14 Glacier Systems

No event in recent geologic history has had as profound an effect on Earth as the last great ice age. Its impact extended far beyond the margins of the ice itself and influenced almost every aspect of the physical and biological world. For example, the present sites of many northern cities, such as Chicago, Detroit, Montreal, and Toronto, were buried beneath thousands of meters of glacial ice as recently as 15,000 to 20,000 years ago.

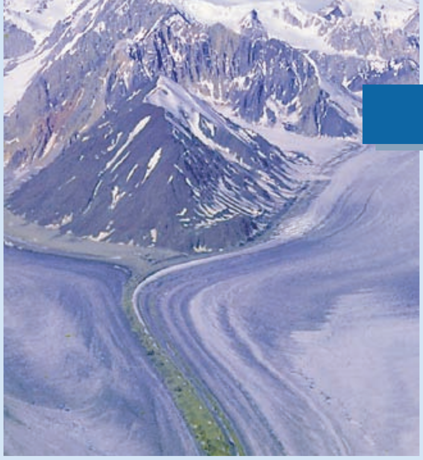
Much of the magnificent mountain scenery in Canada's Yukon Territory shown above was sculpted by valley glaciers, many of which still exist. The Kaskawulsh Glacier and its tributaries have cut the deep U-shaped valleys, carved horns, and transported the eroded debris downhill to be carried away by melt waters and river systems. As we will see in this chapter, the great continental glaciers, which covered much of North America and Europe, had an even more profound effect upon the landscape.

When glaciation occurs, many geologic processes are interrupted or modified significantly. Much precipitation becomes trapped in glaciers instead of flowing immediately back to the ocean. Consequently, sea level drops and the hydrology of streams is greatly

altered. As gigantic ice sheets advance over continents, they obliterate preexisting drainage networks. The moving ice scours and erodes the landscape and deposits the debris near its margins, covering the preexisting topography. The crust of Earth is pushed down by the weight of the ice, and meltwater commonly collects and forms lakes along the ice margins. As the glaciers melt, new drainage systems are established to accommodate the large volume of meltwater. Far beyond the margins of the glaciers, stream systems are modified by changing climatic patterns. Even in arid regions, the imprint of climatic changes associated with glaciation is seen in the development of large lakes in closed basins.

We now know that glacial epochs have come and gone repeatedly over the last few million years. Today, the planet basks in the relative warmth of an interglacial period, but it has been cyclically plunged into cold episodes. Will there be another ice age?

In this chapter, we will study how glaciers operate as systems of flowing ice and how they modify the landscape. We will then consider the causes of an ice age, which remain tantalizing questions still partly unanswered.



MAJOR CONCEPTS

1. Glaciers are systems of flowing ice that form where more snow accumulates each year than melts.
2. As ice flows, it erodes the surface of the land by abrasion and plucking. Sediment is transported by the glacier and deposited where the ice melts. In the process, the landscape is greatly modified.
3. The two major types of glaciers—continental and valley glaciers—produce distinctive erosional and depositional landforms.
4. The Pleistocene ice age began 2 to 3 million years ago. During the ice age, there were several glacial and interglacial epochs. The last glacial maximum was about 18,000 years ago and glaciers have been receding since then.
5. The major effects of an ice age include glacial erosion and deposition, modification of drainage systems, creation of numerous lakes, the fall of sea level, isostatic adjustments of the lithosphere, and migration and selective extinction of plant and animal species.
6. Periods of glaciation have been rare events in Earth's history. The causes of glacial episodes are not completely understood, but they may be related to several simultaneously occurring factors, such as astronomical cycles, plate tectonics, and ocean currents.

GLACIAL SYSTEMS

A glacier is an open system of flowing ice. Water enters the system as snow, which is transformed into ice by compaction and recrystallization. The ice then flows through the system, under the pressure of its own weight, and leaves the system by evaporation and melting. The balance between the rate of accumulation and the rate of melting determines the size of the glacial system.

Glacial Ice

A glacier is a natural body of ice formed by the accumulation, compaction, and recrystallization of snow that is thick enough to flow. It is a dynamic system involving the accumulation and transportation of ice. The movement of the ice is a critical factor. A mass of ice must move or flow to be considered a glacier. Bodies of ground ice, formed by the freezing of groundwater within perennially frozen ground, are not glaciers, nor is the relatively thin sheet of frozen seawater known as sea ice, which is so abundant in the polar regions. Perennial snowfields that do not move are also not considered glaciers. Glacial ice is really a type of metamorphic rock that begins as sediment (an aggregate of mineral particles, or snow) and is then metamorphosed by compaction and recrystallization into glacial ice.

The essential parts of a glacial system are (1) the **zone of accumulation,** where there is a net gain of ice, and (2) the **zone of ablation,** where ice leaves the system by melting, calving (shedding of large blocks of ice from a glacier edge, usually into a body of water), and evaporating (Figure 14.1). The boundary between these zones is the **snow line.** In the zone of accumulation, snow is transformed into glacial ice. Freshly fallen snow consists of delicate hexagonal ice crystals or needles, with as much as 90% of their total volume as empty space (Figure 14.2). As snow accumulates, the ice at the points of the snowflakes melts from the pressure of snow buildup and migrates toward the center of the flake, eventually forming an elliptical granule of recrystallized ice approximately 1 mm in diameter. The accumulation of these particles packed together is called firn, or névé. With repeated annual deposits, the loosely packed névé granules are compressed by the weight of the overlying snow. Meltwater, which results from daily temperature fluctuations

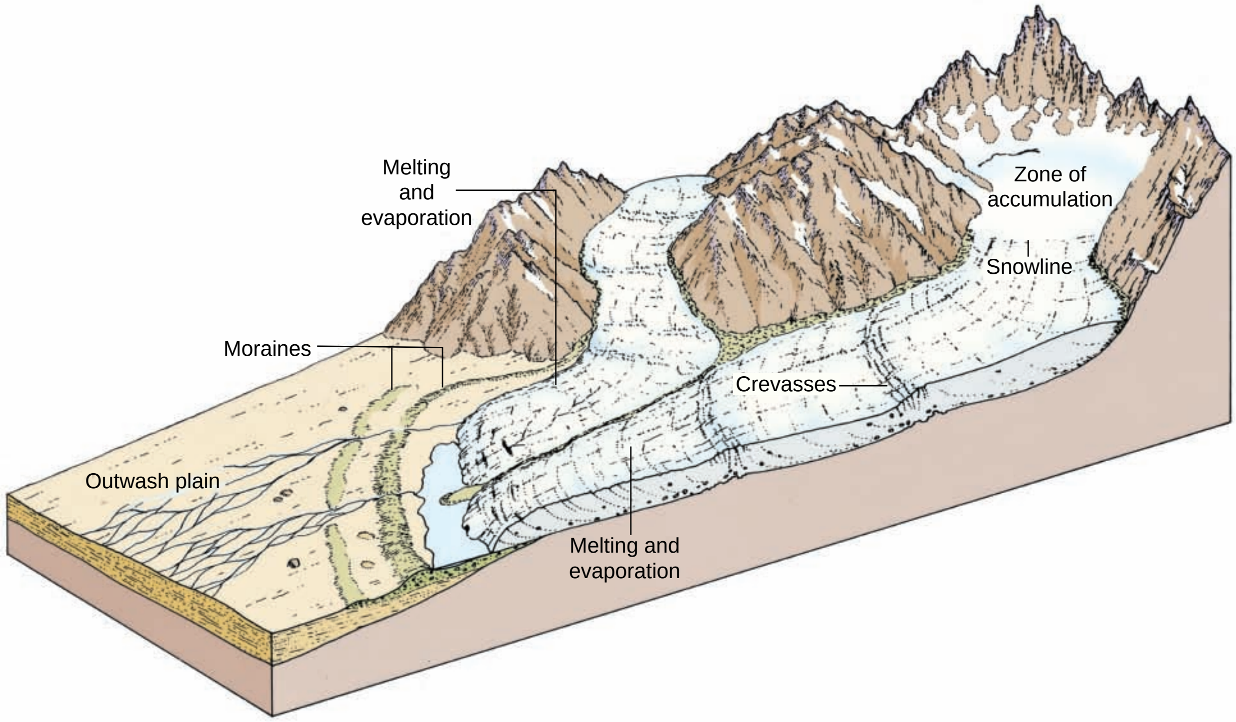


FIGURE 14.1 **A glacial system** is an open system of ice that flows under the pull of gravity. Snow enters the system by precipitation and is transformed into ice. The ice flows outward from the zone of accumulation under the pressure of its own weight. The ice leaves the system by evaporating and melting in the zone of ablation. The boundary between these zones is approximated by the snow line. As the ice moves through the system, it erodes and deposits sediment at the end of the glacier.

and the pressure of the overlying snow, seeps through the pore spaces between the grains; when it freezes, it adds to the recrystallization process. Most of the air in the pore spaces is driven out. When the ice reaches a thickness of approximately 60 m, it can no longer support its own weight and yields to plastic flow.

Types of Glaciers

There are two main types of glaciers: (1) valley glaciers and (2) continental glaciers (Figure 14.3). **Valley glaciers** are ice streams that are confined to the canyons and valleys of mountainous terrains. They originate in snowfields at the mountain crest and flow down the canyons. A valley glacier that emerges from the mountain front and spreads out as a large lobe at the foot of the mountain is commonly called a piedmont glacier. **Continental glaciers** are huge sheets of ice that spread out over a large part of the continent. They are commonly more than 3000 m thick and completely cover the underlying terrain, except for the peaks of the highest

FIGURE 14.2 **Snow crystals** change to granular ice by partial thawing and refreezing along their delicate edges. Burial produces compaction and recrystallization, cementing all the grains into glacial ice. *(Scanning electron microscope images courtesy of E. Erbe, U.S. Department of Agriculture)*

(A) Continental glaciers are huge ice sheets that cover a large part of a continent such as Antarctica, shown here. *(Courtesy of M. F. Sheridan)*

(B) Valley glaciers are streams of ice that flow down canyons and the valleys of mountainous terrains.

FIGURE 14.3 **Types of glaciers** can be recognized by their geometry and relationship to topography.

mountains. These huge sheets of ice generally flow outward in all directions from one or several central regions of accumulation. Flow directions may be influenced by subglacial topography such as highlands and mountain ranges. In rugged terrain, the direction and rate of ice flow may be greatly influenced by mountain ranges, and the ice is funneled through mountain passes in large streams called outlet glaciers. Antarctica and Greenland are present-day examples of continental glaciers with a maximum thickness approaching 5000 m.

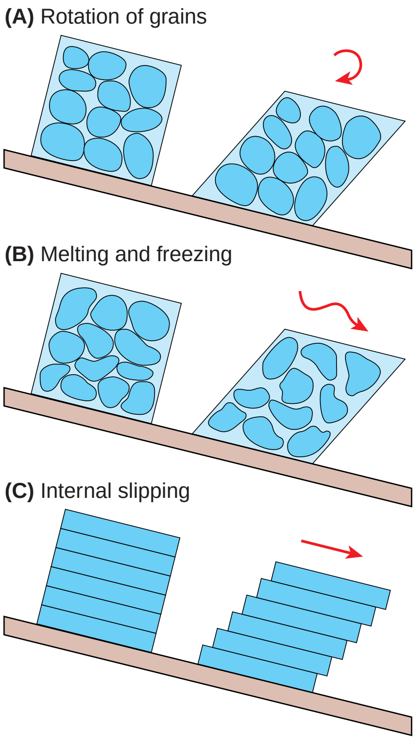


FIGURE 14.4 **Mechanisms of ice flow** involve (A) rotation of grains, (B) melting and freezing, and (C) internal slipping within the ice mass. *(After R. P. Sharp)*

Glacier Flow

Ice is a brittle substance and, when struck sharply, it will fracture and break; however, like many substances that are normally regarded as solids, ice will flow if adequate stress is applied over an extended period of time. Gravity is the fundamental force that causes ice to flow, and where an accumulation of ice exceeds a depth of about 60 m, depending on temperature, slope angle, and so on, flow is initiated. Ice has a much higher viscosity, or resistance to flow, than liquid water. As a result, its flow is not turbulent, but rather the flow of glacial ice is laminar. That is, the planes of flow are parallel. The planes curve but do not intersect or cross.

Several mechanisms have been observed by which ice undergoes solid-state flow (Figure 14.4). In ice composed of loose individual granules, the shifting and rotation of grains can produce a flowlike movement similar to that of sand being poured from a bucket. In glaciers, the ice crystals are packed tightly together, so this type of flow is minimal. Stress exerted on intergrown crystals causes them to melt at points where pressure is concentrated. The water is then moved to areas of lower pressure and refreezes. Another mechanism involves minor displacement along a series of parallel slip planes within individual ice crystals. Thin layers of ice move past each other as a sheared deck of cards would.

The ice in most glaciers normally moves too slowly for us to see at any given moment, but a simple experiment can demonstrate the movement of glacial ice. We need only lay a series of boulders in a straight line across a glacier from wall to wall, and within a year or two the line will no longer be straight (Figure 14.5). This was done in the Alps at least as early as the 1800s. More sophisticated measurements show that various parts of glaciers move at different rates. One method to observe this difference is to drill a vertical hole through the glacier, insert a flexible pipe, and then survey the pipe's position and inclination over a period of several years (Figure 14.5). The results show that the pipe not only moves down the valley, but

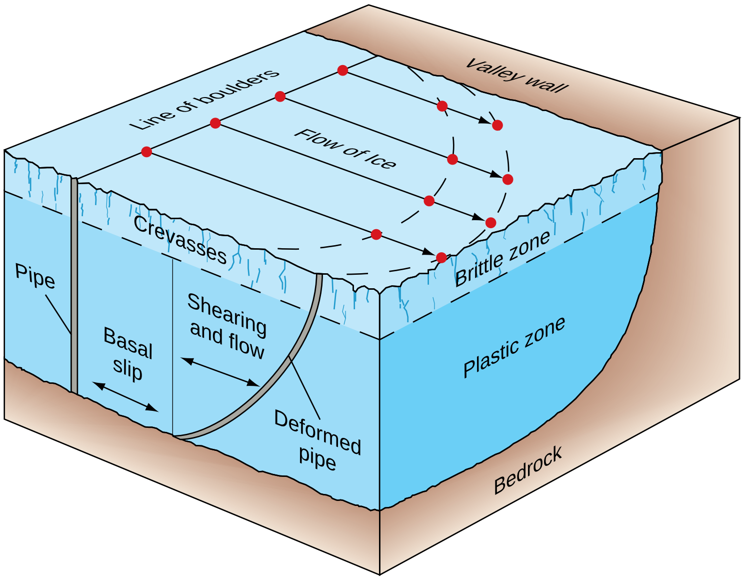


FIGURE 14.5 **Ice flow** in a glacier can be shown by laying a series of rocks in a straight line across the glacier and observing their position in subsequent years. The displaced boulders show that the center of the glacier, where ice is thickest, moves most rapidly. A glacier moves by basal slip across the underlying bedrock and by internal flow. The upper part of the glacier moves faster than the basal part, which drags against bedrock. The upper part of the glacier is brittle and as a result has many fractures or crevasses.

it also bends into a curve, with greater movement at the top than at the bottom. In addition, the total downslope movement is greater than that accounted for by bending. This result indicates that along with internal flow, the glacier also slips over the underlying bedrock surface. Up to 95% of the movement in a glacier can occur by basal slip. Basal slip is accomplished by melting and freezing of the ice near the contact with the bedrock. Indeed, a relatively warm glacier is not everywhere in firm contact with its bed, but it is locally separated from the bedrock below by lubricating pockets of water.

Glacial Advance and Retreat

Direction and Amount of Movement. The movement of glacial ice can best be understood by considering what happens within the zone of accumulation and the zone of ablation of a valley glacier that is in a steady state; that is, the size of the glacier is neither shrinking nor expanding. Each year, a wedge-shaped layer of snow, thickest at the head and thinnest at the snow line, is added to the surface of accumulation (Figure 14.6). A similar wedge of ice, thickest at the end of the glacier and thinnest at the snow line, is removed by melting. If a glacier is at equilibrium, the volume of water represented by these two wedges must be the same. It cannot

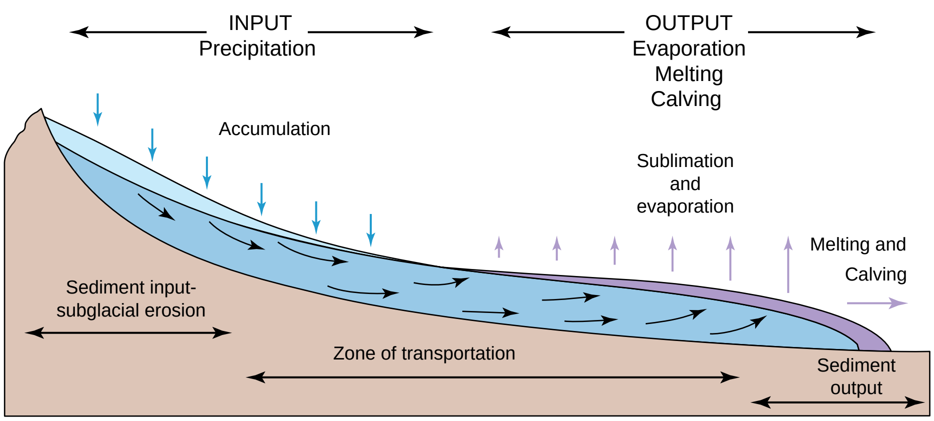


FIGURE 14.6 **Movement of ice through a glacier** is shown in this longitudinal cross section. In the zone of accumulation, a wedge of snow is added each year. It is thickest at the head and thins to a feather edge at the snow line. A similar wedge that is thin at the snow line and thickest at the end of the glacier is removed by ablation. The internal flow of the glacial ice resulting from this accumulation and wastage is shown with arrows. In the zone of accumulation, the ice moves downward. Near the snow line, movement is horizontal. Near the lower end of the glacier, the movement of the ice is upward. *(After R. P. Sharp)*

keep getting thicker at the head and thinner at the snout. It adjusts to the accumulation and removal of ice by changing the inclination of the direction of flow (Figure 14.6). In the zone of accumulation, the direction of movement is inclined downward, with respect to the surface of the glacier. The degree of downward inclination decreases from the head of the glacier to the snow line. At the snow line, the direction of movement is parallel to the surface of the glacier. In the zone of ablation, the movement is upward, toward the surface, with upward inclination increasing from the snow line to the snout. As shown in Figure 14.6, the ice at the head of the glacier flows downward through the glacier. This same ice is near the base of the glacier when it passes the snow line. It then flows upward and laterally to the snout.

