctica, in temperate regions, and in the tropics. Glaciers cover the summits of Mount Kenya in Africa and Mount Cayambe in South America, even though both peaks are near the equator.

Some alpine glaciers flow great distances from the peaks into lowland valleys. For example, the Kahiltna Glacier, which flows down the southwest side of Denali (Mount McKinley) in Alaska, is about 65 kilometers long, 12 kilometers across at its widest point, and about 700 meters thick. Although most alpine glaciers are smaller than the Kahiltna, some are larger.

The growth of an alpine glacier depends on both temperature and precipitation. The average annual temperature in the state of Washington is warmer than that

Figure 17–2 This alpine glacier flows around granite peaks in British Columbia, Canada.

Figure 17–3 The Beardmore glacier is a portion of the Antarctic ice sheet. (Kevin Killelea)

in Montana, yet alpine glaciers in Washington are larger and flow to lower elevations than those in Montana. Winter storms buffet Washington from the moisture-laden Pacific. Consequently, Washington's mountains receive such heavy winter snowfall that even though summer melting is rapid, large quantities of snow accumulate every year. In much drier Montana, snowfall is light enough that most of it melts in the summer, and thus Montana's mountains have no or only very small glaciers.

CONTINENTAL GLACIERS

Winters are so long and cold and summers so short and cool in polar regions that glaciers cover most of the land regardless of its elevation. An **ice sheet**, or **continental glacier**, covers an area of 50,000 square kilometers or more (Fig. 17–3).[1] The ice spreads outward in all directions under its own weight.

Today, the Earth has only two ice sheets, one in Greenland and the other in Antarctica. These two ice sheets contain 99 percent of the world's ice and about three fourths of the Earth's fresh water. The Greenland sheet is more than 2.7 kilometers thick in places and covers 1.8 million square kilometers. Yet it is small compared with the Antarctic ice sheet, which blankets about 13 million square kilometers, almost 1.5 times the size of the United States. The Antarctic ice sheet covers entire mountain ranges, and the mountains that rise above its surface are islands of rock in a sea of ice. If the Antarctic ice sheet melted, the meltwater would create a river the size of the Mississippi that would flow for 50,000 years.

Whereas the South Pole lies in the interior of the Antarctic continent, the North Pole is situated in the Arctic Ocean. Only a few meters of ice freeze on the relatively warm sea surface, and the ice fractures and drifts with the currents. As a result, no ice sheet exists at the North Pole.

[1]A continental glacier with an area of less than 50,000 square kilometers is called an ice cap.

17.2 GLACIAL MOVEMENT

Imagine that you set two poles in dry ground on opposite sides of a glacier, and a third pole in the ice to form a straight line with the other two. After a few months, the center pole would have moved downslope, and the three poles would form a triangle. This simple experiment shows us that the glacier moved downhill.

Rates of glacial movement vary with slope steepness, precipitation, and air temperature. In the coastal ranges of Alaska, where annual precipitation is high and average temperature is relatively high (for glaciers), some glaciers typically move 15 centimeters to a meter a day. In contrast, in the interior of Alaska where conditions are generally cold and dry, glaciers move only a few centimeters a day. At these rates, ice flows the length of an alpine glacier in a few hundred to a few thousand years. In some instances, a glacier may *surge* at a speed of 10 to 100 meters per day.

Glaciers move by two mechanisms: basal slip and plastic flow. In **basal slip**, the entire glacier slides over bedrock in the same way that a bar of soap slides down a tilted board. Just as wet soap slides more easily than dry soap, an accumulation of water between bedrock and the base of a glacier accelerates basal slip.

Several factors cause water to accumulate near the base of a glacier. The Earth's heat melts ice near bedrock. Friction from glacial movement also generates heat. Water occupies less volume than an equal amount of ice. As a result, pressure from the weight of overlying ice favors melting. Finally, during the summer, water melted from the surface of a glacier may seep downward to its base.

A glacier also moves by **plastic flow**, in which it deforms as a viscous fluid. Plastic flow is demonstrated by two experiments. In one, scientists set a line of poles in the ice (Fig. 17–4). After a few years, the ice moves downslope so that the poles form a U-shaped array. This experiment shows us that the center of the glacier moves faster than the edges. Frictional resistance with the valley walls slows movement along the edges and glacial ice flows plastically, allowing the center to move faster than the sides.

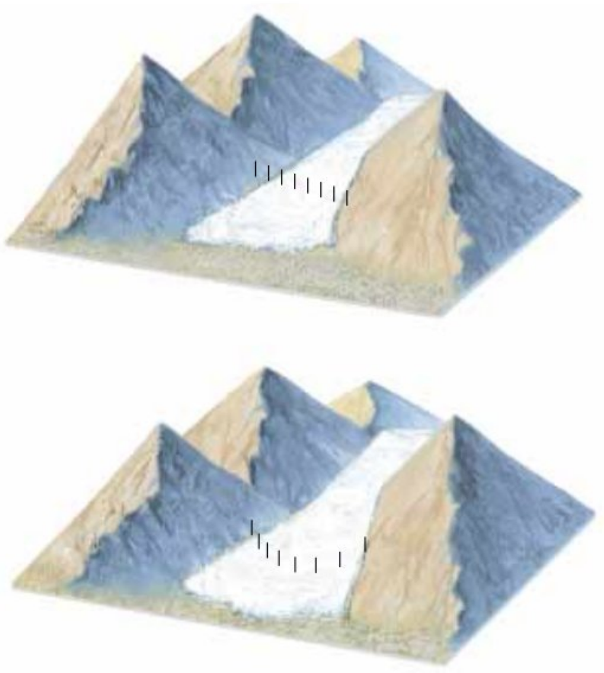

Figure 17–4 If a line of pipes is set into the ice, the pipes near the center of the glaciers move downslope faster than those near the margins.

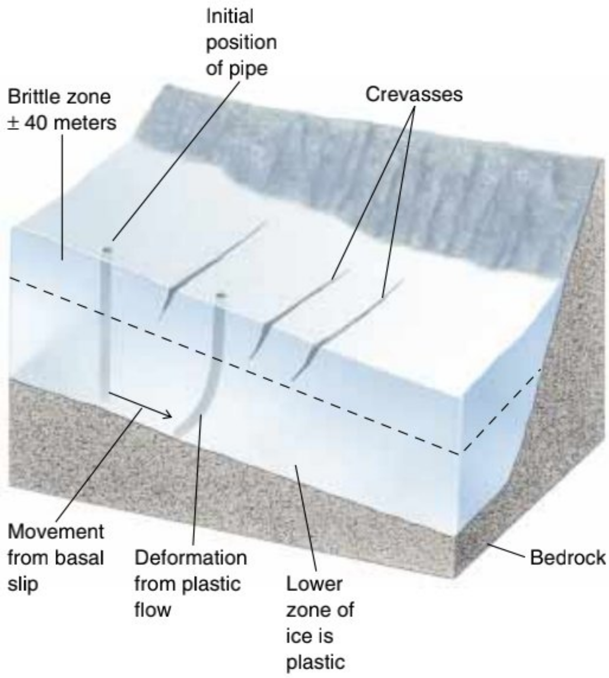

Figure 17–5 In this experiment, a pipe is driven through a glacier until it reaches bedrock. The entire pipe moves downslope. The pipe becomes curved because the center of the glacier deforms plastically and moves faster than the base. The top 40 meters of ice are brittle, and the pipe remains straight in this section.

As another experiment, imagine driving a straight but flexible pipe downward into the glacier to study the flow of ice at depth (Fig. 17–5). At a later date, you notice that not only has the entire pipe moved downslope, but the pipe has become curved. At the surface of a glacier, the ice acts as a brittle solid, like an ice cube or the ice found on the surface of a lake. In contrast, at depths greater than about 40 meters, the pressure is sufficient to allow ice to deform in a plastic manner. The curvature in the pipe shows that the ice has moved plastically and that middle levels of the glacier moved faster than the lower part. The base of the glacier is slowed by friction against bedrock, so it moves more slowly than the plastic portion above it.