Extending and Compressing Flow. The movement of glacial ice is not uniform. The vector lines in Figure 14.6 show that velocities of ice flow in the zone of accumulation increase progressively from the head to the snow line. Here, the ice is under tension and is constantly pulling away from upvalley ice. This is the condition of **extending flow.** Below the snow line, velocities progressively decrease; therefore, upvalley ice is continually pushing against downvalley ice. This is a condition of **compressing flow.** Where bedrock slopes steepen, glacier velocities increase and extending flow prevails; where the bedrock slopes are gentle, velocities decrease and compressing flow occurs (Figure 14.7). Where glaciers descend over extremely steep slopes, the ice descends with high velocities, creating a veritable icefall. These are zones of extreme extending flow, and the ice is greatly thinned and completely broken by numerous deep crevasses (see Figure 14.14B). The flow velocity in an icefall can exceed 10 times that of the glacier elsewhere along its course. At the base of an icefall, conditions are reversed; flow decreases rapidly, compressing flow dominates, and the glacier thickens.

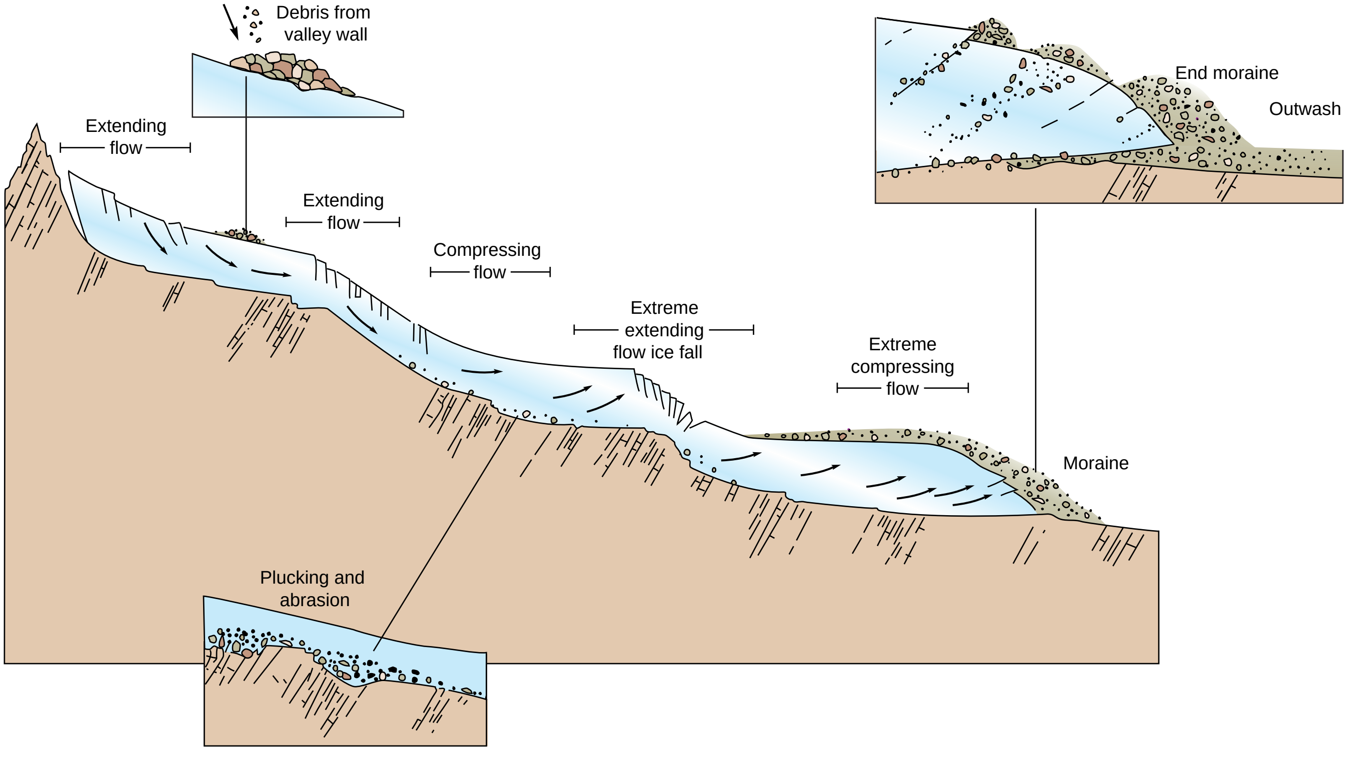


FIGURE 14.7 **Extending and compressing flow** result from variations in velocity. Where velocity increases, a glacier is extended (stretched) and thinned. Where velocity decreases, the glacier is compressed and thickened. Fast-flowing ice over a steep surface results in extreme extending flow. Gentle gradients produce compressing flow. As the ice moves, it erodes and transports sediment in various ways. Rockfalls from the valley walls add sediment to the surface of the ice. Plucking and abrasion erode bedrock at the base of the glacier. Near the terminus, this sediment load is transported upward by the flowing ice and deposited as the ice ablates.

In continental glaciers, the flow is radially outward from the zone of accumulation or from broad domes of maximum thickness. Movement, however, is strongly influenced by the configuration of the subglacial landscape. Preglacial valleys will channelize the flow of ice and greatly influence both direction and rate of flow. Domes or highlands, in contrast, will act as barriers and inhibit flow.

How fast do glaciers flow?

Velocity Variations. The flow of glacial ice, like that of running water in streams and rivers, is not constant, but varies significantly with time and place. Ice flow in a glacier may seem extremely slow compared with the flow of water in rivers, but the movement is continuous, and over the years, vast quantities of ice can move through a glacier. Measurements show that some of Switzerland's large valley glaciers move as much as 180 m/yr. Smaller glaciers move from 90 to 150 m/yr. Some of the most rapid rates have been measured on the outlet glaciers of Greenland, where ice is funneled through mountain passes at a speed of 8 km/yr. From these and other measurements, flow rates of a few centimeters per day appear common, and velocities of 3 m/day are exceptional.

Surging Glaciers. An extremely rapid flow of glacial ice, with velocities more than 100 times normal, is referred to as a glacial surge. Flow is extremely rapid, with daily advances of more than 90 m. One of the most rapid surges on record was observed in the Kutiak Glacier in Asia, where the glacier advanced 12 km in 3 months. In fall 1993, the Bering Glacier in Alaska surged 225 m in a day. Most glaciers occur in remote areas, so few surges were well documented in the past; today, however, satellite imaging monitors the flow velocities of glaciers throughout the world. Preliminary studies indicate that glacier surges are much more common than previously thought.

It is believed that glacial surge results from basal slip, as water gradually accumulates in small, interconnected cavities under the ice. Under such conditions, basal hydraulic pressure could increase to the point at which the glacier is locally raised a centimeter or two off its bed. Raising of the glacier could greatly increase basal slip and initiate a surge. Glacial surges may also result from sudden slippage along the base of a glacier, caused by the buildup of extreme stress upstream. Stagnant or slow-moving ice near the terminus can act as a dam for the faster-moving ice upstream. If this damming happens, stress builds up behind the slow-moving ice, and a surge occurs when a critical point is reached. Surges can also be caused by a sudden addition of mass to the glaciers, such as a large avalanche or landslide on its surface. Glacier surge is more than a feature of academic interest. Where glaciers reach the sea, surging glaciers can create many times more icebergs than normal, which constitute hazards in shipping lanes. Greenland, for example, discharges on the order of 10,000 icebergs each year into the Atlantic Ocean. If this amount were suddenly increased 100 times, it could have a significant effect on shipping lanes.

Crevasses

Why do crevasses form only in the upper part of glaciers?

The most obvious and abundant structures in a glacier are **crevasses**—large cracks opened by the fracturing of a brittle upper layer of ice as the underlying ice continues to flow (Figure 14.5). Crevasses are nearly vertical and may be more than 30 m deep and thousands of meters long. Crevasses are tensional fractures produced by differential motion in the ice (see Figure 14.14B). Almost any part of a glacier involved in differential flow velocities is likely to develop crevasses transverse to the direction of ice flow. Marginal crevasses are present in almost all valley glaciers, along their lateral margins, because the ice drags along the valley walls (see Figure 14.11). These crevasses are usually short and point upstream. Transverse crevasses form at right angles to the direction of flow, where flexing of the ice occurs as the glacier moves over bumps or ridges on the bedrock floor. Similarly, ice-falls are intensely crevassed by the greatly accelerated rate of flow as the ice moves down a steep slope (Figure 14.7). Longitudinal crevasses develop at the terminus of a glacier, where the ice stream spreads out, setting up tensional stresses at right angles to the flow direction. Radial crevasses are similar but form a radial pattern where the ice spreads out in a lobate pattern. Crevasses allow geologists to study the interior of a glacier, but they are extremely hazardous because they may become bridged over with snow, forming veritable ice death traps.

Ablation

The zone of ablation is where ice leaves the system by melting, evaporating, and calving (Figure 14.6). Melting, of course, is a major process. It is influenced by many complex factors, such as cloud cover, air temperature, rain, dust, and dirt on the surface of the glacier. Surface rock debris can significantly influence melting because the darker rock absorbs much more solar radiation than the lighter ice and snow.

Anyone who has visited a glacier during the summer is impressed with the large amount of meltwater. Melting occurs not only at the end of a glacier (see Figure 14.14C), but over its entire surface. When meltwater is abundant, it percolates into the crevasses and pore spaces between the ice grains, creating a zone of saturation within the glacier. A water table is thus created in the glacier and is commonly seen a few meters below the surface in many crevasses. Near the snow line, a thin layer of snow covers the impervious glacial ice below, and the concentration of meltwater may create snow swamps. Water derived from these swamps collects into a surface drainage system in which streams may cut steep-walled channels tens of meters deep. Velocity in these streams may be abnormally fast because the smooth ice surface of the channel offers minimal resistance to flow.

A surface stream may disappear down a large cylindrical hole in the ice and into a system of subglacial tunnels (see Figure 14.11). Subglacial tunnels are largest and most numerous near the end of a glacier. Some are tightly confined and may be completely full of meltwater and operate under pressure like domestic water pipes. Where the water is brought back to the surface, it may emerge with enough force to form a geyserlike eruption. The amount of water lost by melting is apparent in the expanse of braided streams in the outwash plain beyond the glacier.

Calving occurs primarily where the glacier enters the sea and is broken into large fragments that float away as icebergs and ultimately melt (see Figure 14.15). Most of the ice on the entire Antarctic continent reaches the sea; some of it extends over the ocean's surface as a floating ice shelf. Calving is thus a major form of wastage for Antarctic glaciers, as huge tabular icebergs break away from the shores and drift northward. Calving is also a major process of wastage in valley glaciers that reach the sea.

In the zone of ablation, only a small volume of ice changes from the solid state directly to the vapor state. This accounts for less than 1% of the total ablation. In most glaciers, melting and calving are the dominant processes of ablation.

Does ice flow through a glacier even though the end of the glacier is receding?

Glacial Equilibrium

Glaciers are open systems and have much in common with other gravity flow systems, such as rivers and groundwater. Water enters the system primarily in the upper parts of the glacier, where snow accumulates and is transformed into ice. The ice then flows out of the zone of accumulation. At the glacier's lower end, or terminus, ice leaves the system by melting, calving, and evaporating. For most glaciers, ice accumulation dominates during winter when snowfall is greatest, and ablation is highest during spring and summer. The annual difference between accumulation and ablation on a glacier is the net mass balance. If more snow is added in the zone of accumulation than is lost by melting or evaporation at the end of the glacier, the ice mass increases and the glacial system expands. If the accumulation of ice is less than ablation, there is a net loss of mass and the size of the glacial system is reduced. If accumulation and ablation are in balance, the mass of ice remains constant, the size of the system remains constant, and the terminus of the ice remains stationary. It is important to understand that the margins of a glacier constitute the boundaries of a system of flowing ice, much as the banks and mouth of a river constitute the boundaries of a river system. Ice within the glacier continually flows toward the terminus, or terminal margins, regardless of whether the terminal margins are advancing, retreating, or stationary.

The behavior of a glacial system (the size of the mass of ice) is determined by the balance between the rate of input and the rate of output of ice. The two major variables in this balance are temperature and precipitation. A glacier can grow or shrink with an unchanging rate of precipitation if the temperature varies enough to increase or decrease the rate of melting (rate of output). The size of a glacier in no way represents the amount of ice that has moved through the system, just as the length of a river does not represent the volume of water that has flowed through it. Size simply shows the amount of ice currently in the system.

An example, from the last ice age, illustrates this point. A glacial valley 20 km long in the Rocky Mountains was eroded 600 m deeper than the original stream valley. This large amount of erosion was not accomplished by 20 km of ice moving down the valley. It was the result of many thousands of kilometers of ice flowing through the valley. If the ice occupied the valley during each glacial epoch and moved 0.3 m/day, a total of approximately 72,000 km of ice would have moved down the valley. Yet, the glacier was never more than 20 km long. The enormous abrasion caused by such a long stream of ice would be able to wear down the valley to a depth of 600 m.

Erosion

Continental ice sheets and valley glaciers are powerful agents of erosion. An ice sheet may erode its base at a rate of 0.1 to 0.35 mm/yr. The North American ice sheet may have eroded as much as 1 to 2 m of bedrock during the last glacial cycle and tens of meters during the entire series of glacial advances. Because of the cold temperature accompanying glaciation, ice wedging contributes to the process. Wherever hills or mountains stand higher than the surface of the glacier, intense ice wedging occurs, loosening blocks of rock that then roll onto the surface of the glacier, which carries them away. Indeed, ice wedging is responsible for much of the detailed form of the sharp, jagged peaks that characterize glaciated mountains (Figure 14.3).

Glacial plucking is the lifting out and removal of fragments of bedrock by the moving ice (Figure 14.7). It is one of the most effective ways in which a glacier erodes the land. The process involves ice wedging. Beneath the glacier, meltwater seeps into joints or fractures, where it freezes and expands, wedging loose blocks of rock. The loosened blocks freeze to the bottom of the glacier and are plucked, or quarried, from the bedrock, becoming incorporated in the moving ice. The process is especially effective where the bedrock is cut by numerous joints and where the surface of the bedrock is unsupported on the downstream side.

Abrasion is essentially a filing process. The angular blocks plucked and quarried by the moving ice freeze firmly into the glacier; thus firmly gripped, they are ground against the bedrock over which the glacier moves (Figure 14.7). The process is similar to the rasping action of a file or sandpaper. Rivers, wind, and waves do not have this ability to grasp and use rock fragments as a rasp. The process is a trademark of glaciers. Aided by the pressure of the overlying ice, the angular blocks are very effective agents of erosion, capable of wearing away large quantities of bedrock. The fragments become abraded and worn down as they grind against the bedrock surface. As a result, glacial boulders usually develop flat surfaces that are deeply scratched.

Evidence of the distinctive abrasive and quarrying action of glaciers can be seen on most bedrock surfaces over which glacial ice has moved. Hills of bedrock

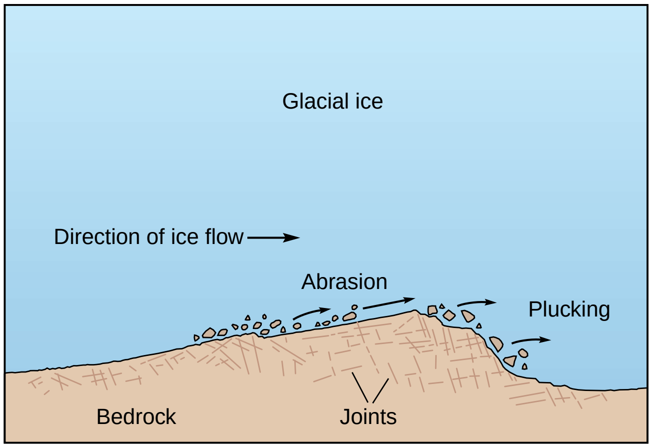


FIGURE 14.8 **A roche moutonnée,** like this one in a fjord in Norway, is an erosional feature that forms as ice moves over bedrock, eroding it into a streamlined shape by a combination of abrasion and plucking. Abrasion produces a smooth, grooved, and striated surface on one flank; plucking develops a jagged irregular cliff on the downstream flank. Roches moutonnées range from small knobs a few meters high to major domes more than 200 m high.