The relative rates of basal slip and plastic flow depend on the steepness of the bedrock underlying the glacier and on the thickness of the ice. A small alpine glacier on steep terrain moves mostly by basal slip. In contrast, the bedrock beneath portions of the Antarctica and Greenland ice sheets is relatively level, so the ice cannot slide downslope. Thus, these continental glaciers are huge plastic masses of ice (with a thin rigid cap) that ooze outward mainly under the forces created by their own weight.

When a glacier flows over uneven bedrock, the deeper plastic ice bends and flows over bumps, stretching the brittle upper layer of ice so that it cracks, forming **crevasses** (Fig. 17–6). Crevasses form only in the brittle upper 40 meters of a glacier, not in the lower plastic zone. Crevasses open and close slowly as a glacier moves. An **ice fall** is a section of a glacier consisting of crevasses and towering ice pinnacles. The pinnacles form where ice blocks break away from the crevasse walls and rotate as the glacier moves. With crampons, ropes, and ice axes, a skilled mountaineer might climb into a crevasse. The walls are a pastel blue, and sunlight filters through the narrow opening above. The ice shifts and cracks, making creaking sounds as the glacier advances. Many mountaineers have been crushed by falling ice while traveling through ice falls.

THE MASS BALANCE OF A GLACIER

Consider an alpine glacier flowing from the mountains into a valley (Fig. 17–7). At the upper end of the glacier, snowfall is heavy, temperatures are below freezing for much of the year, and avalanches carry large quantities of snow from the surrounding peaks onto the ice. Thus, more snow accumulates in winter than melts in sum-

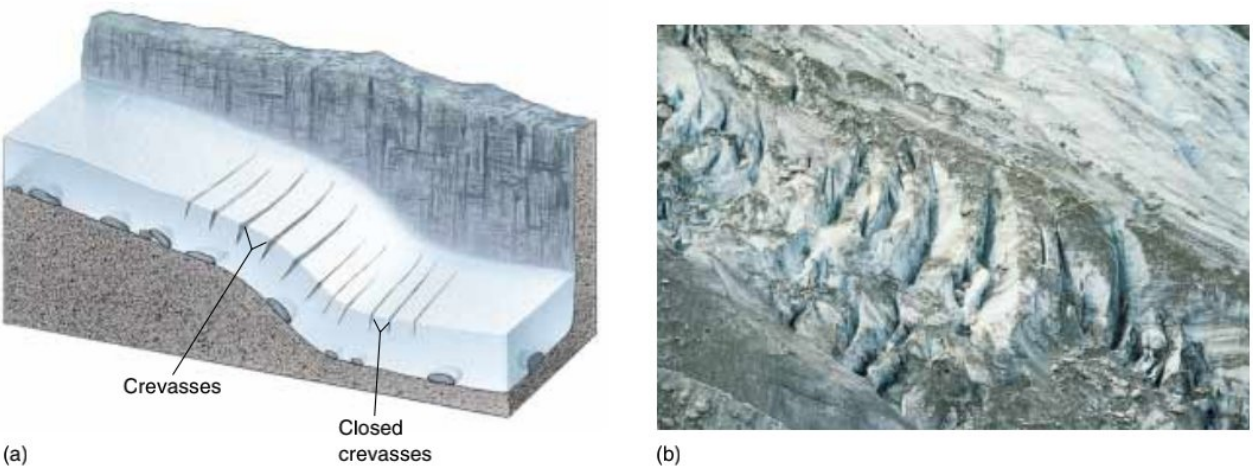

Figure 17–6 (a) Crevasses form in the upper, brittle zone of a glacier where the ice flows over uneven bedrock. (b) Crevasses in the Bugaboo Mountains of British Columbia.

mer, and snow piles up from year to year. This higher-elevation part of the glacier is called the **zone of accumulation**. There the glacier's surface is covered by snow year round.

Lower in the valley, the temperature is higher throughout the year, and less snow falls. This lower part of a glacier, where more snow melts in summer than accumulates in winter, is called the **zone of ablation**. When the snow melts, a surface of old, hard glacial ice is left behind. The **snowline** is the boundary between permanent snow and seasonal snow. The snowline shifts up and down the glacier from year to year, depending on weather.

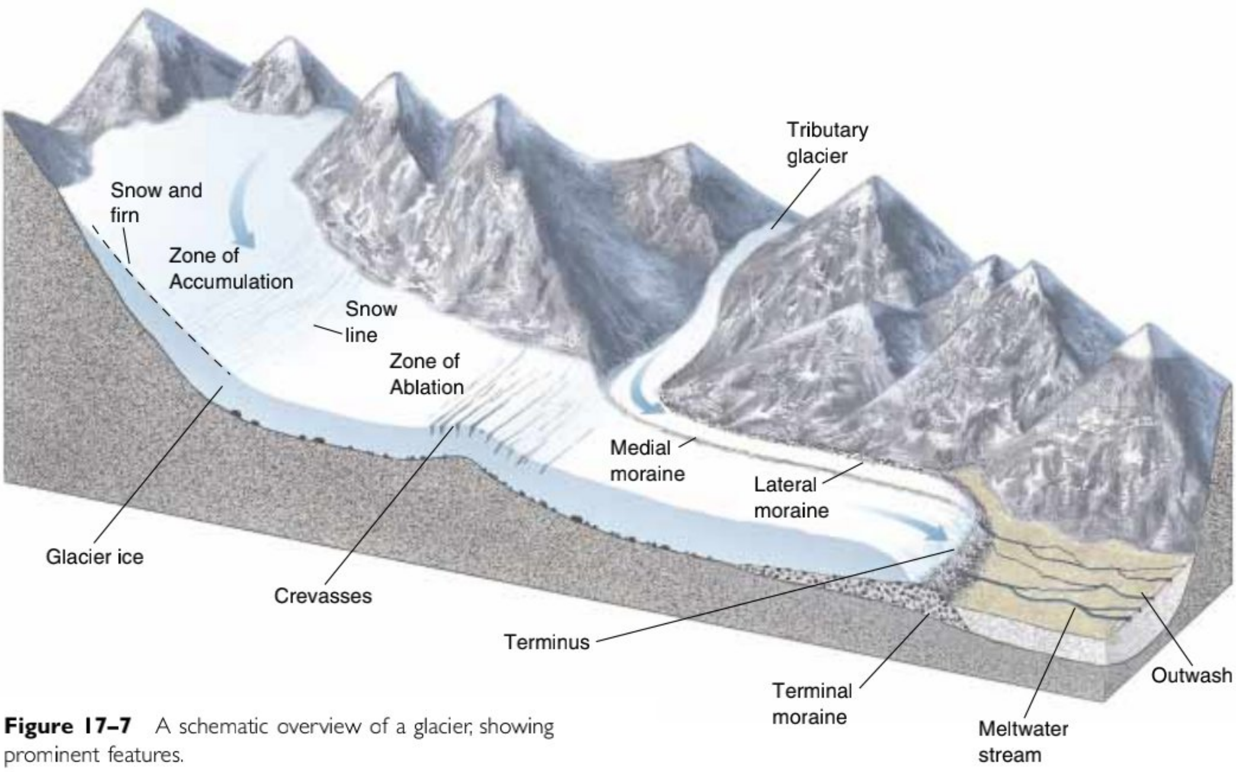

Figure 17–7 A schematic overview of a glacier, showing prominent features.

Ice exists in the zone of ablation because the glacier flows downward from the accumulation area. Farther down-valley, the rate of glacial flow cannot keep pace with melting, so the glacier ends at its **terminus** (Fig. 17–8).

Glaciers grow and shrink. If annual snowfall increases or average temperature drops, more snow accumulates; then the snowline of an alpine glacier descends to a lower elevation, and the glacier grows thicker. At first the terminus may remain stable, but eventually it advances farther down the valley. The lag time between a change in climate and a glacial advance may range from a few years to several decades depending on the size of the glacier, its rate of motion, and the magnitude of the climate change. On the other hand, if annual snowfall decreases or the climate warms, the accumulation area shrinks and the glacier retreats.