(roches moutonnées) commonly are streamlined by glacial abrasion. Their upstream sides typically are rounded, smoothed, striated, and locally polished by abrasion, while their downstream sides are made steep and rugged by glacial plucking (Figure 14.8).

Roches moutonnées range in size from small knobs a few meters long to large hills that rise 50 to 200 m above the surrounding landscape. Many are elongate in the direction of the ice flow and are best developed in resistant but jointed rock. *Whalebacks* are similar to roches moutonnées but are smooth, elongate features that are typically grooved and polished. They lack the rugged downstream face produced by glacial plucking and perhaps are more common than roches moutonnées.

Glacial striations are numerous, small scratches, a fraction of a millimeter deep and several tens of centimeters long. They are formed by angular sand-sized particles dragged across the rock surface by the flowing ice. The striations are parallel to the direction of ice movement. When used in conjunction with other features like moraines and drumlins, they reveal the direction that the ice flowed. Glacial polish is produced where very fine debris is incorporated into the basal ice. Glacial grooves are similar to striations but are larger, longer, and deeper. They are distinctively linear and U-shaped, with a smooth base, walls, and rounded edges (Figure 14.9). Typical grooves are 10 to 20 cm wide and 50 to 100 m long. Exceptional grooves, 30 m deep and 12 km long, are found in northwestern Canada.

VALLEY GLACIER SYSTEMS

Erosion and deposition by valley glaciers produce many distinctive landforms, the most important of which are (1) U-shaped valleys, (2) cirques, (3) hanging valleys, (4) horns, (5) moraines, and (6) outwash plains.

Valley glaciers are responsible for some of the most rugged and scenic mountainous terrain on Earth. The Alps, the Sierra Nevadas, the Rockies, and the Himalayas were all greatly modified by glaciers during the last ice age, and the shapes of their valleys, peaks, and divides retain the unmistakable imprint of erosion by ice.

As a result, they have been studied for many years, and their general characteristics are well understood. Valley glaciers are long, narrow streams of ice that originate in the snowfields of high mountain ranges and flow down preexisting stream valleys (Figure 14.10). They range from a few hundred meters to more than a hundred kilometers in length. In many ways, they resemble river systems. They

FIGURE 14.9 Glacial grooves and striations result from the abrasive action of a glacier and (when used in conjunction with other features) clearly show the direction in which the ice moved across this landscape in southern Ontario.

FIGURE 14.10 Valley glaciers on Bylot Island just off the northern end of Canada's Baffin Island originate in the snowfields that almost completely cover the mountain peaks. Note that the snow line extends down almost to sea level. The main glaciers extend down from the highland as tongues of ice (blue). Note that glaciers, like river systems, consist of a main trunk stream and an intricate system of branching tributaries. *(Courtesy of NASA)*

receive an input of water (in the form of snow) in the higher reaches of mountains, and they have a system of tributaries leading to a main trunk system. Their flow direction is controlled by the valley the glacier occupies, and as the ice moves, it erodes and modifies the landscape over which it flows. Unlike a stream of liquid water, the ice may be as much as 1000 m deep and flow slowly, perhaps a fraction of a meter a day. As the ice moves, it picks up rock and debris along its margins from abrasion, forming a marginal zone of dirty ice. In addition, the mass movement of rock debris from the valley walls above the glacier contributes to the rock debris along the ice margin. Below the snow line, the melting of the dirty ice concentrates the debris into a linear band along the side of the glacier that is called a **lateral moraine** (see Figure 14.14A) Where a tributary glacier joins the main stream, the two adjacent lateral moraines merge to form a **medial moraine.** Remember that the debris in a **moraine** represents only the outcropping of a band of dirty ice normally extending from the surface to the floor of the glacier (Figure 14.11). Thus, most valley glaciers are composed of multiple ice streams from tributary glaciers, separated by zones of dirty ice underlying the moraines at the surface. Downstream, the glacier undergoes progressive melting, and the morainal ridges become higher and broader.

Valley Glaciers

What unique landforms result from sediment deposited by valley glaciers?

If the floors of two merging glaciers join at the same level, the ice streams merge side by side, each extending from the surface to the floor of the valley, separated by a zone of dirty ice and debris. If a tributary glacier enters the main stream above the floor of the main glacier, the tributary glacier does not extend down to the floor of the main stream but rests above it.

The idealized diagrams in Figure 14.12 and the photographs in Figures 14.13 and 14.14 illustrate the major erosional landforms resulting from valley glaciation. Figure 14.12 permits a comparison and contrast of landscapes formed only by running water with those that have been modified by valley glaciers. Figure 14.12A shows the typical topography of a mountain region being eroded by streams. A relatively thick mantle of soil and weathered rock debris covers the slopes. The valleys are V-shaped, in cross section, and have many bends at tributary junctions so that ridges and divides between tributaries appear to overlap if you look up the valley. In Figure 14.12B, the valleys are shown occupied by glaciers. The growing glaciers expand down the tributary valleys and merge to form a major glacier.

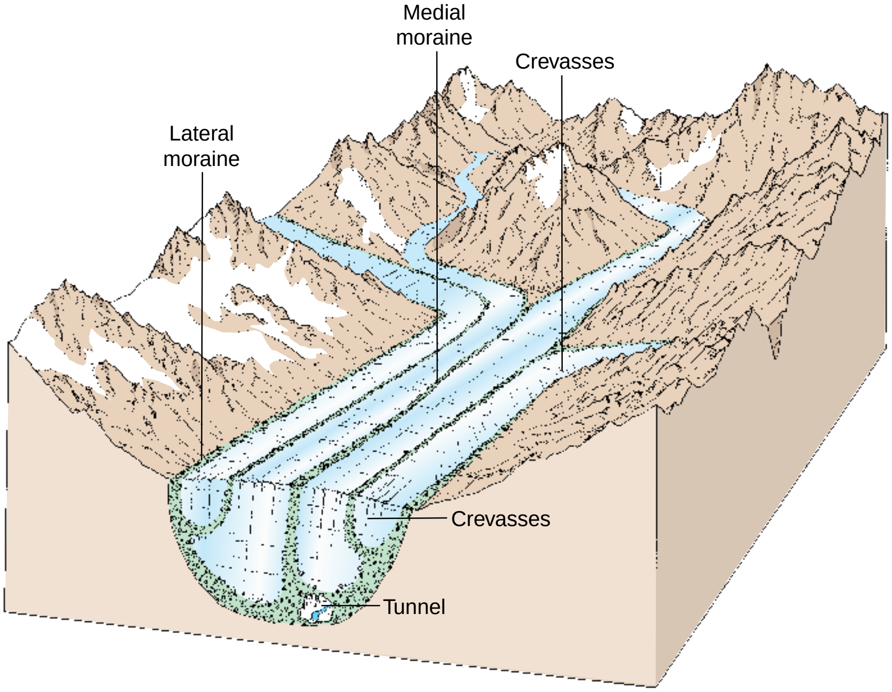
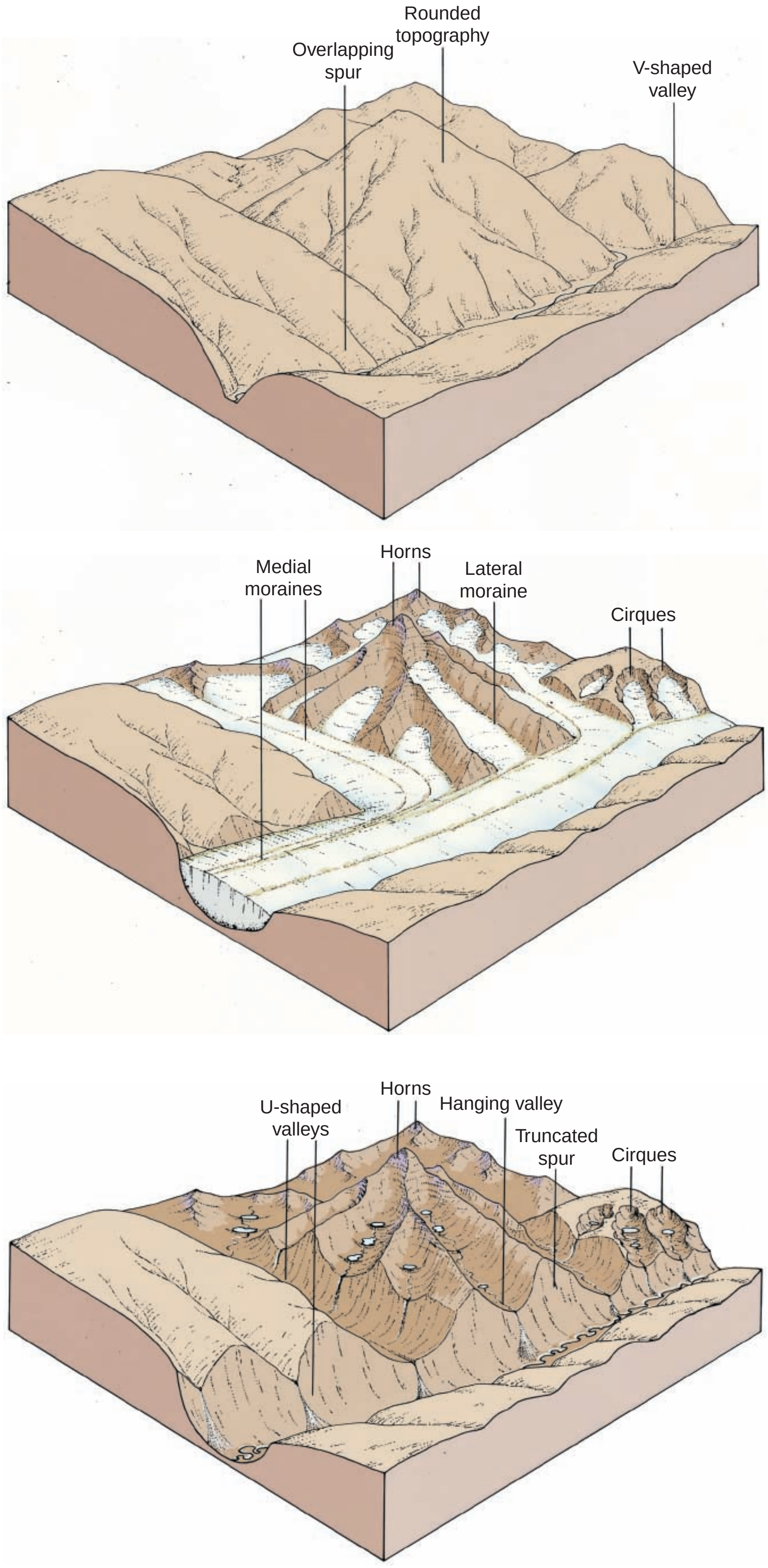


FIGURE 14.11 The internal structure of a valley glacier consists of the merging of different ice streams. Each tributary is separated from the others by morainal debris or dirty ice. Crevasses develop in the upper, brittle part of the glacier by differential motion in the ice. Common types of crevasses in valley glaciers include marginal crevasses due to drag along the valley walls, transverse crevasses that form as the glacier moves over irregularities on the bedrock floor, and longitudinal crevasses that develop at the end of a glacier where the ice stream begins to spread out. Meltwater may accumulate in marginal lakes or flow in short streams before seeping into the interior of the ice. Much of the meltwater moves through tunnels in or at the base of the ice.



(A) The topography before glaciation is shaped by running water. Valleys typically are V-shaped and have many curves and irregularities in map view. Hills are rounded.

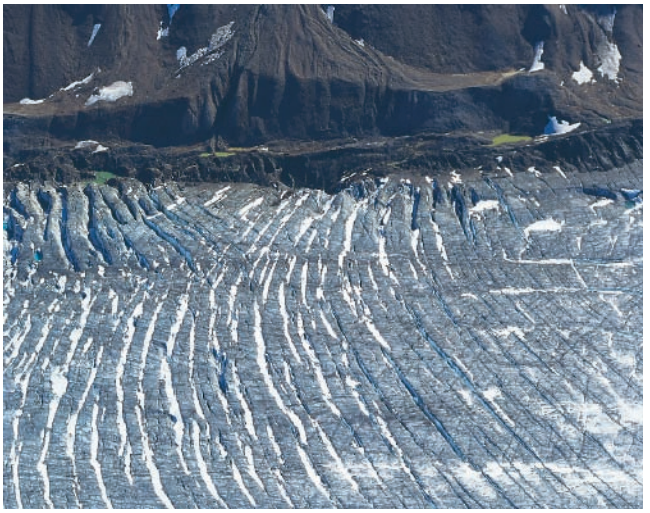
(B) Valley glaciers form in high areas and move down major stream valleys. A network of tributaries delivers ice to the main glacier. Ice wedging on the valley walls produces abundant rock fragments that accumulate as lateral moraines on the glacier's flanks.

(C) When the glacier recedes, the topography has been significantly modified. Sharp, angular landforms dominate. The valleys previously occupied by glaciers are deep and U-shaped. Bowl-shaped depressions called cirques develop at the heads of the valleys. Where several cirques meet, a sharp, pyramid-like peak called a horn is formed. Tributaries form hanging valleys that can have spectacular waterfalls.

FIGURE 14.12 Landforms produced by valley glaciers constitute some of the most spectacular scenery in the world. In these diagrams, an idealized landscape formed by stream erosion is shown as it might appear before, during, and after glaciation.

FIGURE 14.13 Glaciated topography in the Alps of Switzerland shows most of the classic landforms produced by valley glaciers. Note the major U-shaped valley and its tributaries. Cirques and horns dominate the landscape in the background, where remnants of valley glaciers still exist. Compare the landforms shown here with those in Figure 14.12C. *(Courtesy of Petroconsultants, S. A., Geneva, Switzerland)*

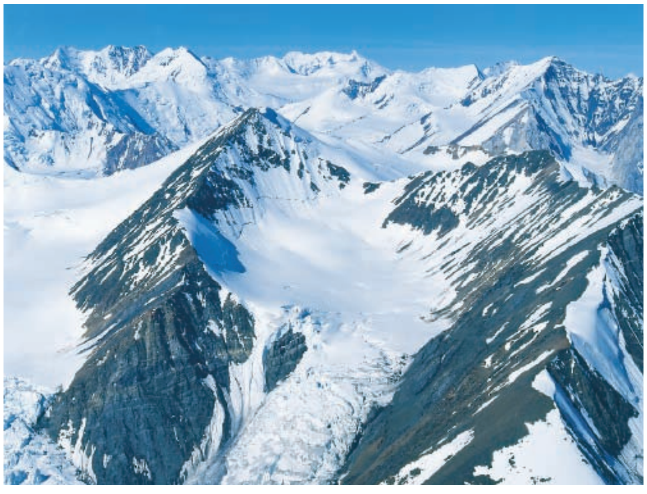
(A) Lateral moraines form on the margins of valley glaciers. Where two glaciers merge, the lateral moraines merge to form a medial moraine.



(B) Crevasses are large cracks in the brittle upper part of a glacier. These transverse crevasses formed perpendicular to the flow direction as the glacier moved over bumps on the valley floor.

(C) The outwash plain is covered by braided streams emanating from the melting Nabesna glacier of the Yukon Territory.

(D) A terminal moraine forms a high arcuate ridge after a valley glacier receded in California's Sierra Nevada range.



(E) Extending flow forms crevasses and may occur where a glacier descends over a steep slope. Compressing flow is common at the end of the glacier, where stagnant ice prevents its forward motion.

(F) Glacial erosion features, such as the horns shown here, dominate glaciated mountain regions. The Grand Teton, Wyoming, was shaped by erosion during the ice age.

FIGURE 14.14 **Valley glaciers** produce distinctive erosion and deposition features.

What unique landforms result from erosion by valley glaciers?

A valley glacier commonly fills more than half of the valley depth, and as it moves, it modifies the former V-shaped stream valley into a broad U-shaped, or troughlike form. The head of the glacier is enlarged by plucking and grows headward toward the mountain crest to form a **cirque** (Figure 14.12)**.** Where two or more cirques approach the summit crest, they sculpt the mountain crest into a sharp, pyramid-shaped peak, called a **horn.** The projecting ridges and divides, between glacial valleys, are subjected to rigorous ice wedging, abrasion, and mass movement. In contrast to the rounded topography developed by stream erosion, these processes produce sharp, angular crests and divides, called **arêtes**.

Note that where tributaries enter the main glacier, the upper surfaces of the glaciers are at the same level. The main glacier, however, is much thicker, and it therefore erodes its valley to a greater depth than that of the tributary valleys. When the glaciers recede from the area, the floors of the tributary valleys will be higher than the floor of the main valley; the tributary valleys are therefore known as **hanging valleys.**

Part of a valley glacier's load consists of rock fragments that avalanche down the steep valley sides and accumulate along the glacier margins. Frost action is especially active in the cold climate of valley glaciers and produces large quantities of angular rock fragments. This material is transported along the surface of the glacial margins, forming conspicuous lateral moraines (Figure 14.11). Where a tributary glacier enters the main valley, the lateral moraine of the tributary glacier merges with a lateral moraine of the main glacier to form a medial moraine in the central part of the main glacier. In addition to transporting the load near its base, a valley glacier thus acts as a conveyor belt and transports a large quantity of surface sediment to the terminus. At the terminus, ice leaves the system through melting and evaporation, and the load is deposited as an **end moraine**. End moraines commonly block the ends of the valleys, so meltwater from the ice accumulates and forms ponds and lakes (Figure 14.14D). Downstream from the glacier, meltwater reworks the glacial sediments and redeposits them to form an outwash plain (Figure 14.14C).