When a glacier retreats, its ice continues to flow downhill, but the terminus melts back faster than the glacier flows downslope. In Glacier Bay, Alaska, glaciers have retreated 60 kilometers in the past 125 years, leaving barren rock and rubble. Over the centuries, seabird droppings will mix with windblown silt and weathered rock to form thin soil. At first, lichens will grow on the bare rock, and then mosses will take hold in sheltered niches that contain soil. The mosses will be followed by grasses, bushes, and, finally, trees, as vegetation reclaims the landscape. Eventually, the glacier may advance again, destroying the vegetation.

Figure 17–8 The terminus of an alpine glacier on Baffin Island, Canada, in mid-summer. Dirty, old ice forms the lower part of the glacier below the firn line, and clean snow lies higher up on the ice above the firn line. (Steve Sheriff)

TIDEWATER GLACIERS

In equatorial and temperate regions, glaciers commonly terminate at an elevation of 3000 meters or higher. However, in a cold, wet climate, a glacier may extend into the sea to form a **tidewater glacier**. The terminus of a tidewater glacier is often a steep ice cliff dropping abruptly into the sea (Fig. 17–9). Giant chunks of ice break off, or **calve**, forming **icebergs**.

The largest icebergs in the world are those that calve from the Antarctic ice shelf. In January 1995, the edge of the 300-meter-thick Larson Ice Shelf cracked and an iceberg almost as big as Rhode Island broke free and floated into the Antarctic Ocean. The tallest icebergs in the world calve from tidewater glaciers in Greenland. Some extend 150 meters above sea level; since the visible portion of an iceberg represents only about 10 to 15 percent of its mass, these bergs may be as much as 1500 meters from base to tip.

Figure 17–9 A kayaker paddles among small icebergs that calved from the Le Conte glacier, Alaska.

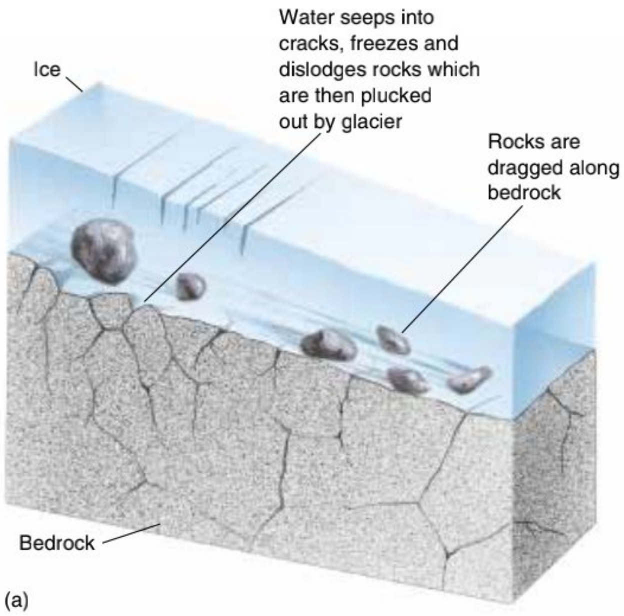

Figure 17–10 (a) A glacier plucks rocks from bedrock and then drags them along, abrading both the loose rocks and the bedrock. (b) Plucking formed these crescent-shaped depressions in granite at Le Conte Bay, Alaska.

17.3 GLACIAL EROSION

Rock at the base and sides of a glacier may have been fractured by tectonic forces and may be loosened by weathering processes, such as frost wedging or pressure-release fracturing. The moving ice then dislodges the loosened rock in a process called **plucking** (Fig. 17–10). Ice is viscous enough to pick up and carry particles of all sizes, from silt-sized grains to house-sized boulders. Thus glaciers erode and transport huge quantities of rock and sediment.

Ice itself is not abrasive to bedrock because it is too soft. However, rocks embedded in the ice scrape across bedrock like a sheet of rough sandpaper pushed by a giant's hand. This process cuts deep, parallel grooves and scratches in bedrock called **glacial striations** (Fig. 17–11). When glaciers melt and striated bedrock is exposed, the markings show the direction of ice movement. Glacial striations are used to map the flow directions of glaciers. Rocks that were embedded in the base of a glacier also commonly show striations.

Sand and silt embedded in a glacier polish bedrock to a smooth, shiny finish. The abrasion grinds rocks into fine silt-sized grains called **rock flour**. Characteristically, a glacial stream is so muddy with rock flour that it is gritty and brown or gray in color. Sometimes the suspended silt scatters sunlight to make alpine streams and lakes appear turquoise, blue, or green.

EROSIONAL LANDFORMS CREATED BY ALPINE GLACIERS

Let's take an imaginary journey through a mountain range that was glaciated in the past but is now mostly ice

Figure 17–11 Stones embedded in the base of a glacier gouged these striations in bedrock in British Columbia.

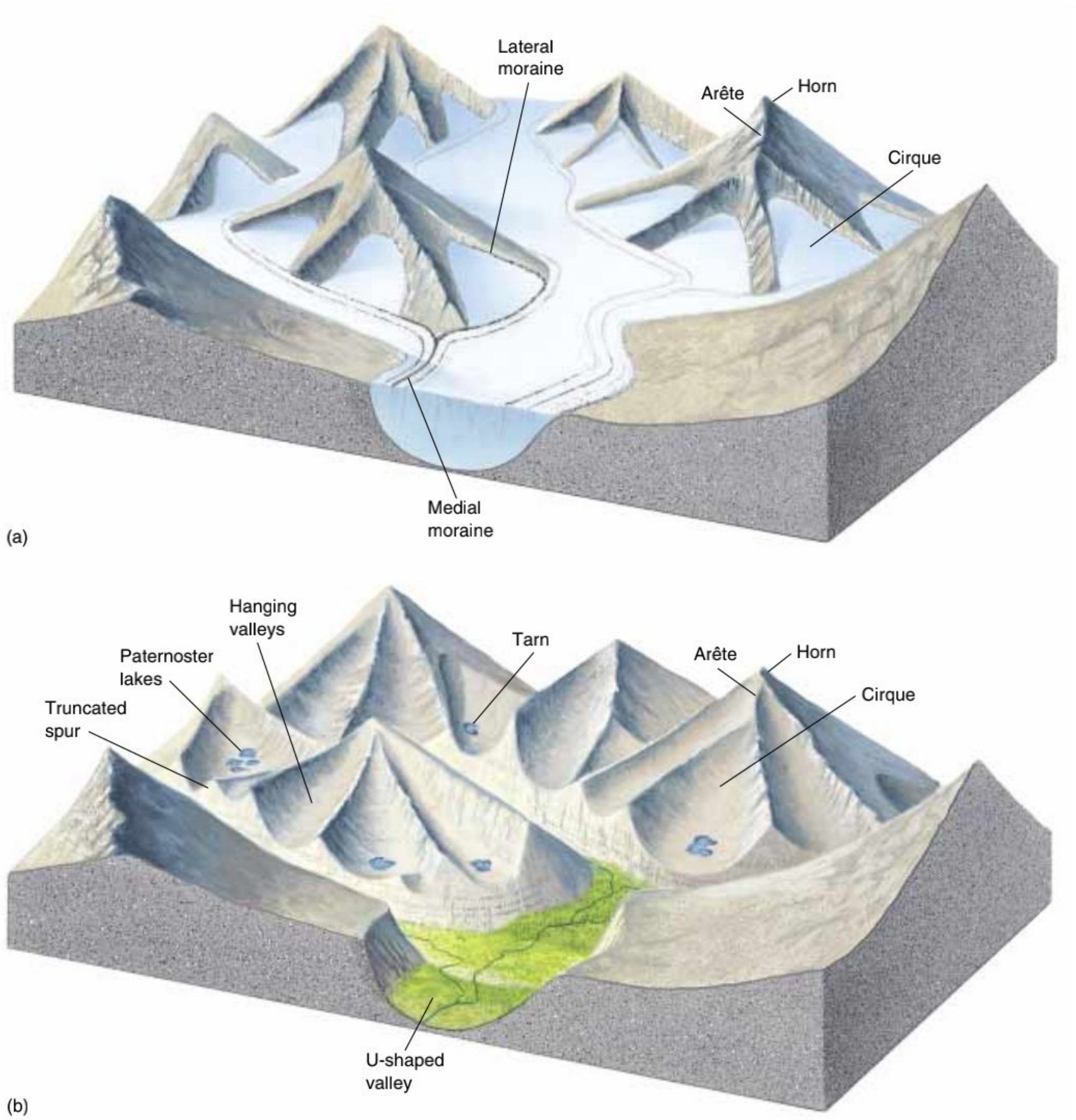

Figure 17–12 Glacial landscapes. (a) A landscape as it appears when it is covered by glaciers. (b) The same landscape as it appears after the glaciers have melted.

free. We start with a helicopter ride to the summit of a high, rocky peak. Our first view from the helicopter is of sharp, jagged mountains rising steeply above smooth, rounded valleys (Fig. 17–12).