Figures 14.12C and 14.13 show regions after glaciers have disappeared. The most conspicuous and magnificent landforms developed by valley glaciers are the long, straight, U-shaped valleys, or troughs. Many are several hundred meters deep and tens of kilometers long. The heads of glacial valleys terminate in large amphitheater-shaped or bowl-like cirques, which commonly contain small lakes.

The landforms that develop at the terminus of a valley glacier are illustrated in Figures 14.1 and 14.14. The **terminal moraine** characteristically extends in a broad arc, conforming to the shape of the terminus of the ice. It commonly traps meltwater and forms a temporary lake. If periods of stabilization occur during the recession of ice, **recessional moraines** may form behind the terminal moraine.

The great volume of meltwater released at the terminus of a glacier reworks much of the previously deposited moraine and redeposits the material beyond the glacier in an **outwash plain** (Figures 14.1 and 14.14C). Outwash sediment has all of the characteristics of stream deposits, and the sediment is typically rounded, sorted, and stratified.

CONTINENTAL GLACIER SYSTEMS

Continental glaciers greatly modify the entire landscape they cover. The flowing ice removes the soil and commonly erodes several meters of the underlying bedrock. Material is transported long distances and deposited near the ice margins, producing depositional landforms such as moraines, drumlins, eskers, kettles, lake sediment, and outwash plains. The preexisting drainage is disrupted or obliterated, so numerous lakes form after the ice melts.

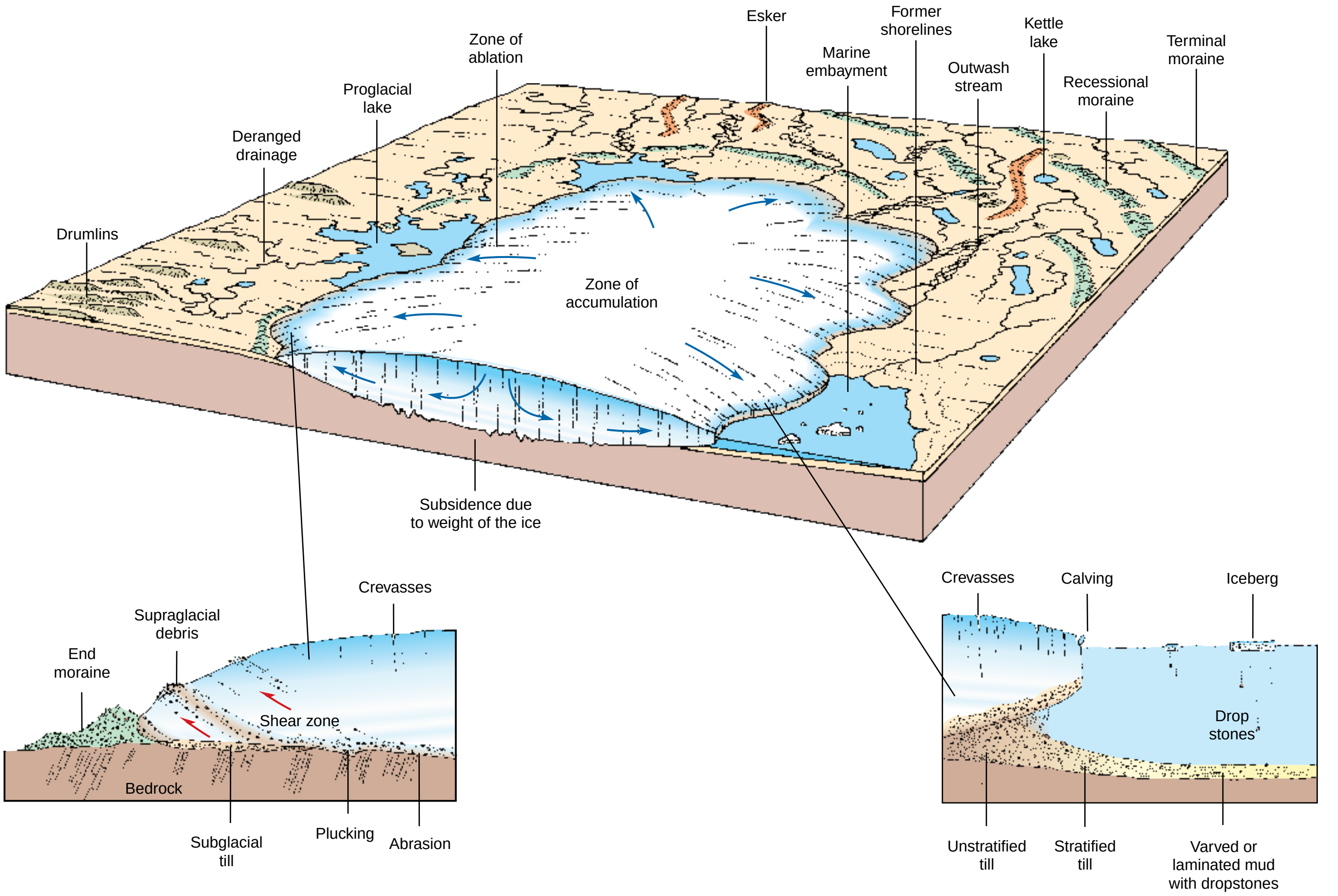


FIGURE 14.15 **A continental glacier system** covers a large part of a continent and causes significant changes across the entire landscape. The weight of the ice depresses the ground surface, so the land commonly slopes toward the glacier, and lakes form in the depressions along ice margins, or an arm of the ocean may invade the depression. The preexisting river systems are greatly modified, and streams that flow toward the ice margins are impounded to form lakes. The glacier advances more rapidly into lowlands, so the margins are not straight but are typically irregular or lobate. As the system expands and contracts, ridges of sediment are deposited along the margins, and a variety of erosional and depositional landforms develop beneath the ice. The balance between the rate of accumulation and rate of melting determines the size of the glacier.

In terms of their effect on the landscape and on Earth's hydrologic system, continental glaciers are by far the most important type of glacial system. These large ice sheets form in some of the most rigorous and inhospitable climates on Earth. Nonetheless, teams of scientists from various countries use modern technology to study existing continental glaciers in Canada, Greenland, and Antarctica. From these studies, we can construct a reasonably accurate model of an idealized continental glacial system and analyze how it operates (Figure 14.15).

What are the major elements in a continental glacier system?

The basic elements of a continental glacier are much the same as those in a valley glacier. Both systems have a zone of accumulation, where there is a net gain of ice from snowfall. The ice flows out from the zone of accumulation to the zone of ablation, where it leaves the system through melting, evaporation, and calving. A continental glacier is a roughly circular or elliptical plate of ice, rarely more than 3000 m thick. Ice does not have the strength to support the weight of an appreciably thicker accumulation. If more ice is added by increased precipitation, the glacier simply flows out from the centers of accumulation more quickly.

The weight of such a huge ice mass causes Earth's crust to subside, so the surface of the land commonly slopes toward the glacier. Subsidence creates a lowland along the ice margin, which traps meltwater to form large lakes. If the margin of the glacier is near the coast, an arm of the sea may flood the depression.

Preexisting drainage systems are modified or completely obliterated. Rivers that flow toward the ice margins are impounded, forming lakes, which may overflow and develop a new river channel parallel to the ice margin. Drainage systems covered by the glacier are destroyed. Thus, when the ice melts, no established, integrated drainage system exists, so numerous lakes form in the natural depressions.

Continental Glaciers

The margins of continental glaciers commonly form large lobes. These develop because the ice moves most rapidly into preexisting lowlands. The sediment deposited at the ice margins form arcuate or lobate terminal moraines. Erosion is at a minimum where the ice extends into the near polar regions because ice is frozen to the land surface. Most of the movement occurs in the middle of the sheet rather than at its bottom.

The Barnes Ice Cap of Baffin Island, Canada (Figure 14.16), is one of the last remnants of the glacier that covered much of Canada and parts of the northern United States only 14,000 years ago. This example illustrates the relationship between the continental glacier and the regional landforms. As shown on the map, the glacier is elliptical, with irregular, or lobate, margins. The ice is thickest in the central part and thins toward the edges. The presence of the glacier has caused an isostatic subsidence of the crust, so the land slopes toward the ice margins. In addition, the glacier has completely disrupted the former drainage system. Meltwater has therefore accumulated along the ice margins, forming a group of lakes. A photograph of the southern margins of the ice cap (Figure 14.17) shows the large, gently arched surface of the glacier, sediment deposited along the ice contact, and stream channels formed by meltwater on the glacier's surface.

The ice cap that covers nearly 80% of Greenland is much larger than the remnant on Baffin Island. In cross section, the glacier is shaped like a drop of water on a table (Figure 14.18). Its upper surface is a broad, almost flat-topped arch and is typically smooth and featureless. The base of the glacier is relatively flat. The

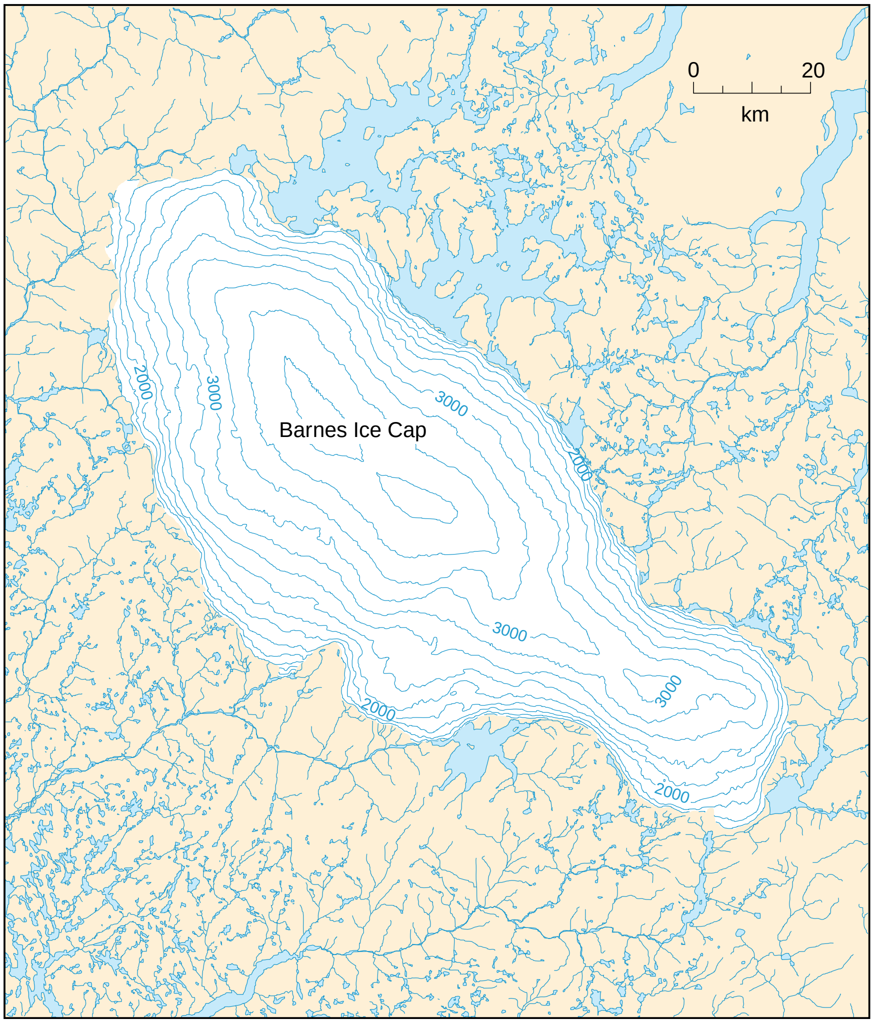


FIGURE 14.16 The Barnes Ice Cap, Baffin Island, Canada, is a remnant of the last continental glacier that covered large parts of North America and shows many features typically produced by continental glaciation. Isostatic adjustment of the crust causes the surface of the land to slope toward the ice, so lakes form along the ice margins. Drainage coming from the north is blocked by the ice and also contributes to lake formation near the ice margins. Irregularities in the surface over which the ice flows cause the ice margins to be uneven, or lobate.

FIGURE 14.17 **The margins of the Barnes Ice Cap** are marked by ridges of sediment deposited as the ice melts. The glacier's upper surface is gently arched, and meltwater has formed small meandering streams. The landscape of the Great Lakes region must have appeared something like this 20,000 years ago. *(Photograph by J. D. Ives)*

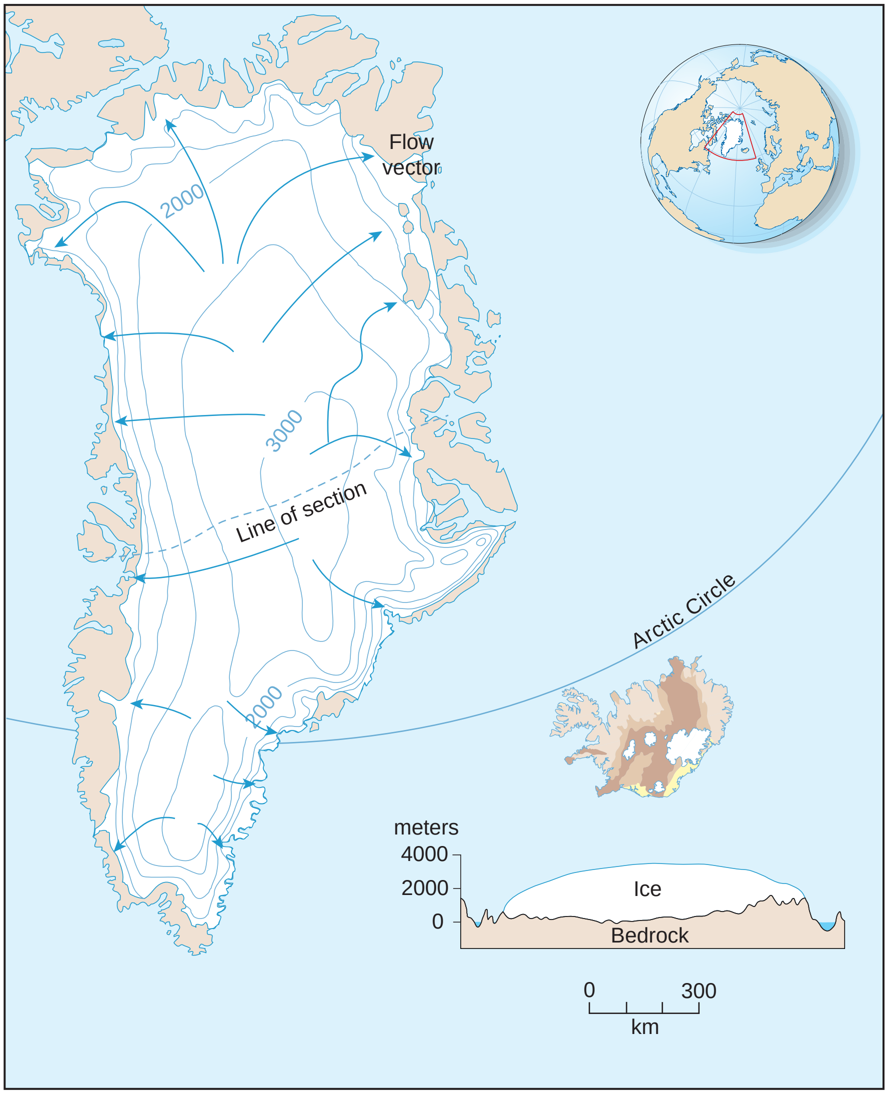


FIGURE 14.18 **The Greenland Ice Sheet** covers nearly 80% of the island. In this diagram, the thickness of the glacier is shown by contour lines. The upper surface of the glacier is a broad, almost flat-topped arch and is typically smooth and featureless. The arrows show the direction of ice flow. Note from the cross section that the central part of Greenland has been depressed below sea level by the weight of the ice.

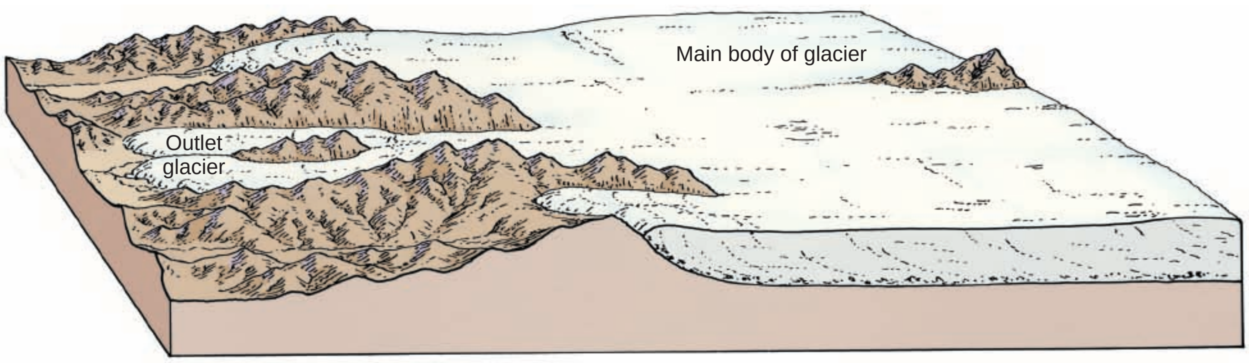


FIGURE 14.19 **Outlet glaciers** are segments of a continental glacier that advance rapidly through a mountain pass. A mountain range is a physical barrier to the movement of a continental glacier, and great pressure builds up in the ice behind the range. This pressure causes the ice in an outlet glacier to move very rapidly, in comparison with the main body ice.

Greenland glacier is more than 3000 m thick in its central part, but it thins toward the margins. The zone of accumulation is in the central part of the island, where the ice sheet is nourished by snowstorms moving from west to east. The snowline lies from 50 to 250 km inland; thus, the area of ablation constitutes only a narrow belt along the glacial margins.

What are outlet glaciers?

In rugged terrain, especially in areas close to the margins, the direction of ice movement is greatly influenced by mountain ranges, and the ice moves through mountain passes in large streams of **outlet glaciers** (Figure 14.19). These resemble valley glaciers in that they are confined by the topography. Pressure builds up in the ice behind a mountain range and forces outlet glaciers through mountain passes at relatively high speeds. Measurements in Greenland show that the main ice mass advances at approximately 10 to 30 cm/day. Outlet glaciers, however, can move as fast as 1 m/hr. In some places, you can actually see the ice move.

Antarctica

The glacier of Antarctica is similar to that of Greenland in that it covers essentially the entire land mass (Figure 14.20). Antarctica, however, is much larger than Greenland, and its glacier contains more than 90% of Earth's ice. Much of the glacier is more than 3000 m thick, and its weight has depressed large parts of the continent's surface below sea level. Parts of Antarctica (mostly near the continental margins) are mountainous, with the higher peaks and ranges protruding above the ice. In the mountains, outlet glaciers funnel ice from the interior to the coast.

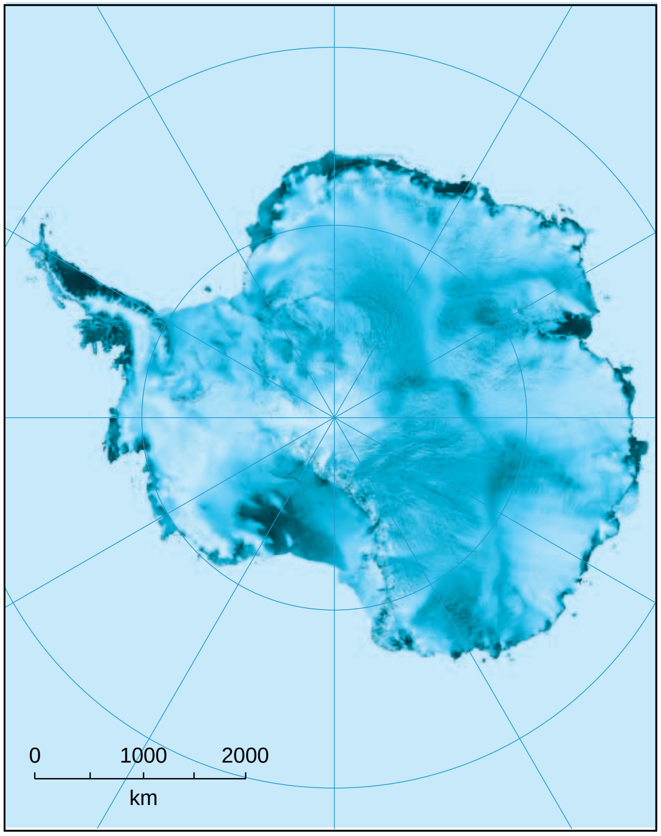
In addition to the continental glacier that blankets most of the land surface, Antarctica possesses two vast, fringing ice shelves and several smaller ones. These are not true glaciers but tabular bodies of ice that float on the ocean waters in the embayments of the Ross and Weddell seas. The shelves are several hundred meters thick and are fed by glaciers flowing out toward the edge of the Antarctic landmass. They are attached to the coast but calve off into the sea to form huge tabular icebergs that may exceed 100 km in length.

Many outlet glaciers flow through the valleys of the rugged Transantarctic Mountains onto the western edge of the Ross Ice Shelf (Figure 14.20). The largest of these is the Byrd Glacier, which is more than 20 km wide and 100 km long. The flow of ice is expressed by long ridges and furrows, parallel to the valley walls. Byrd Glacier is one of the fastest-moving glaciers in Antarctica, flowing at a rate of 750 to 800 m/yr.

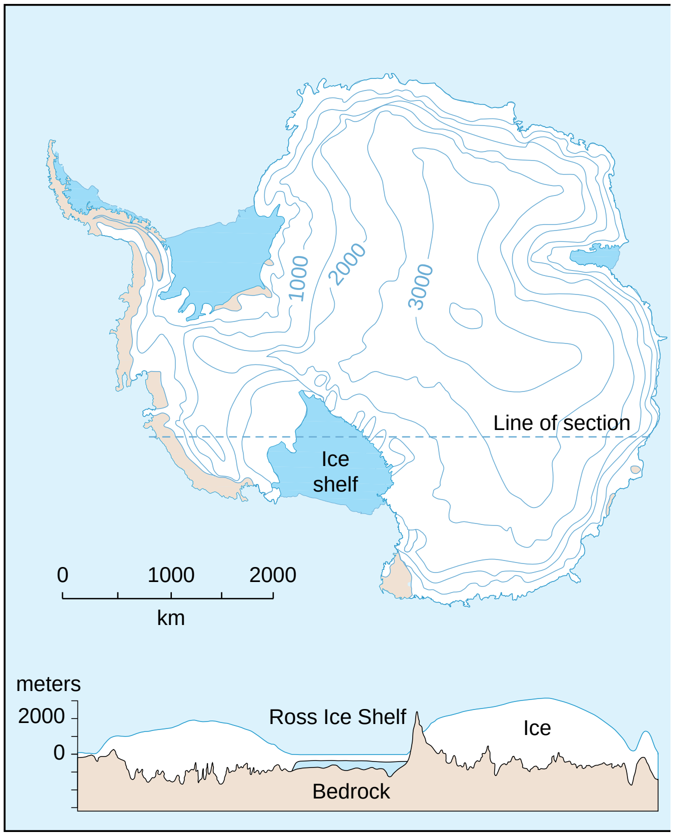
Lambert Glacier

Both Greenland and Antarctica are surrounded by water, so there is an ample supply of moisture to feed their glaciers. In contrast, Siberia is cold enough for glaciers to exist, but it lacks sufficient precipitation for ice to accumulate, so it has no glaciers.

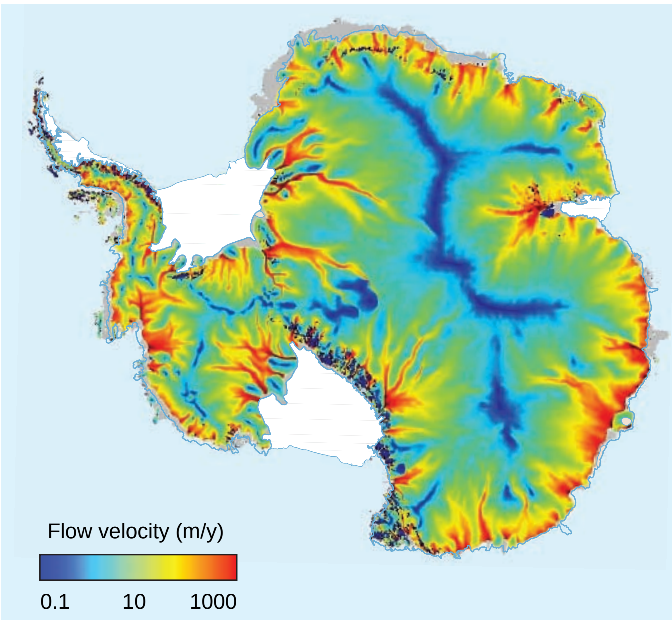
Perhaps the best way to approach the study of landforms produced by continental glaciers is to study the photograph of an ice cap in Iceland (Figure 14.21) and the block diagrams of an ice sheet margin (Figure 14.22). From viewpoints on the ground, the landforms developed by continental glaciers are relatively inconspicuous and not nearly as spectacular as those produced by valley glaciers. Regionally, however,



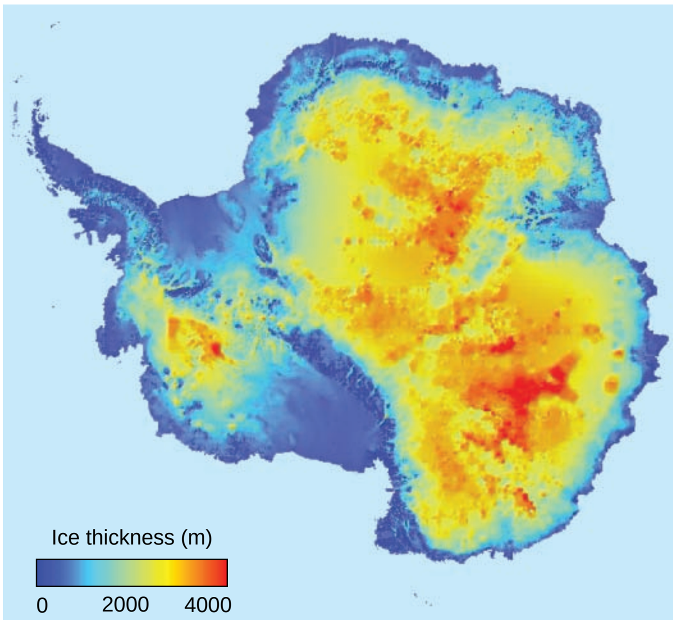
(A) Satellite image of Antarctica shows the vast extent of a continental glacier. Two large ice shelves and several smaller ones float on seawater. The ice shelves appear smooth and flat. *(Courtesy of NASA)*



(B) The tremendous weight of the Antarctic ice sheet has depressed large parts of the continent below sea level. The higher peaks of Antarctica's mountain ranges protrude above the glacier as "islands of rock" in a sea of ice.



(C) The ice moves as much as several hundred meters per year as shown in this computer model. "Drainage basins" are bounded by slow ice. Fast streams of ice are concentrated on the margins but extend deep into the interior. *(Roland Warner, Antarctic CRC and Australian Antarctic Division)*



(D) The Antarctic ice sheet is as much as 3000 m thick but tapers toward the margins of the continent. *(Data from the BEDMAP Project)*

FIGURE 14.20 Antarctica is buried by Earth's largest mass of ice. The maps show its topography, velocity, and thickness of the glacier.

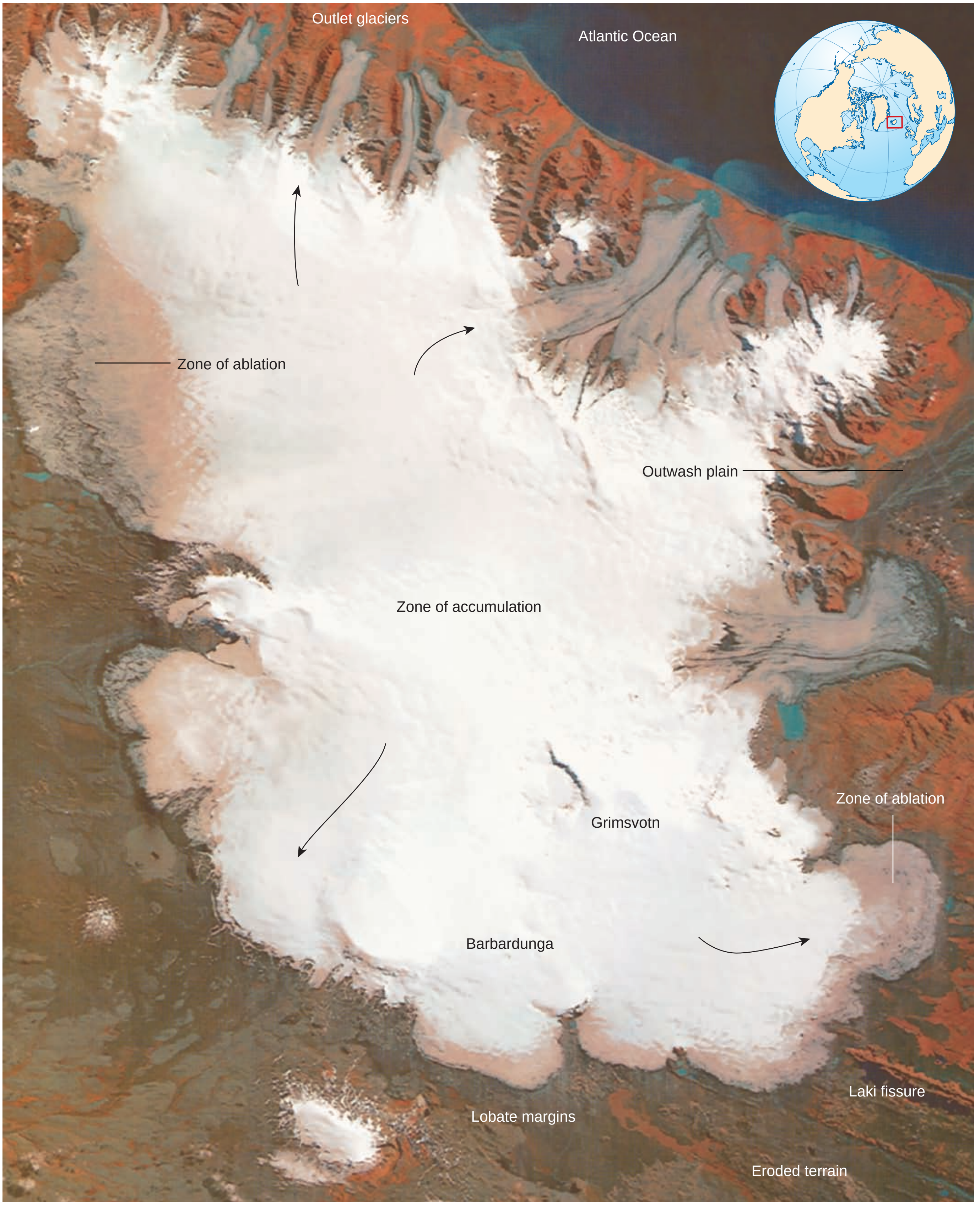
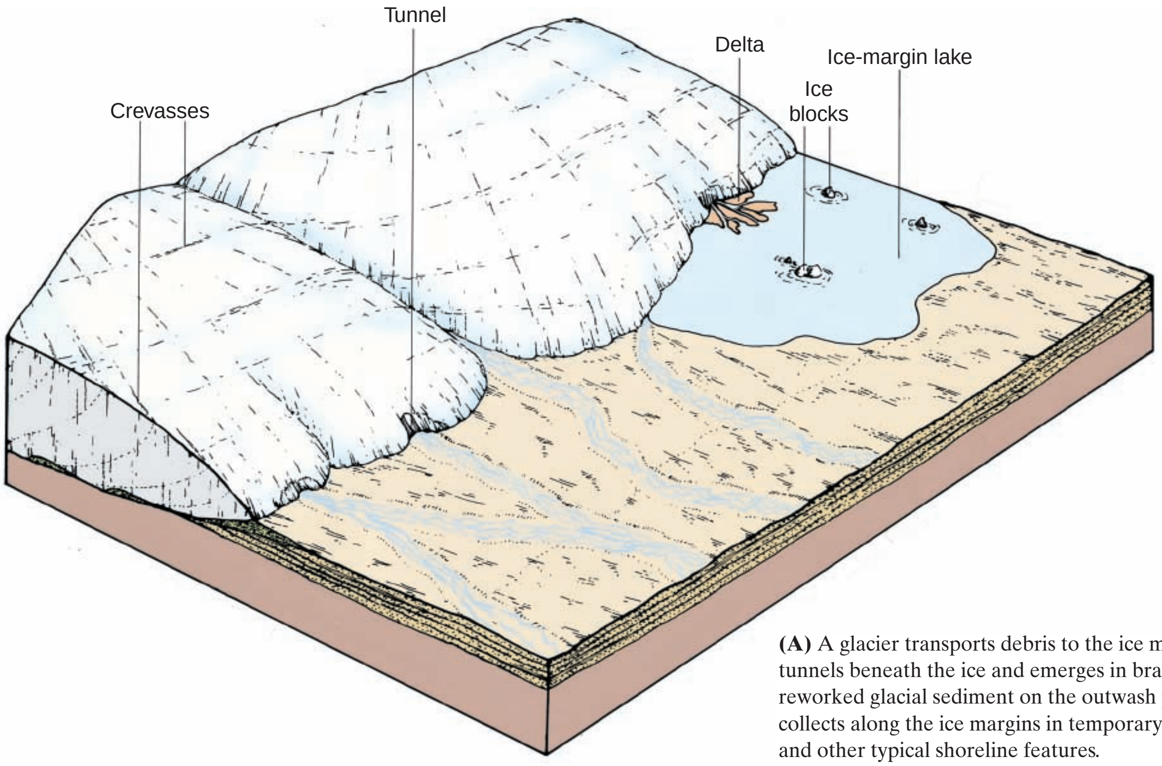
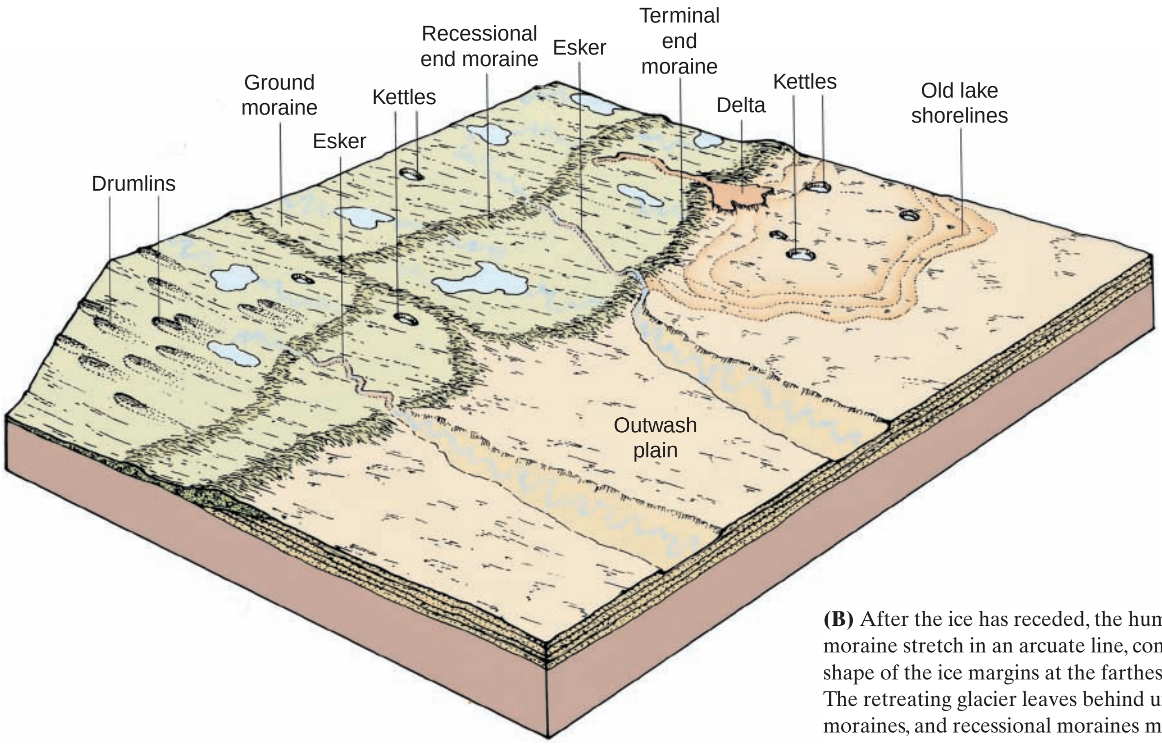