A mountain stream commonly erodes downward into its bed, cutting a steep-sided, V-shaped valley. A glacier, however, is not confined to a narrow stream bed but instead fills its entire valley. As a result, it scours the sides of the valley as well as the bottom, carving a broad, rounded, **U-shaped valley** (Fig. 17–13).

We land on one of the peaks and step out of the helicopter. Beneath us, a steep cliff drops off into a horseshoe-shaped depression in the mountainside called a **cirque**. A small glacier at the head of the cirque reminds us of the larger mass of ice that existed in a colder, wetter time (Fig. 17–14a).

Figure 17–13 Pleistocene glaciers carved this U-shaped valley in the Canadian Rockies, Alberta.

To understand how a glacier creates a cirque, imagine a gently rounded mountain. As snow accumulates and a glacier forms, the ice flows down the mountainside (Fig. 17–14b). The ice plucks a small depression that grows slowly as the glacier flows (Fig. 17–14c). With time, the cirque walls become steeper and higher. The glacier carries the eroded rock from the cirque to lower parts of the valley (Fig. 17–14d). When the glacier finally melts, it leaves a steep-walled, rounded cirque.

Streams and lakes are common in glaciated mountain valleys. As a cirque forms, the glacier commonly erodes a depression into the bedrock beneath it. When the glacier melts, this depression fills with water, forming a small lake, or **tarn**, nestled at the base of the cirque. If we hike down the valley below the high cirques, we may encounter a series of lakes called **paternoster lakes**, which are commonly connected by rapids and waterfalls

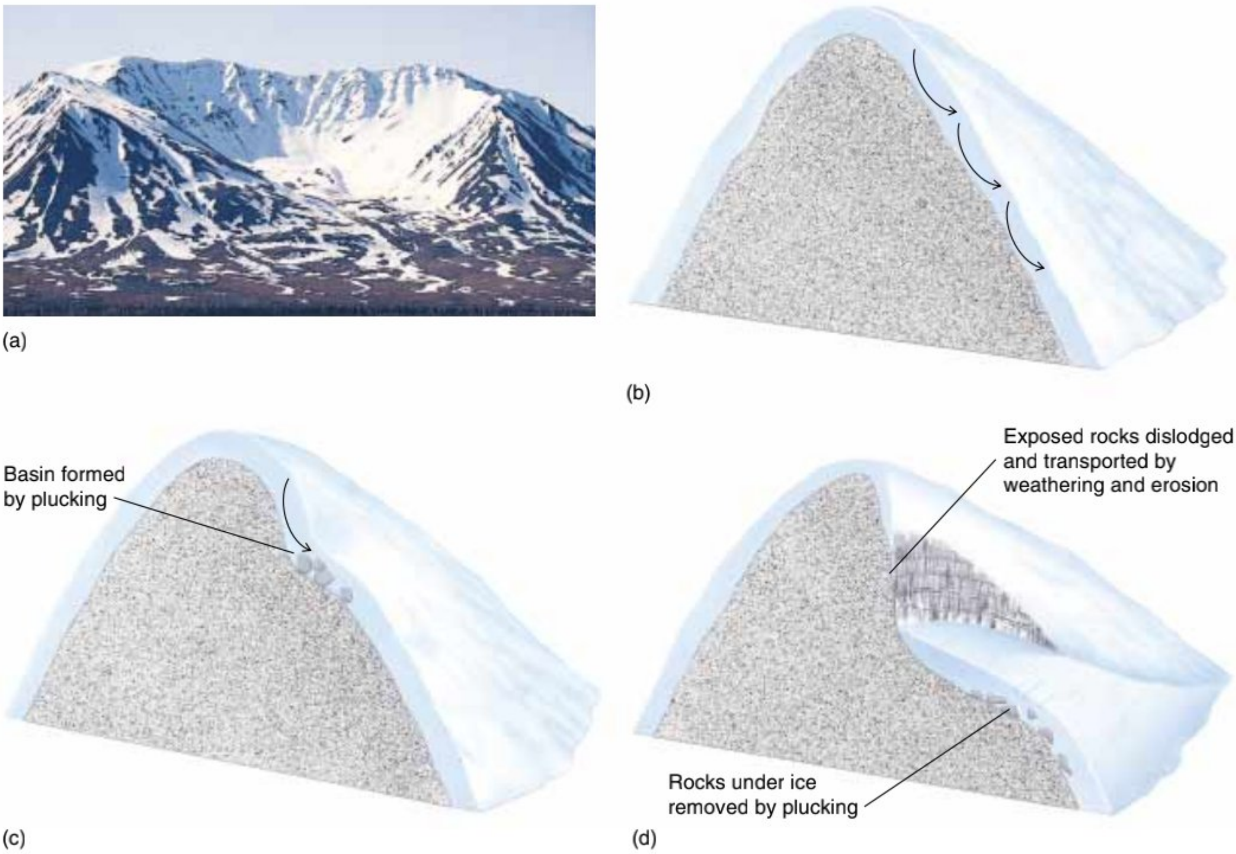

Figure 17–14 (a) A glacier eroded this concave depression, called a cirque, into a mountainside in the Alaska Range. (McCutcheon/Visuals Unlimited) (b) Snow accumulates, and a glacier begins to flow downslope from the summit of a peak. (c) Glacial plucking erodes a small depression in the mountainside. (d) Continued glacial erosion and weathering enlarge the depression. When the glacier melts, it leaves a cirque carved in the side of the peak, as in the photograph.

Figure 17–15 Glaciers cut this string of paternoster lakes in the Sierra Nevada.

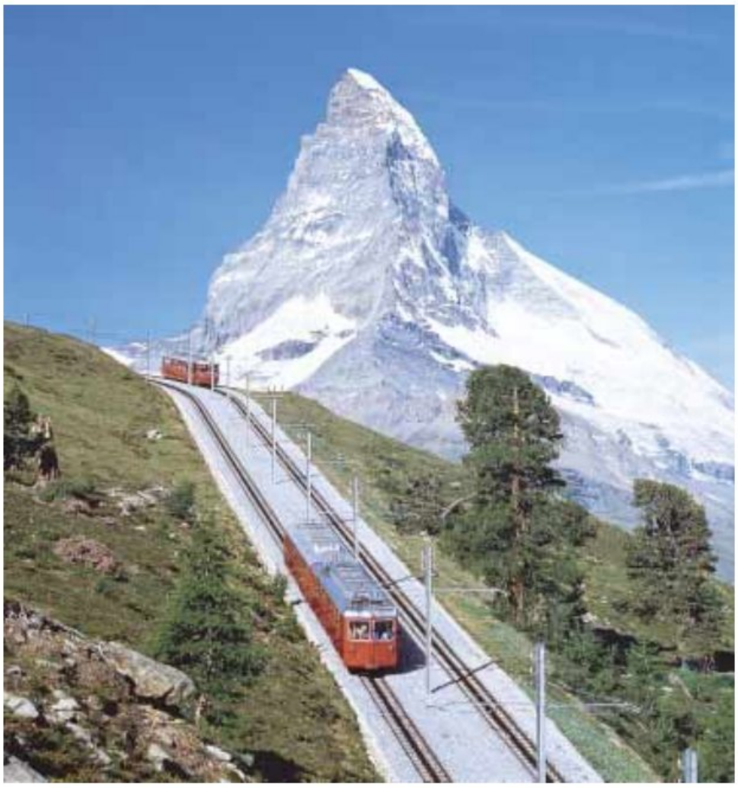

Figure 17–16 The Matterhorn formed as three glaciers eroded cirques into the peak from three different sides. (Swiss Tourist Board)

(Fig. 17–15). Paternoster lakes are a sequence of small basins plucked out by a glacier. The name *paternoster* refers to a string of rosary beads or in this case, a string of small lakes strung out across a valley. When the glacier recedes, the basins fill with water.