FIGURE 14.21 **Iceland's Vatnajokull glacier** completely buries the underlying surface, including two large volcanoes. Beyond the snow line, large lobes form the margins of the ice cap. In the more-rugged terrain, toward the top, outlet glaciers advance through the valleys toward the sea. Sediment, carried by braided rivers on the outwash plains, tints the near-shore water. A subglacial eruption in 1996 caused a huge subglacial flood to burst from the glacier and flow down the outwash plain to the ocean, destroying bridges and roads. *(Courtesy of Earth Observation Satellite Company)*



(A) A glacier transports debris to the ice margins. Meltwater carves tunnels beneath the ice and emerges in braided streams that deposit reworked glacial sediment on the outwash plain. In places, meltwater collects along the ice margins in temporary lakes that develop deltas and other typical shoreline features.

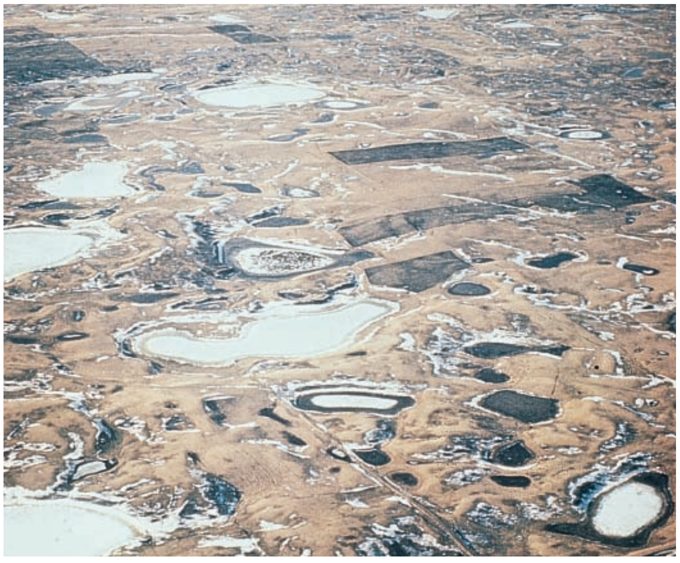


(B) After the ice has receded, the hummocky hills of a terminal moraine stretch in an arcuate line, conforming to the original shape of the ice margins at the farthest advance of the glacier. The retreating glacier leaves behind unsorted debris in ground moraines, and recessional moraines mark the positions of the ice margin where the glacier paused during its retreat. Hills of ground moraine can be reshaped by a subsequent advance of ice, forming drumlins. Sinuous eskers remain where sediment was deposited by subglacial streams, and sediment reworked by meltwater forms outwash plain and lake deposits. Where ice blocks were stranded by the receding glacier and partly buried under debris, the melting of the ice produces kettles.

FIGURE 14.22 **Landforms developed by continental glaciers** commonly are related to the position of the ice margin or the direction of the flow. *(After A. N. Strahler,* Physical Geography. *New York: Wiley, 1951)*

(A) Glacial till resting on horizontal limestone in Iowa is responsible for much of the rich farmland in that area.

(B) Varves are annual layers of sediment accumulated in glacial lakes. Large boulders dropped from melting icebergs (dropstones) accumulate contemporaneously.



(C) Moraines form a distinctive topography of rolling hills and numerous closed depressions. *(Courtesy of D. Easterbrook)*

(D) Eskers form long, sinuous ridges composed of sand and gravel deposited by streams that flowed beneath the glacier. *(D. Easterbrook)*

(E) Drumlins are streamlined hills that were shaped by the movement of the glacier and show the direction in which the ice flowed.

(F) The outwash plain forms from meltwaters from the glacier and is characterized by fluvial sediments deposited by braided streams. *(Courtesy of D. Easterbrook)*

FIGURE 14.23 **Glacial landforms** reveal the former presence of vast continental glaciers.

FIGURE 14.24 **Erratics** are large boulders transported by glaciers and then dropped far from their point of origin. This isolated block was carried 300 km by glacial ice and now lies near Okotok, Alberta, Canada. In some areas, diamond and other ore deposits have been found by tracing distinctive erratics back to their bedrock sources.

continental glaciation modifies the entire landscape, producing many important and distinctive surface features (Figure 14.23). Debris **(till)** transported by the glacier accumulates at the ice margin as a terminal moraine. Beneath the ice is a variable thickness of till, transported by the glacier and deposited as a **ground moraine.** This material, together with outwash plain sediment, can be reshaped by subsequent advances of ice to produce streamlined hills, called **drumlins.** The upstream end of a drumlin is blunt and steeper than the tail, so the form resembles a raindrop. The long axis is oriented parallel to the direction of ice movement. Drumlins are usually found in groups or swarms containing as many as 10,000 individuals. Excellent drumlin fields are found in Ireland, England, Canada, Michigan, Wisconsin, New England, New York, and western Washington. Some of the islands in Boston Harbor are drumlins, as is Bunker Hill, a famous landmark in U.S. history.

Streams of meltwater flow in tunnels within (and beneath) the ice and carry a large bed load, which is ultimately deposited to form a long, sinuous ridge known as an **esker** (Figure 14.23D). Debris-laden meltwater forms braided streams that flow from the glacier, over the outwash plain, where they deposit much of their load. During the retreat of the glaciers, meltwater forms subglacial channels and tunnels, which open into the outwash plain. Temporary lakes can develop where meltwater is trapped along the edges of the glacier, and deltas and other shoreline features form along the lake margins. Deposits on the lake bottom typically are stratified in a series of alternating light and dark layers known as **varves** (Figure 14.23B). The coarse, light-colored material accumulates during spring and summer runoff. During the winter, when the lake is frozen over, no new sediment enters the lake, and the fine mud settles out of suspension to form the thin, dark layers.

Ice blocks, left behind by the retreating glacier front, can be partly or completely buried in the outwash plain or in moraines. Where an isolated block of debris-covered ice melts, a depression known as a **kettle** is formed.

Figure 14.22B shows the area after the glacier has disappeared completely. The end moraine appears as a belt of hummocky hills, which mark the former position of the ice. The size of the moraine reflects the duration of a stable ice front. Continental moraines can be large. For example, the Bloomington Moraine in central Illinois is 25 to 30 km wide and more than 300 km long but only 20 to 60 m high. From the ground, it probably would not be recognized by an untrained observer as anything more than a series of hills. Mapped over a large area, however, it can be seen to have an arcuate pattern, conforming to the lobate margin of the glacier. Many small depressions occur throughout the moraine, some of which may be filled with water, forming small lakes and ponds.

Scattered across the surface of the glaciated regions of North America and Europe are large fields of boulders known as **erratics** (Figure 14.24). Many midwestern U.S. erratics are composed of igneous or metamorphic rocks and are completely different from the underlying bedrock of sandstone, limestone, and shale. They could come only from the interior of Canada, hundreds of kilometers to the

FIGURE 14.25 Pleistocene glaciers covered large areas in North America, Europe, and Asia, as well as many high mountain regions. Parts of Alaska and Siberia were not glaciated because those areas were too dry. They were cold enough, but not enough precipitation fell for glaciers to develop. With the accumulation of so much ice on the land, the shoreline moved as much as 200 km seaward along the Atlantic coast of the United States. The drop in sea level formed a broad land bridge between Siberia and North America (gray). Sea ice covered most of the Arctic Ocean and extended into the North Atlantic well south of Iceland (light blue). Ocean temperatures dropped by as much as 10°C.

north. Some erratics are incorporated in the body of glacial sediment, whereas others lie free on the ground. Most erratics are small but many exceed 3 m in diameter, and others are enormous, weighing thousands of tons like the one shown in Figure 14.24.

PLEISTOCENE GLACIATION

The Pleistocene ice age was one of the most significant events in recent Earth history. The major effects of the ice age were (1) glacial erosion and deposition over large parts of the continents that modified river systems, (2) creation of millions of lakes, (3) changes in sea level, (4) pluvial lakes developed far from the ice margins, (5) isostatic adjustment of the crust, (6) abnormal winds, (7) impact on the oceans, (8) catastrophic flooding, and (9) modifications of biologic communities.

The cycles of glacial and interglacial periods, which began between 2 and 3 million years ago, constitute one of the most significant events in the recent history of Earth. During this time, the normal hydrologic system was completely interrupted throughout large areas of the world and was considerably modified in others. The evidence of such an event in the recent past is overwhelmingly abundant. Over the last century, extensive field observations have provided incontestable evidence that continental glaciers covered large parts of Europe, North America, and Siberia (Figure 14.25). These ice sheets started to disappear only between 15,000 and 20,000 years ago (Figure 14.26). A detailed map of glacial features in the northeastern United States is given in Figure 14.27. These maps were compiled after many years of fieldwork by hundreds of geologists who mapped the location and orientation of drumlins, eskers, moraines, striations, and glacial stream channels. These maps revealed the extent of the ice sheet, the direction of flow, and the locations of systems of meltwater channels, and they allowed us to decipher a history of multiple advances and retreats of the ice.

FIGURE 14.26 Successive positions of the ice front during the recession of the last ice sheet have been mapped from data collected by geologists in Canada and the United States. Contours indicate the position and age of the ice front in thousands of years before the present.

Four major periods of Pleistocene glaciation in the United States are recorded by broad sheets of till and complex moraines, separated by ancient soils and layers of wind-blown silt. Striations, drumlins, eskers, and other glacial features show that almost all of Canada, the mountain areas of Alaska, and the eastern and central United States, down to the Missouri and Ohio rivers, were covered with ice (Figure 14.27). There were three main zones of accumulation, the largest of which was centered over Hudson Bay. Ice advanced radially from there, northward to the Arctic islands and southward into the Great Lakes area. A smaller center was located in the Labrador Peninsula. Ice spread southward from this center into what are now the New England states. In the Canadian Rockies, to the west, valley glaciers coalesced into ice caps. These grew into a single ice sheet, which then moved westward to the Pacific shores and eastward down the Rocky Mountain foothills, until it merged with the large sheet from Hudson Bay.

Throughout much of central Canada, the glaciers eroded from 15 to 25 m of regolith and solid bedrock. This material was transported to the glacial margins and accumulated as ground moraine, end moraines, and outwash in a broad belt from Ohio to Montana (Figure 14.27). In places, the glacial debris is more than 300 m thick, but the average thickness is about 15 m. Meltwater carried sediment down the Mississippi River, and much of the fine-grained sediment was transported and redeposited by wind.

What evidence indicates multiple cycles of advance and retreat of the glaciers during the ice age?

Even before the theory of worldwide glaciation was generally accepted, many observers recognized that more than a single advance and retreat of the ice had occurred during the **Pleistocene Epoch.** Extensive evidence now shows that a number of periods of growth and retreat of continental glaciers occurred during the ice age. The interglacial periods of warm climate are represented by buried soil profiles, peat beds, and lake and stream deposits separating the unsorted, unstratified deposits of glacial debris.

Radiometric dating shows that the ice first began to advance between 2 and 3 million years ago, and the last glacier began to retreat between 15,000 and 20,000 years ago. Remnants of these last glaciers, now occupying about 10% of the world's land surface, still exist in Greenland and Antarctica.

The Effects of the Pleistocene Glaciation

The presence of so much ice upon the continents had a profound effect upon almost every aspect of Earth's hydrologic system. The most obvious effects, of course, are the spectacular mountain scenery and other continental landscapes fashioned