If glaciers erode three or more cirques into different sides of a peak, they may create a steep, pyramid-shaped rock summit called a **horn**. The Matterhorn in the Swiss Alps is a famous horn (Fig. 17–16). Two glaciers flowing along opposite sides of a mountain ridge may erode both sides of the ridge, forming a sharp, narrow **arête** between adjacent valleys.

Looking downward from our peak, we may see a waterfall pouring from a small, high valley into a larger, deeper one. A small glacial valley lying high above the floor of the main valley is called a **hanging valley** (Fig. 17–17). The famous waterfalls of Yosemite Valley in California cascade from hanging valleys. To understand how a hanging valley forms, imagine these mountain valleys filled with glaciers, as they were several millennia ago (Fig. 17–12). The main glacier gouged the lower valley deeply. In contrast, the smaller tributary glacier did not scour its valley as deeply, creating an abrupt drop where the small valley joins the main valley. If the main valley glacier cuts off the lower portion of an arête, a triangular-shaped rock face called a **truncated spur** forms.

Figure 17–17 Two hanging valleys in Yosemite National Park. (Ward's Natural Science Establishment, Inc.)

Figure 17–18 A steep-sided fjord bounded by thousand-meter-high cliffs in Baffin Island, Canada.

Figure 17–19 A glacier flowed from right to left over a bedrock hill to carve this streamlined roche moutonnée in Rocky Mountain National Park, Colorado. (Don Dickson/Visuals Unlimited)

Deep, narrow inlets called **fjords** extend far inland on many high-latitude seacoasts. Most fjords are glacially carved valleys that were later flooded by rising seas as the glaciers melted (Fig. 17–18).

EROSIONAL LANDFORMS CREATED BY A CONTINENTAL GLACIER

A continental glacier erodes the landscape just as an alpine glacier does. However, a continental glacier is considerably larger and thicker and is not confined to a valley. As a result, it covers vast regions, including entire mountain ranges.

If a glacier flows over a bedrock knob, it carves an elongate, streamlined hill called a **roche moutonnée**. (This term is derived from the French words *roche*, for "rock," and *mouton*, for "sheep." Clusters of roches moutonnées resemble herds of grazing sheep.) The upstream side of the roche moutonnée is typically gently inclined, rounded, and striated by abrasion. As the ice rides over the bedrock, it plucks rocks from the downstream side, producing a steep, jagged face (Fig. 17–19). Both alpine and continental glaciers form roches moutonnées.

17.4 GLACIAL DEPOSITS

In the 1800s, geologists recognized that the large deposits of sand and gravel found in some places had been transported from distant sources. A popular hypothesis at the time explained that this material had drifted in on icebergs during catastrophic floods. The deposits were called "drift" after this inferred mode of transport.

Today we know that continental glaciers covered vast parts of the land only 10,000 to 20,000 years ago, and these glaciers carried and deposited drift. Although the term *drift* is a misnomer, it remains in common use. Now geologists define **drift** as all rock or sediment transported and deposited by a glacier. Glacial drift averages 6 meters thick over the rocky hills and pastures of New England and 30 meters thick over the plains of Illinois.

Drift is divided into two categories. **Till** was deposited directly by glacial ice. **Stratified drift** was first carried by a glacier and then transported and deposited by a stream.

LANDFORMS COMPOSED OF TILL

Ice is so much more viscous than water that it carries particles of all sizes together. When a glacier melts, it deposits its entire sediment load; fine clay and huge boulders end up mixed together in an unsorted, unstratified mass (Fig. 17–20). Within a glacier, each rock or grain of sediment is protected by the ice that surrounds it. Therefore, the pieces do not rub against one another, and glacial transport does not round sediment as a stream does. If you find rounded gravel in till, it became rounded by a stream before the glacier picked it up.

If you travel in country that was once glaciated, you occasionally find large boulders lying on the surface. In

Figure 17–20 Unsorted glacial till. Note that large cobbles are mixed with smaller sediment. The cobbles were rounded by stream action before they were transported and deposited by the glacier.

Figure 17–21 An end moraine is a ridge of till piled up at a glacier's terminus.

many cases the boulders are of a rock type different from the bedrock in the immediate vicinity. Boulders of this type are called **erratics** and were transported to their present locations by a glacier. The origins of erratics can be determined by exploring the terrain in the direction the glacier came from until the parent rock is found. Some erratics were carried 500 or even 1000 kilometers from their point of origin and provide clues to the movement of glaciers. Plymouth Rock, where the pilgrims allegedly landed, is a glacial erratic.

Moraines

A **moraine** is a mound or a ridge of till. Think of a glacier as a giant conveyor belt. An airport conveyor belt carries suitcases to the end of the belt and dumps them in a pile. Similarly, a glacier carries sediment and deposits it at its terminus. If a glacier is neither advancing nor retreating, its terminus may remain in the same place for years. During that time, sediment accumulates at the terminus to form a ridge called an **end moraine**. An end moraine that forms when a glacier is at its greatest advance, before beginning to retreat, is called a **terminal moraine** (Fig. 17–21).

If warmer conditions prevail, the glacier recedes. If the glacier stabilizes again during its retreat and the terminus remains in the same place for a year or more, a new end moraine, called a **recessional moraine**, forms.

When ice melts, till is deposited in a relatively thin layer over a broad area, forming a **ground moraine**. Ground moraines fill old stream channels and other low spots. Often this leveling process disrupts drainage patterns. Many of the swamps in the northern Great Lakes region lie on ground moraines formed when the most recent continental glaciers receded.

End moraines and ground moraines are characteristic of both alpine and continental glaciers. An end moraine deposited by a large alpine glacier may extend for several kilometers and be so high that even a person in good physical condition would have to climb for an hour to reach the top. Moraines may be dangerous to hike over if their sides are steep and the till is loose. Large boulders are mixed randomly with rocks, cobbles, sand, and clay. A careless hiker can dislodge boulders and send them tumbling to the base.

Terminal moraines leave record of the maximum extent of Pleistocene continental glaciers. In North America they lie in a broad, undulating front extending across the northern United States. Enough time has passed since the glaciers retreated that soil and vegetation have stabilized the till and most of the hills are now wooded (Fig. 17–22).

When an alpine glacier moves downslope, it erodes the valley walls as well as the valley floor. Therefore, the edges of the glacier carry large loads of sediment.

Figure 17–22 This terminal moraine in New York State marks the southernmost extent of glaciers in that region. (Ward's Natural Science Establishment, Inc.)

Additional debris falls from the valley walls and accumulates on and near the sides of mountain glaciers. Sediment near the glacial margins forms a **lateral moraine** (Fig. 17–23).

If two glaciers converge, the lateral moraines along the edges of the two glaciers merge into the middle of the larger glacier. This till forms a visible dark stripe on the surface of the ice called a **medial moraine** (Fig. 17–24).

Figure 17–24 Three separate medial moraines formed by merging lateral moraines from coalescing glaciers, Baffin Island, Canada.

Figure 17–23 A lateral moraine lies against the valley wall in the Bugaboo Mountains, British Columbia.

Drumlins

Elongate hills, called **drumlins**, cover parts of the northern United States and are well exposed across the rolling farmland in Wisconsin (Fig. 17–25). Each one looks like a whale swimming through the ground with its back in the air. Drumlins are usually about 1 to 2 kilometers long and about 15 to 50 meters high. Most are made of till, while others consist partly of till and partly of bedrock. In either case, the elongate shape of a drumlin develops when a glacier flows over a mound of sediment. The flow of the ice creates the streamlined shape, which is elongated in the same direction as the glacial flow.