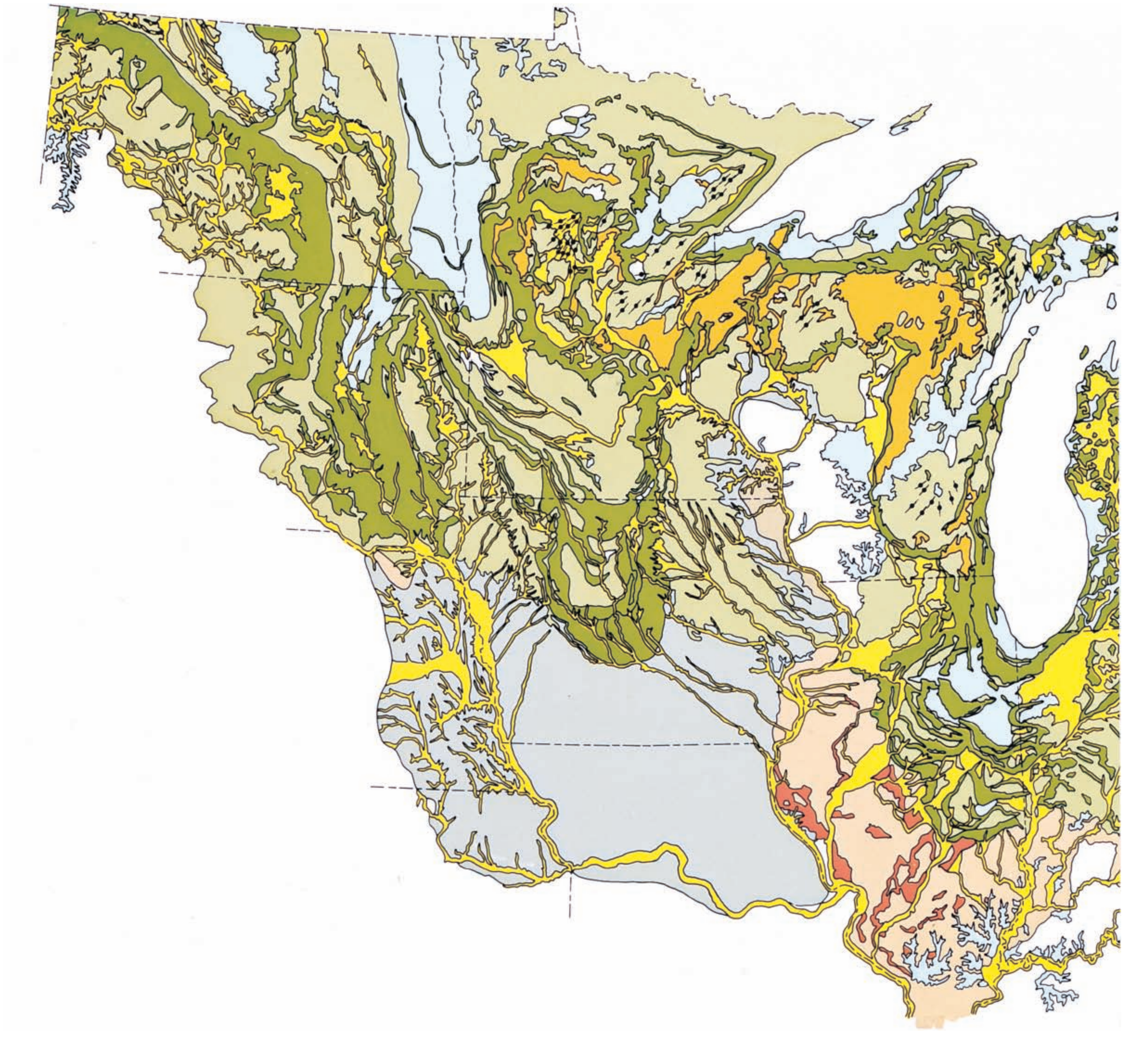
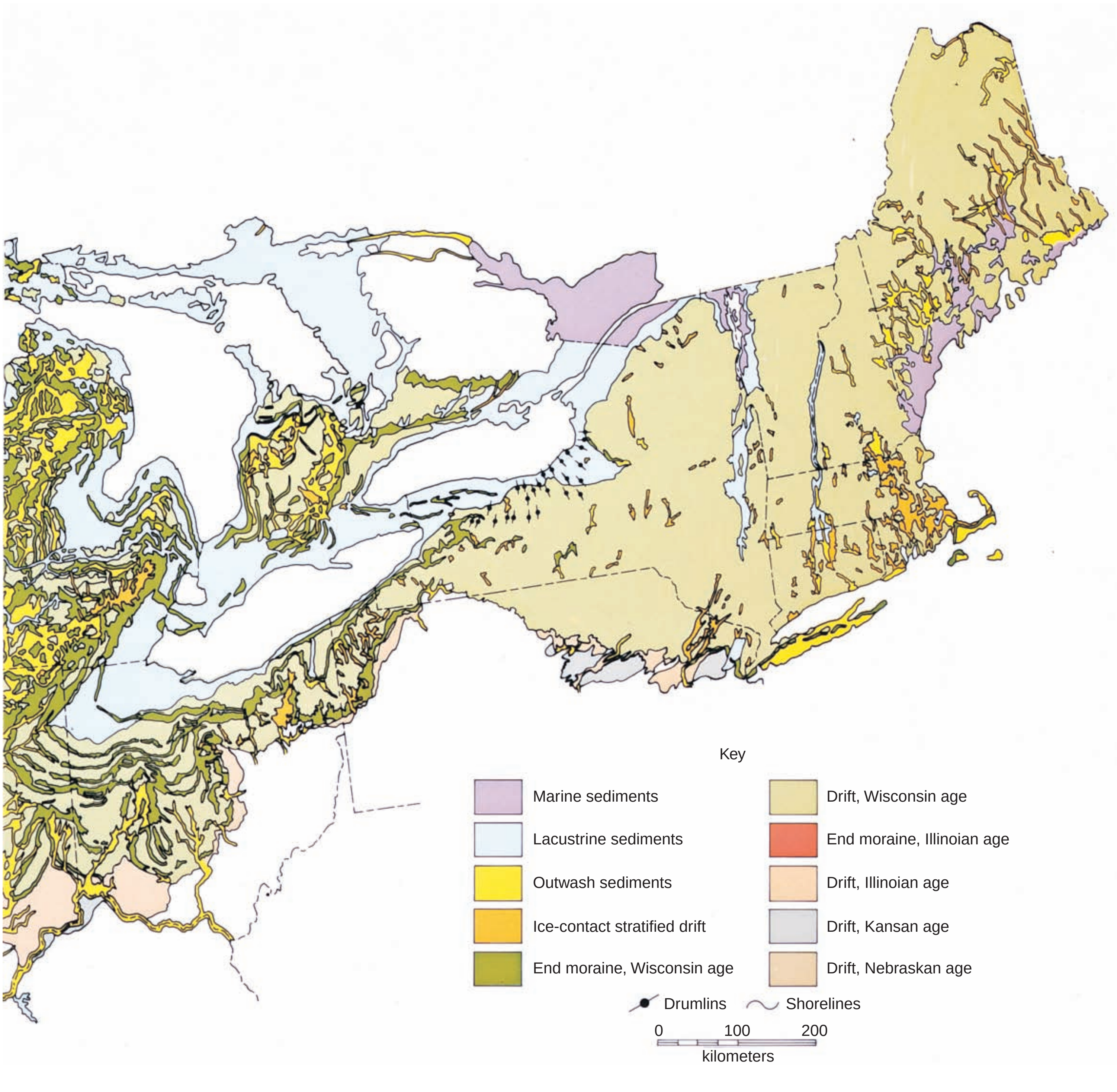
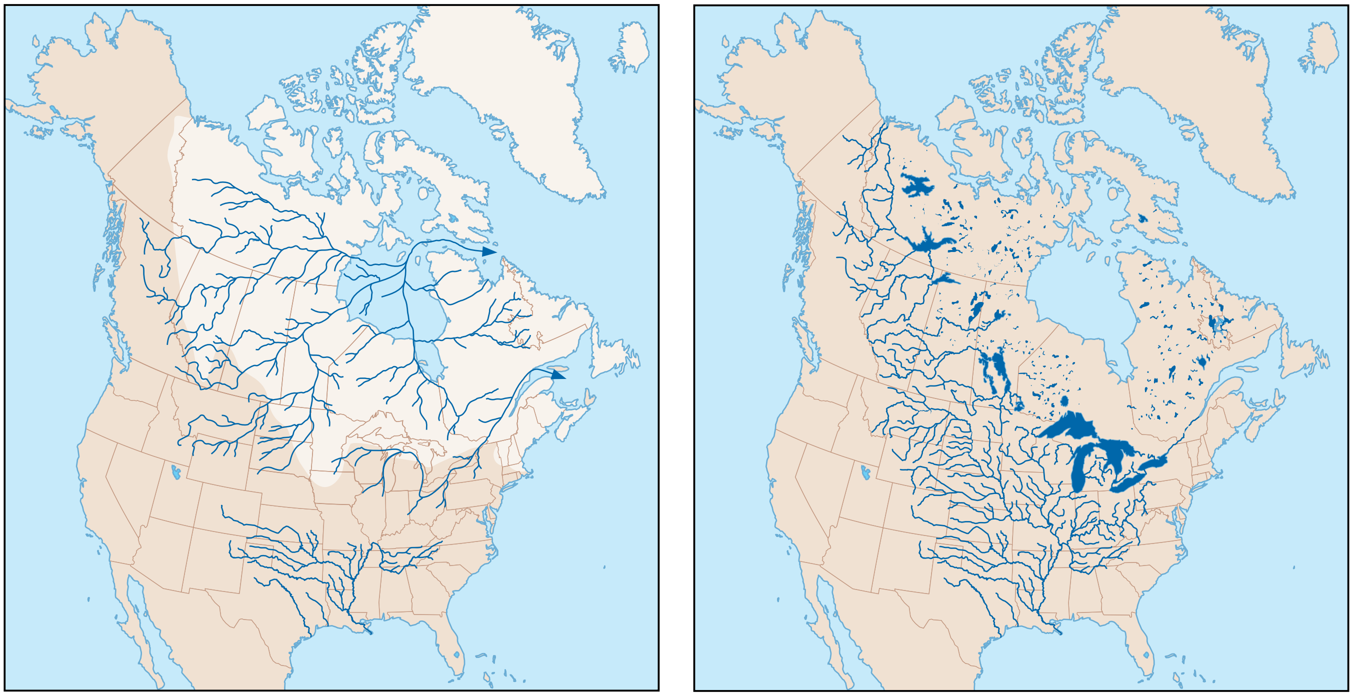


FIGURE 14.27 The major glacial features in the eastern United States have been mapped in considerable detail. They tell a story of repeated advance and retreat of the great ice sheets over much of the north-central part of the United States. Four major periods of glaciation are recorded; each had multiple cycles of expansion and contraction, and all are shown on this map in different colors. The older glacial deposits (Nebraskan, Kansan, and Illinoian) have been modified by erosion and partly covered by the most recent deposits of Wisconsin age (shown in various shades of green). The only part of this area not covered by ice was in southern Wisconsin. It was protected from ice advance by the Wisconsin highlands to the north, which diverted lobes of ice around the area.

The moraines (darker tones) indicate the former positions of the ice margins. Two major lobes of ice moved into the lowlands of the Great Lakes area and another large lobe moved south from the Dakotas and Minnesota and into Iowa. These lobes scoured out the basins, which were filled with



water for large glacial lakes (shown in blue) much larger than the present Great Lakes. In New England, the ice moved southeastward beyond the present coastline and deposited moraines out on the continental shelf; they are now covered with water. Long Island and Cape Cod are the northernmost remnants of this morainal system. Eskers formed in subglacial streams are shown in linear patterns of orange and are especially abundant in Maine. Spillways or meltwater channels, shown in yellow, reveal the drainage system that carried off the meltwater from the ice. Note the major drumlin fields in New York, Wisconsin, and Minnesota, which indicate the direction of ice movement. Isostatic depression of the crust due to the weight of the ice permitted the sea to invade the coast of Maine and large parts of the St. Lawrence lowlands in southern Canada. *(Compiled from glacial map of the United States east of the Rocky Mountains, The Geological Society of America)*



(A) Before the ice age, drainage of central North America was northeastward, from the northern and central Rocky Mountains into the St. Lawrence Bay, Hudson Bay, and the Arctic area. The area eventually covered by ice is shown with the light shading

(B) Present drainage patterns show major modifications. Preglacial drainage was impounded against the glacial margins and developed new outlets to the ocean through the Missouri, Ohio, and Mackenzie rivers. The drainage system beneath the ice was obliterated. The present drainage in most of Canada is deranged, consisting of numerous lakes, swamps, and unintegrated meandering streams.

FIGURE 14.28 **Glacial modification** of North American drainage was extensive and created thousands of lakes.

by both glacial erosion and deposition instead of by running water. Entirely new landscapes covering millions of square kilometers were formed in a relatively short period of geologic time. In addition, the vast bodies of glacial ice affected the Earth well beyond the glacier margins. Directly or indirectly, the effects of glaciation were felt in every part of the globe.

Modification of Drainage Systems. Before glaciation, the landscape of North America was eroded mainly by running water. Well-integrated drainage systems collected runoff and transported it to the ocean. Much of North America was drained by rivers flowing northeastward into Canada because the regional slope throughout the north-central part of the continent was to the northeast. The preglacial drainage patterns are not known in detail. Various features of the present system, however, together with segments of ancient stream channels now mostly buried by glacial sediments, suggest a pattern similar to that shown in Figure 14.28. Before glaciation, the major tributaries of the upper Missouri and Ohio rivers were part of a northeastward-flowing drainage system. This system also included the major rivers draining the Canadian Rockies, such as the Saskatchewan, Athabasca, Peace, and Liard rivers. It emptied into the Arctic Ocean, probably through Lancaster Sound and Baffin Bay, and an eastern drainage was out of the St. Lawrence River.

As the glaciers spread over the northern part of the continent, they effectively buried the trunk streams of the major drainage systems, damming up the northward-flowing tributaries along the ice front. This damming created a series of lakes along the glacial margins. As the lakes overflowed, the water drained along the ice front and established the present courses of the Missouri and Ohio rivers. A similar situation created Lake Athabasca, Great Slave Lake, and Great Bear Lake, and their drainage through the Mackenzie River. This process established the present drainage pattern over much of North America (Figure 14.28). Compare this diagram with Figure 14.16, which shows a drainage system currently undergoing similar modifications as a result of the Barnes Ice Cap.

We can clearly see extensive and convincing evidence of these changes in South Dakota. There, the Missouri River flows in a deep, trenchlike valley, roughly parallel to the regional contours. All important tributaries enter from the west. East of the Missouri River, preglacial valleys are now filled with glacial debris, marking the remnants of preglacial drainage. The pattern of preglacial drainage is also supported by recent discoveries of huge, thick, deltaic deposits in the mouth of Lancaster Sound and in Baffin Bay. These deposits are difficult or impossible to explain as results of the present drainage pattern because no major drainage system currently empties into those areas.

Beyond the margins of the ice, the hydrology of many streams and rivers was profoundly affected, either by the increased flow from meltwater or by the greater precipitation associated with the glacial epoch. With the appearance of the modern Ohio and Missouri rivers, water that formerly emptied into the Arctic and Atlantic oceans was diverted to the Gulf of Mexico through the Mississippi River. Other streams became overloaded and their valleys partly filled with sediment. Still others became more effective agents of downcutting, as a result of glacial sediment, and their valleys deepened. Although the history of each river is complex, the general effect of glaciation on rivers was to produce thick alluvial fill in their valleys; the fill is now being eroded to form stream terraces.

FIGURE 14.29 Lakes created by continental glaciation in the shield area of North America were photographed from a height of approximately 900 km. More lakes were created by glaciation than by all other geologic processes combined. *(Courtesy of Department of Energy, Mines, and Resources, Canada)*

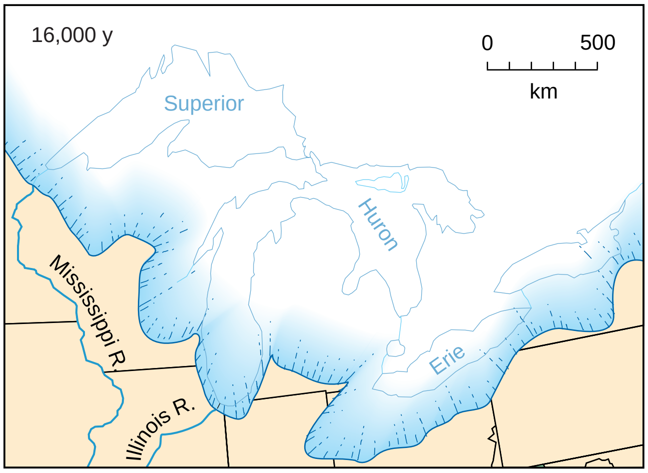
Lakes. Pleistocene glaciation created more lakes than all other geologic processes combined. The reason is obvious if we recall that a continental glacier completely disrupts the preglacial drainage system. The surface over which the glacier moved was scoured and eroded by the ice, leaving myriad closed, undrained depressions in the bedrock. These depressions filled with water and became lakes (Figure 14.29).

Farther south, in the north-central United States, lakes formed in a different manner. There, the surface was covered by glacial deposits of ground moraine and end moraines. Throughout Michigan, Wisconsin, and Minnesota, these deposits formed closed depressions that soon filled with water to form tens of thousands of lakes. Many of these lakes still exist. Others have been drained or filled with sediment, leaving a record of their former existence in peat bogs, lake silts, and abandoned shorelines.

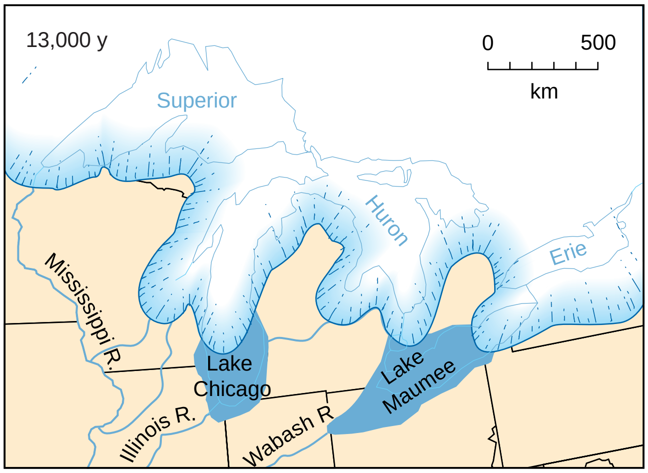
Exceptionally large lakes were created along the glacial margins. We can envision their formation with the help of the basic model of continental glaciation shown in Figure 14.15. The ice on both North America and Europe was about 3000 m thick near the centers of maximum accumulation, but it tapered toward the glacier margins. Crustal subsidence was greatest beneath the thickest accumulation of ice. In parts of Canada and Scandinavia, the crust was depressed more than 600 m. As the ice melted, rebound of the crust lagged behind, producing a regional slope toward the ice. This slope formed basins that have lasted for thousands of years. These basins became lakes or were invaded by the ocean. The Great Lakes of North America and the Baltic Sea of northern Europe were formed primarily in this way.

Although the origin of the Great Lakes is extremely complex, the major elements of their history are known and are illustrated in the four diagrams in Figure 14.30. The preglacial topography of the Great Lakes region was influenced greatly by the structure and character of the rocks exposed at the surface. A geologic map of this region shows that the major structural feature is the Michigan Basin, which exposed a broad, circular belt of weak Devonian shale and Silurian salt formations, surrounded by the more-resistant Silurian limestone. Preglacial erosion undoubtedly formed a wide valley or lowland along the shale, and escarpments developed on the resistant limestone.

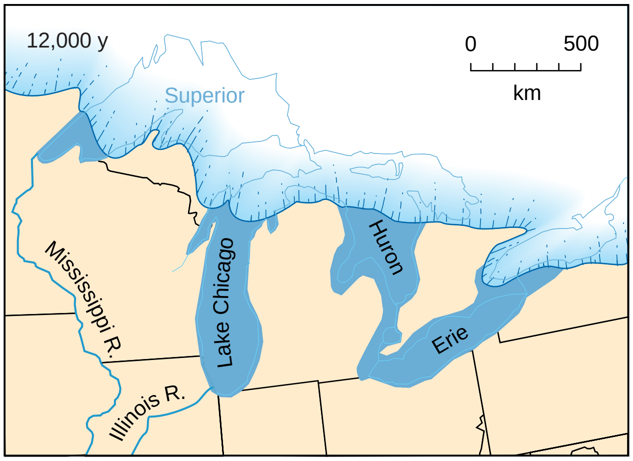
As the glaciers moved southward into this area, large lobes of ice advanced down the great valleys, eroding them into broad, deep basins. Lakes Michigan,



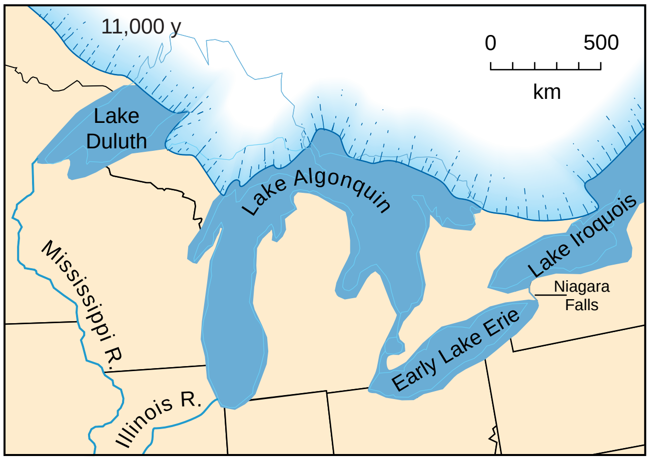
(A) Approximately 16,000 years ago, the ice front extended beyond the present Great Lakes. The ice advanced into lowlands surrounding the Michigan Basin, with large lobes extending down from the present sites of Lakes Erie and Michigan.