Landforms Composed of Stratified Drift

Because of the great amount of sediment eroded by a glacier, streams flowing from a glacier are commonly laden with silt, sand, and gravel. The stream deposits this sediment beyond the glacier terminus as **outwash**

Figure 17–25 Crop patterns emphasize glacially streamlined drumlins in Wisconsin. (Kevin Horan/Tony Stone Images)

(Fig. 17–26). Glacial streams carry such a heavy load of sediment that they often become braided, flowing in multiple channels. Outwash deposited in a narrow valley is called a **valley train**. If the sediment spreads out from the confines of the valley into a larger valley or plain, it forms an **outwash plain** (Fig. 17–27). Outwash plains are also characteristic of continental glaciers.

During the summer, when snow and ice melt rapidly, streams form on the surface of a glacier. Many are too wide to jump across. Some of these streams flow off the front or sides of the glacier. Others plunge into crevasses and run beneath the glacier over bedrock or drift. These streams commonly deposit small mounds of sediment, called **kames**, at the margin of a receding glacier or where the sediment collects in a crevasse or other depression in the ice. An **esker** is a long, sinuous ridge that forms as the channel deposit of a stream that flowed within or beneath a melting glacier.

Because kames, eskers, and other forms of stratified drift are stream deposits and were not deposited directly by ice, they show sorting and sedimentary bedding, which distinguishes them from unsorted and unstratified till. In addition, the individual cobbles or grains are usually rounded.

Figure 17–26 Streams flowing from the terminus of a glacier filled this valley on Baffin Island with outwash.

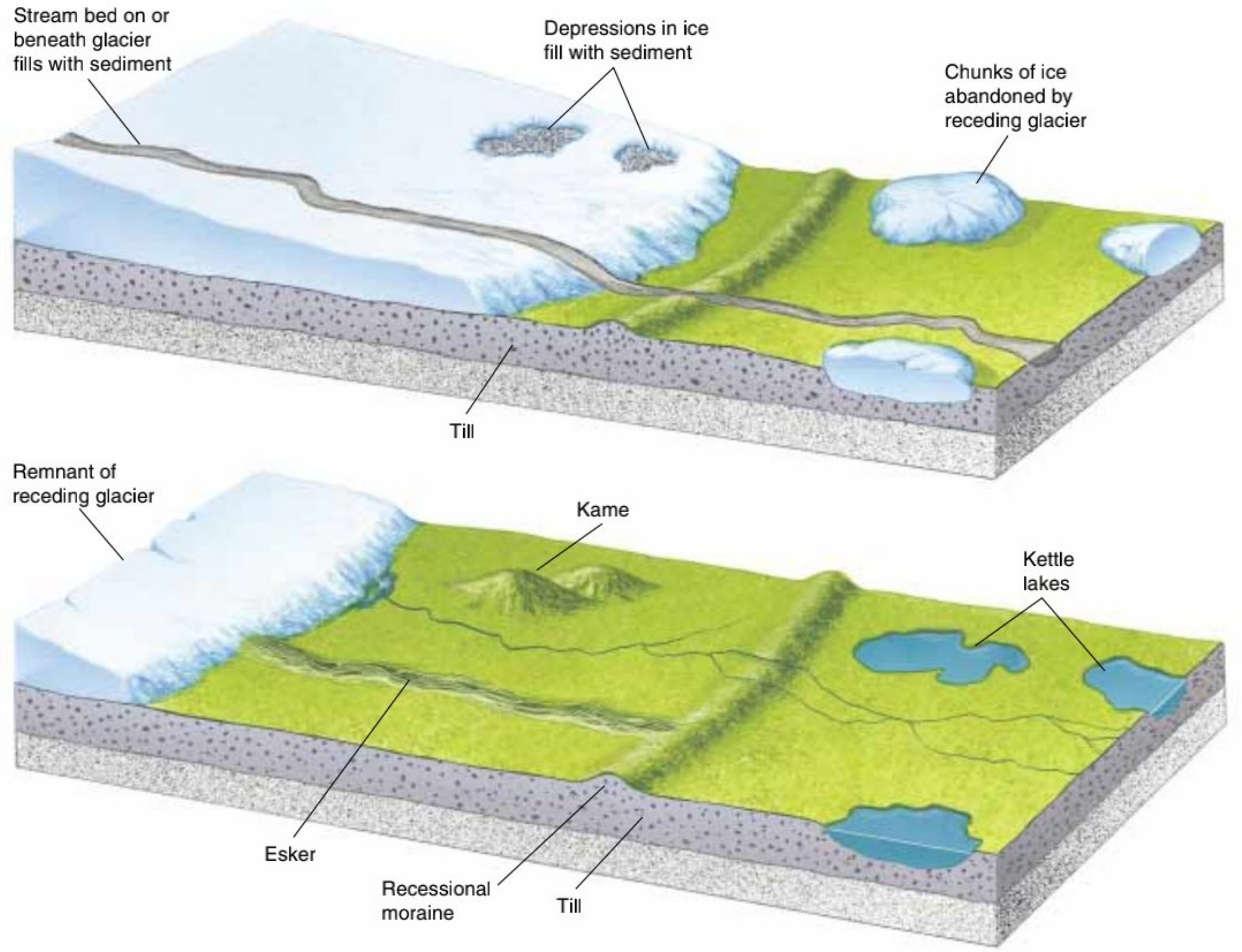

Figure 17–27 Landforms created as a glacier retreats.

Large blocks of ice may be left behind in a moraine or an outwash plain as a glacier recedes. When such an ice block melts, it leaves a depression called a **kettle**. Kettles fill with water, forming kettle lakes. A kettle lake is as large as the ice chunks that melted to form the hole. The lakes vary from a few tens of meters to a kilometer or so in diameter, with a typical depth of 10 meters or less.

17.5 THE PLEISTOCENE ICE AGE

The extent of glacial landforms is proof that glaciers once covered much larger areas than they do today. A time when alpine glaciers descend into lowland valleys and continental glaciers spread over land in high latitudes is called an **ice age**. Geologic evidence shows that the Earth has been warm and relatively ice free for at least 90 percent of the past 1 billion years. However, at least five major ice ages occurred during that time (Fig. 17–28). Each one lasted from 2 to 10 million years.

Glacial landforms created during older ice ages have been mostly obliterated by erosion and tectonic processes. However, in a few places till from older glaciers has been lithified into a glacial conglomerate called **tillite**. Geologists know that tillites were deposited by glaciers because the cobbles in tillite are often angular and striated.

The most recent ice age took place mainly during the Pleistocene Epoch and is called the **Pleistocene Ice Age**. It began about 2 million years ago (although evidence of an earlier beginning has been found in the Southern Hemisphere). However, the Earth has not been glaciated continuously during the Pleistocene Ice Age; instead, climate has fluctuated and continental glaciers grew and then melted away several times (Fig. 17–28). Although the climate has been relatively warm for the most recent 15,000 years, most climate models indicate

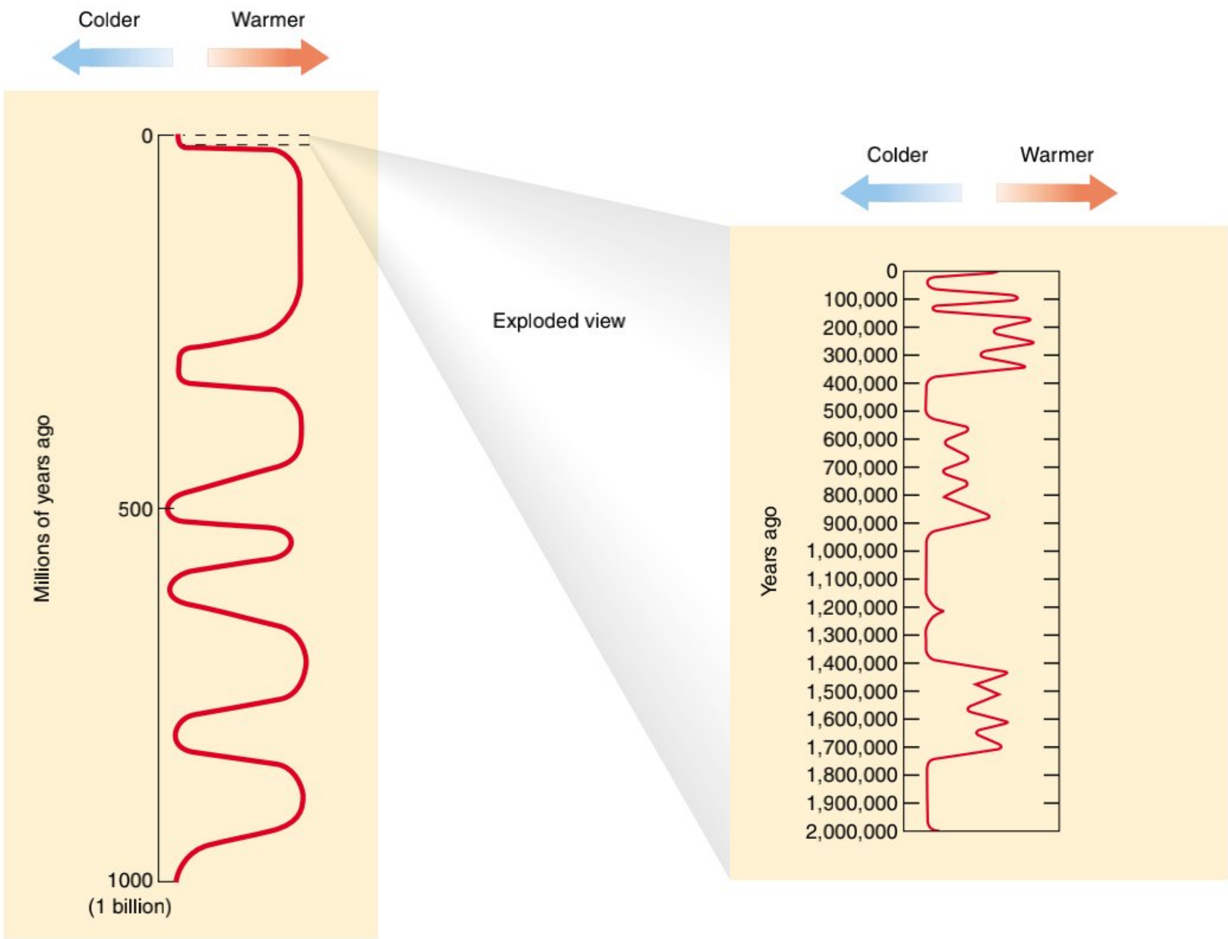

Figure 17–28 Glacial cycles. The scale on the left shows an approximate curve for average global temperature variation during the past billion years. Times of lowest temperature are thought to coincide with major ice ages. The scale on the right is an exploded view of the Pleistocene Ice Age. We are probably still living within the Pleistocene Ice Age, and continental ice sheets will advance again.

that we are still in the Pleistocene Ice Age and the glaciers will advance again.

PLEISTOCENE GLACIAL CYCLES

Most scientists now think that the relatively rapid climate fluctuations that caused the Pleistocene glacial cycles resulted from periodic variations in the Earth's orbit and spin axis (Fig 17–29). Astronomers have detected three types of variations:

1. The Earth's orbit around the Sun is elliptical rather than circular. The shape of the ellipse is called **eccentricity**. The eccentricity varies in a regular cycle lasting about 100,000 years.
2. The Earth's axis is currently tilted at about 23.5° with respect to a line perpendicular to the plane of its orbit around the Sun. The **tilt** oscillates by 2.5° on about a 41,000-year cycle.
3. The Earth's axis, which now points directly toward the North Star, circles like that of a wobbling top. This circling, called **precession**, completes a full cycle every 23,000 years.

Although these changes do not appreciably affect the total solar radiation received by the Earth, they do affect the distribution of solar energy with respect to latitude and season. Therefore, these changes influence the duration of the seasons. Seasonal changes in sunlight reaching higher latitudes can cause an onset of glaciation by reducing summer temperature. If summers are cool and short, winter snow and ice persist, leading to growth of glaciers.

Early in the 20th century, a Yugoslavian astronomer, Milutin Milankovitch, calculated the combined effects of

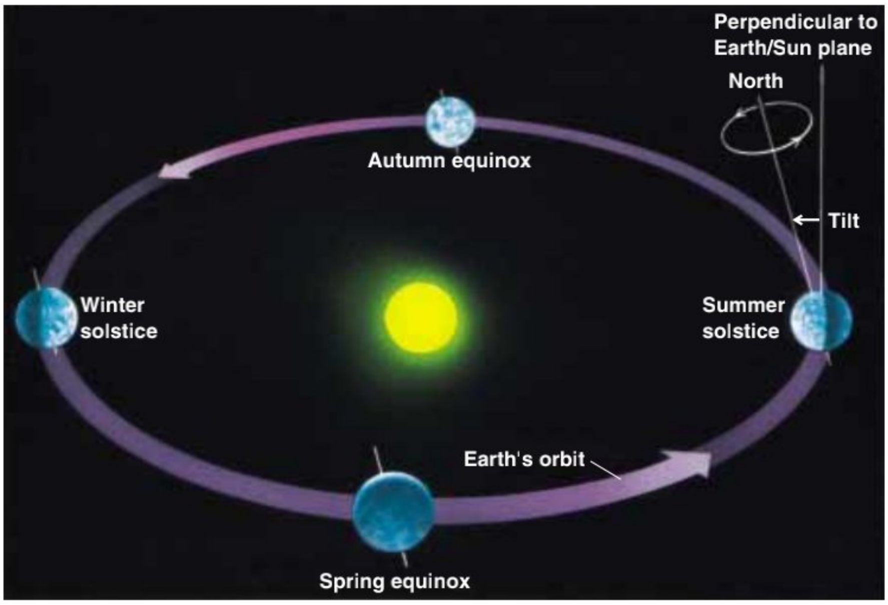

Figure 17–29 Earth orbital variations may explain the temperature oscillations and glacial advances and retreats during the Pleistocene Epoch. Orbital variations occur over time spans of tens of thousands of years.

the three orbital variations on climate. His calculations showed that they should interact to generate alternating cool and warm climates in the mid- and high latitudes. Moreover, the timing of the calculated high-latitude cooling coincided with that of Pleistocene glacial advances.

EFFECTS OF PLEISTOCENE CONTINENTAL GLACIERS

At its maximum extent about 18,000 years ago, the most recent North American ice sheet covered 10 million square kilometers—most of Alaska, Canada, and parts of the northern United States (Fig. 17–30). At the same time, alpine glaciers flowed from the mountains into the lowland valleys.

The erosional features and deposits left by these glaciers dominate much of the landscape of the northern states. Today terminal moraines form a broad band of rolling hills from Montana across the Midwest and eastward to the Atlantic Ocean. Long Island and Cape Cod are composed largely of terminal moraines. Kettle lakes or lakes dammed by moraines are abundant in northern Minnesota, Wisconsin, and Michigan. Drumlins dot the landscape in the northern states. Ground moraines, outwash, and loess (windblown glacial silt) cover much of the northern Great Plains. These deposits have weathered to form the fertile soil of North America's "breadbasket."

Pleistocene glaciers advanced when mid- and high-latitude climates were colder and wetter than today. When the glaciers melted, the rain and meltwater flowed through streams and collected in numerous lakes. Later, as the ice sheets retreated and the climate became drier, many of these streams and lakes dried up.

Today, extinct stream channels and lake beds are common in North America. The extinct lakes are called **pluvial lakes**, a term derived from the Latin word *pluvia*, meaning "rain." The basin that is now Death Valley was once filled with water to a depth of 100 meters or more. Most of western Utah was also covered by a pluvial lake called Lake Bonneville. As drier conditions returned, Lake Bonneville shrank to become Great Salt Lake, west of Salt Lake City.

When glaciers grow, they accumulate water that would otherwise be in the oceans, and sea level falls. When glaciers melt, sea level rises again. When the Pleistocene glaciers reached their maximum extent 18,000 years ago, global sea level fell to about 130 meters below its present elevation. As submerged continental shelves became exposed, the global land area increased by 8 percent (although about one third of the land was ice covered).

When the ice sheets melted, much of the water returned to the oceans, raising sea level again. At the same time, portions of continents rebounded isostatically as the weight of the ice was removed. The effect along any specific coast depends upon the relative amounts of sea level rise and isostatic rebound. Some coastlines were submerged by the rising seas. Others rebounded more than sea level rose. Today, beaches in the Canadian Arctic lie tens to a few hundred meters above the sea. Portions of the shoreline of Hudson's Bay have risen 300 meters.

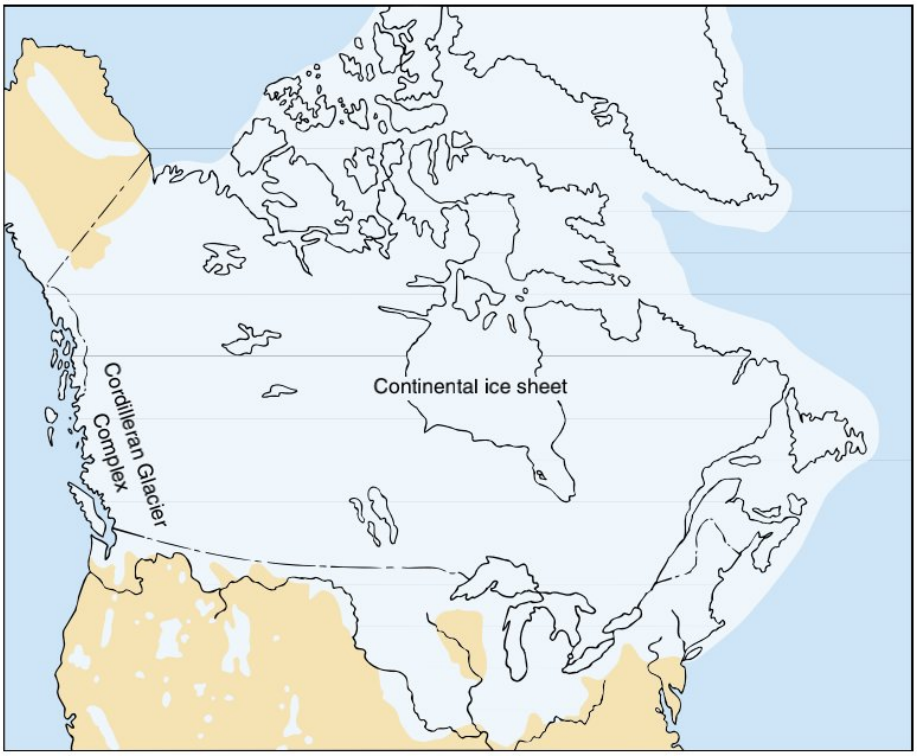

Figure 17–30 Maximum extent of the continental glaciers in North America during the latest glacial advance, approximately 18,000 years ago.

SUMMARY

If snow survives through one summer, it becomes a relatively hard, dense material called **firn**. A **glacier** is a massive, long-lasting accumulation of compacted snow and ice that forms on land and creeps downslope or outward under the influence of its own weight. **Alpine glaciers** form in mountainous regions; **continental glaciers** cover vast regions. Glaciers move by both **basal slip** and **plastic flow**. The upper 40 meters of a glacier is too brittle to flow, and large cracks called **crevasses** develop in this layer.

In the **zone of accumulation** of a glacier, the annual rate of snow accumulation is greater than the rate of melting, whereas in the **zone of ablation**, melting exceeds accumulation. The **snowline** is the boundary between permanent snow and seasonal snow. The end of the glacier is called the **terminus**.

Glaciers erode bedrock by **plucking** and by abrasion. Glaciated mountains often contained U-shaped valleys and other landforms eroded by flowing ice. A knob of bedrock streamlined by glacial erosion is called a **roche moutonnée**.

Drift is any rock or sediment transported and deposited by a glacier. The unsorted drift deposited directly by a glacier is **till**. Most glacial terrain is characterized by large mounds of till known as **moraines**. **Terminal moraines**, **ground moraines**, **recessional moraines**, **lateral moraines**, **medial moraines**, and **drumlins** are all depositional features formed by glaciers. **Stratified drift** consists of sediment first carried by a glacier and then transported, sorted, and deposited by streams flowing on, under, or within a glacier. **Valley trains**, **outwash plains**, **kames**, and **eskers** are formed from stratified drift. **Kettles** are depressions created by melting of large blocks of ice abandoned by a retreating glacier.

During the past 1 billion years, at least five major ice ages have occurred. The most recent occurred during the **Pleistocene Epoch**, when continental glaciers created many topographic features that are prominent today. One theory contends that Pleistocene advances and retreats were caused by climate changes induced by changes in the Earth's orbit and the orientation of its rotational axis. **Pluvial lakes** formed in the wetter climate of those times. Ice sheets isostatically depress continents, which later rebound when the ice melts. Sea level falls when continental ice sheets form and rises again when the ice melts.

KEY WORDS

firn *298*
glacier *298*
alpine glacier *298*
ice sheet *299*
continental glacier *299*
basal slip *299*
plastic flow *299*
crevasse *300*
ice fall *300*
zone of accumulation *301*
zone of ablation *301*
snowline *301*
terminus *302*
tidewater glacier *302*
iceberg *302*
plucking *303*
glacial striation *303*
rock flour *303*
U-shaped valley *304*
cirque *304*
tarn *305*
paternoster lake *305*
horn *306*
arête *306*
hanging valley *306*
truncated spur *306*
fjord *307*
roche moutonnée *307*
drift *307*
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stratified drift *307*
erratic *308*
moraine *308*
end moraine *308*
terminal moraine *308*
recessional moraine *308*
ground moraine *308*
lateral moraine *309*
medial moraine *309*
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valley train *310*
outwash plain *310*
kame *310*
esker *310*
kettle *311*
ice age *311*
tillite *311*
Pleistocene Ice Age *311*
pluvial lake *313*

REVIEW QUESTIONS

1. Outline the major steps in the metamorphism of newly fallen snow to glacial ice.
2. Differentiate between alpine glaciers and continental glaciers. Where are alpine glaciers found today? Where are continental glaciers found today?
3. Distinguish between basal slip and plastic flow.
4. Why are crevasses only about 40 meters deep, even though many glaciers are much thicker?
5. Describe the surface of a glacier in the summer and in the winter in (a) the zone of accumulation and (b) the zone of ablation.
6. How do icebergs form?
7. Describe how glacial erosion can create (a) a cirque, (b) striated bedrock, and (c) smoothly polished bedrock.
8. Describe the formation of arêtes, horns, hanging valleys, and truncated spurs.
9. Distinguish among ground, recessional, terminal, lateral, and medial moraines.
10. Why are kames and eskers features of receding glaciers? How do they form?
11. What topographic features were left behind by the continental ice sheets? Where can they be found in North America today?
12. How do geologists recognize the existence and movement of continental glaciers that advanced hundreds of millions of years ago?

DISCUSSION QUESTIONS

1. Compare and contrast the movement of glaciers with stream flow.
2. Outline the changes that would occur in a glacier if (a) the average annual temperature rose and the precipitation decreased; (b) the temperature remained constant but the precipitation increased; and (c) the temperature decreased and the precipitation remained constant.
3. Explain why plastic flow is a minor mechanism of movement for thin glaciers but is likely to be more important for a thick glacier.
4. In some regions of northern Canada, both summer and winter temperatures are cool enough for glaciers to form, but there are no glaciers. Speculate on why continental glaciers are not forming in these regions.
5. If you found a large boulder lying in a field, how would you determine whether or not it was an erratic?
6. A bulldozer can only build a pile of dirt when it is moving forward. Yet a glacier can build a terminal moraine when it is neither advancing nor retreating. Explain.
7. Imagine you encountered some gravelly sediment. How would you determine whether it was a stream deposit or a ground moraine?
8. Explain how medial moraines prove that glaciers move.
9. If you were hiking along a wooded hill in Michigan, how would you determine whether or not it was a moraine?