(B) The ancestral Great Lakes appeared about 13,000 years ago, as the ice receded. The northern margins of the lakes were against the retreating ice. Drainage was to the south, to the Mississippi River.



(C) As the ice front continued to retreat, an eastern outlet developed to the Hudson River in what is now New York, but the western lakes still drained into the Mississippi.



(D) Niagara Falls originated about 11,000 years ago, when the glacier receded past the Lake Ontario basin, and water from Lake Erie flowed over the Niagara Escarpment into Lake Ontario. The lakes began to assume their present outlines about 10,500 years ago.

FIGURE 14.30 **The evolution of the Great Lakes** can be traced from their origin along the ice margins about 16,000 years ago. The sequence of events and modifications of the landscape are inferred from numerous studies of glacial features in the Great Lakes area.

Huron, and Erie were scoured from the belt of weak Devonian shale by these lobes of ice. Figure 14.30A shows the Great Lakes area as it probably appeared at the time the Wisconsin glaciers began to recede, about 16,000 years ago. Meltwaters flowed away from the glacier margin to the south. As the glaciers receded, lower land was uncovered, and meltwaters became impounded in front of the ice margins to form the ancestral Great Lakes (Figure 14.30B). Drainage was still to the south through various ancient channels that joined the Mississippi River. As deglaciation continued, an eastern outlet was established (Figure 14.30C) through the Mohawk and Hudson valleys. Finally, as the ice receded farther (Figure 14.30D), a new outlet was developed through the St. Lawrence estuary. Niagara Falls came into existence at this time, when water from Lake Erie flowed across the Niagara Escarpment into Lake Ontario. The exposed sequence of rock consists of a resistant limestone formation underlain by a weak shale. Undercutting of the shale below the limestone causes the falls to retreat upstream.

To the northwest, another group of lakes formed in much the same way, but they have since been reduced to small remnants of their former selves. The largest of these marginal lakes, known as Lake Agassiz, covered the broad, flat region of Manitoba, in northwestern Minnesota, and the eastern part of North Dakota (Figure 14.31). It drained into the Mississippi River and then, at lower stages, developed outlets into Lake Superior. Later, when the ice dam retreated, it drained into Hudson Bay. Remnants of this vast lake include Lake Winnipeg, Lake Manitoba, and Lake of the Woods. The sediments deposited on the floor of Lake Agassiz provided much of the rich soil for the wheatlands of North Dakota, Manitoba, and the Red River Valley of Minnesota. Even now, ancient shorelines of Lake Agassiz remain, marking its former margins.

Northward, along the margin of the Canadian Shield, Lake Athabasca, Great Slave Lake, and Great Bear Lake are remnants of the other great ice-marginal lakes. In northern Europe, the recession of the Scandinavian ice sheet caused similar depressions along the ice margins, and the large lakes that were thus produced ultimately connected with the ocean to form the Baltic Sea.

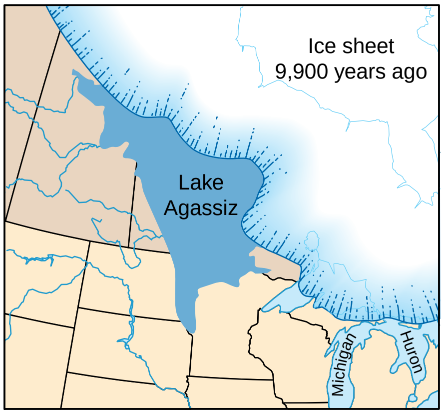


FIGURE 14.31 **Lake Agassiz** was the largest glacial lake in North America. Its former shorelines are now marked by beach ridges, spits, and bars. The dry lake bed now forms the fertile soils of Manitoba and North Dakota. Remnants of this former glacial lake include Lake Winnipeg, Lake Manitoba, and Lake of the Woods. *(After Teller, Canadian Geological Survey)*

Changes of Sea Level. One of the most important effects of Pleistocene glaciation was the repeated worldwide rise and fall of sea level, a phenomenon that corresponded to the retreat and advance of the glaciers. During a glacial period, water that normally returned to the ocean by runoff became locked on the land as ice, and sea level was lowered. When the glaciers melted, sea level rose again. The amount of change in sea level can be calculated because the area of maximum ice coverage is known in considerable detail, and the thickness of the ice can be estimated from the known volumes of ice in the glaciers of Antarctica and Greenland. The Antarctic ice sheet alone contains enough water to raise sea level throughout the world by about 70 m.

The dates of sea level changes are well documented by radiocarbon dates from terrestrial organic matter and from near-shore marine organisms obtained by drilling and dredging off the continental shelf. These dates show that about 35,000 years ago, the sea was near its present position. Gradually, it receded. By 18,000 years ago, it had dropped nearly 137 m. It then rose rather rapidly to within 6 m of its present level. The fall in sea level caused the Atlantic shoreline to recede between 100 and 200 km, exposing vast areas of the continental shelf (Figure 14.25). Early humans probably inhabited large parts of the shelf that are now more than 100 m below sea level.

Sea Level Rise

The glaciers extended far across the exposed shelf of the New England coast, as is evidenced by unsorted morainal debris and the remains of mastodons dredged from the seafloor in those areas. In the oceans off the central and southern Atlantic states, depth soundings reveal drainage systems and eroded stream valleys that extended across the shelf. Great Britain was connected to the European continent during glacial maximums. Moreover, Asia was connected to North America by a land bridge across the Bering Strait allowing humans to migrate on dry land.

Pluvial Lakes. The climatic conditions that caused glaciation had an indirect effect on arid and semiarid regions far removed from the large ice sheets. The increased precipitation that fed the glaciers also increased the runoff of major rivers and intermittent streams, resulting in the growth and development of large **pluvial lakes** (Latin *pluvia,* "rain") in numerous isolated basins in nonglaciated areas throughout the world. Most pluvial lakes developed in relatively arid regions where, prior to the glacial epoch, there was insufficient rain to establish an integrated, through-flowing drainage system to the sea. Instead, stream runoff in those areas flowed into closed basins and formed playa lakes. With increased rainfall, the playa lakes enlarged and sometimes overflowed. They developed a variety of shoreline features—wave-built terraces, bars, spits, and deltas—now recognized as high-water marks in many desert basins. Pluvial lakes were most extensive during glacial intervals. During interglacial stages, when less precipitation

FIGURE 14.32 **Pluvial lakes** were formed in the closed basins of the western United States as a result of climatic changes associated with the glacial epoch. Most are now dry lake beds because of the arid climate. Former shorelines of the pluvial lakes are well marked along the basin margins. Lake Bonneville, in western Utah, was the largest. Great Salt Lake, Utah, is one of its remnants. *(Courtesy of Ken Perry, Chalk Butte, Inc.)*

fell, the pluvial lakes shrank to form small salt flats or dry, dusty playas.

The greatest concentration of pluvial lakes in North America was in the northern part of the Basin and Range Province of western Utah and Nevada. The fault-block structure there has produced more than 140 closed basins, many of which show evidence of former lakes or former high-water levels of existing lakes. The distribution of the former lakes is shown in Figure 14.32. Lake Bonneville was the largest, by far, and occupied a number of coalescent intermontane basins. Remnants of this great body of fresh water are Great Salt Lake and Utah Lake. At its maximum extent, Lake Bonneville was about the size of Lake Michigan, covering an area of 50,000 km^2, and was 300 m deep. The principal rivers entered the lake from the high Wasatch Range, to the east. They built large deltas, shoreline terraces, and other coastal features that are now high above the valley floors along the mountain front (Figure 14.33).

As the level of the lake rose to 300 m above the floor of the valley, it overflowed to the north into the Snake River and thence to the ocean. The outlet, established on unconsolidated alluvium, rapidly eroded down to bedrock, 100 m below the original pass. The level of the lake was then stabilized, fluctuating only with the pluvial epochs associated with glaciation. Some valley glaciers from the Wasatch Range extended down to the shoreline of the old lake, and some of their moraines were carved by wave action. This wave erosion shows conclusively that glaciation was contemporaneous with the high level of the lake. As the climate became drier, the lake dried up, leaving faint shorelines at lower levels.

FIGURE 14.33 **Shoreline features of Lake Bonneville** include deltas, beaches, bars, spits, and wave-cut cliffs. Multiple shorelines were produced as Lake Bonneville dried up. This photograph shows shorelines on Fremont Island, Great Salt Lake, Utah. Note the wave-cut cliffs and terraces at the highest levels.

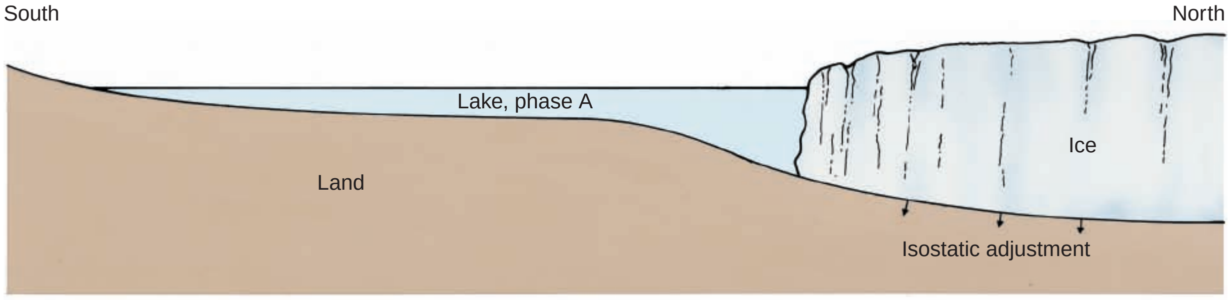
Isostatic Adjustment. Major isostatic adjustments of the lithosphere during the Pleistocene glaciation were caused by the weight of the ice, which depressed the continents. In Canada, a large area around Hudson Bay was depressed below sea level, as was the area in Europe around the Baltic Sea. The land has been rebounding from these depressions ever since the ice melted. The area around Washington's Puget Sound rose at a rate of more than 10 cm/yr shortly after the ice disappeared 13,500 years ago, but the rate slowed to 2 cm/yr by 11,000 years ago. The total uplift in the area is about 150 m. The former seafloor around Hudson Bay has risen almost 300 m and is still rising at a rate maximum rate of about 3.5 cm/yr. The land must rise an additional 80 m before it regains its preglacial level and reestablishes isostatic balance. Some of these isostatic movements triggered large earthquakes in Scandinavia about 9000 years ago. These earthquakes are unique in that they are not associated with plate boundaries.

The tilting of Earth's crust, as it rebounds from the weight of the ice, can be measured by careful surveying and also by mapping the elevations of the shorelines of ancient lakes (Figure 14.34). The shorelines were level when they formed but were tilted as the crust rebounded from the unloading of the ice. In the Great Lakes region, old shorelines slope downward to the south, away from the centers of maximum ice accumulation, indicating a rebound of 400 m or more.

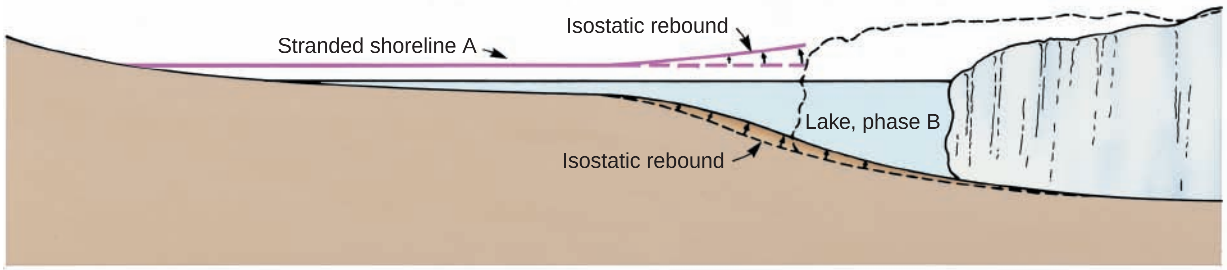
Effects of Winds. The presence of ice over so much of the continents greatly modified patterns of atmospheric circulation. Winds near the glacial margins were strong and unusually persistent because of the abundance of dense, cold air coming off the glacier fields. These winds picked up and transported large quantities of loose, fine-grained sediment brought down by the glaciers. This dust accumulated as **loess** (wind-blown silt), sometimes hundreds of meters thick, forming an irregular blanket over much of the Missouri River valley, central Europe, and northern China.

Sand dunes were much more widespread and active in many areas during the Pleistocene. A good example is the Sand Hills region in western Nebraska, which covers an area of about 60,000 km^2. This region was a large, active dune field during the Pleistocene, but today the dunes are largely stabilized by a cover of grass.

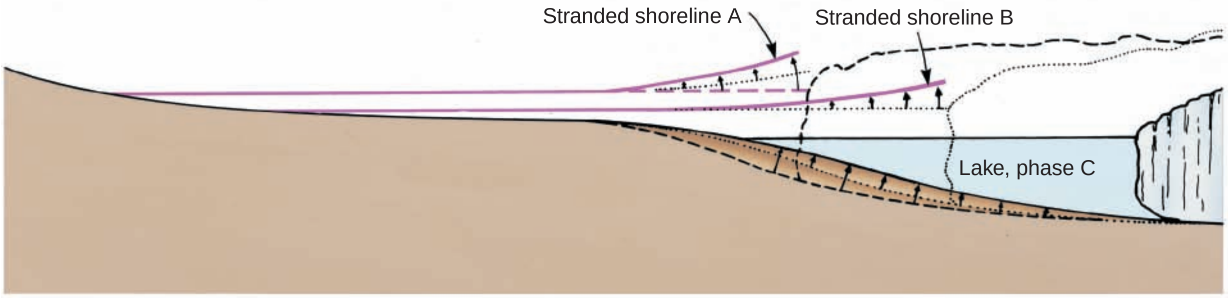
The Oceans. Pleistocene glaciation affected to some extent the waters of all of the oceans. Besides changing the sea level so that shorelines were altered and much



(A) When a lake develops along a glacier's margins, the shoreline features, such as beaches and bars, are horizontal.



(B) As the ice recedes, isostatic rebound occurs. The shoreline features formed during phase A are tilted away from the ice. Younger horizontal shoreline features are formed by the lake during phase B.



(C) Continued retreat of the ice causes further isostatic rebound and tilting of both shorelines A and B, which converge away from the glacier.

FIGURE 14.34 **The tilted shorelines of glacial lakes** can be used to measure the rate and extent of isostatic adjustment of the crust after the ice recedes. *(After R. F. Flint)*

of the continental shelves were exposed, the glacial periods cooled the ocean waters by as much as 10°C. The lower temperatures affected the kind and distribution of marine life and also influenced seawater chemistry. Furthermore, patterns and strengths of oceanic currents were changed. Circulation was significantly restricted by glacially formed features such as the Bering Strait, extensive pack ice, and exposed shelves.

As sea level rose at the end of the last ice age other dramatic events occurred. For example, during the Ice Age the Black Sea became an isolated freshwater lake separated from the salty Mediterranean Sea by a dry strip of land where the Straits of Bosporus are today. But about 7500 years ago, the Mediterranean Sea had risen sufficiently to spill over the barrier and into the Black Sea basin. The "flood" cut a 90 m deep trough and triggered a deluge that flooded the coastal area around the Black Sea.

Even the deep-ocean basins did not escape the influence of glaciation. Where glaciers entered the ocean, icebergs broke off and rafted their enclosed load of sediment out into the ocean. As the ice melted, debris ranging from huge boulders to fine clay settled on the deep-ocean floor, resulting in an unusual accumulation

(A) Scabland channels west of Spokane, Washington.

(B) Giant ripple marks west of Spokane, Washington. *(Courtesy of D. Easterbrook)*

(C) Patterned ground formed by permafrost activity at the end of the glacial period. *(Courtesy of D. Easterbrook)*

FIGURE 14.35 **The Channeled Scablands** of Washington consist of a complex of deep channels cut into the basalt bedrock. The scabland topography is completely different from that produced by a normal drainage system. It is believed to have been produced by "catastrophic" flooding.

of coarse glacial boulders in fine oceanic mud. Ice-rafted sediment is most common in the Arctic, the Antarctic, the North Atlantic, and the northeastern Pacific.

In the warmer reaches of the oceans, the glacial and interglacial periods are recorded by alternating layers of red clay and small calcareous shells of microscopic organisms. The red mud accumulated during cold periods, when fewer organisms inhabited the colder water. During the warmer interglacial periods, life flourished, and layers of shells mixed with mud were deposited.

Channeled Scablands. The continental glacier in western North America moved southward from Canada only a short distance into Washington, but it played an important role in producing a strange complex of interlaced deep channels, a type of topography found nowhere else on Earth. This area, the **Channeled Scablands,** covers much of eastern Washington and consists of a network of braided channels from 15 to 30 m deep. The term *scabland* is appropriately descriptive because,

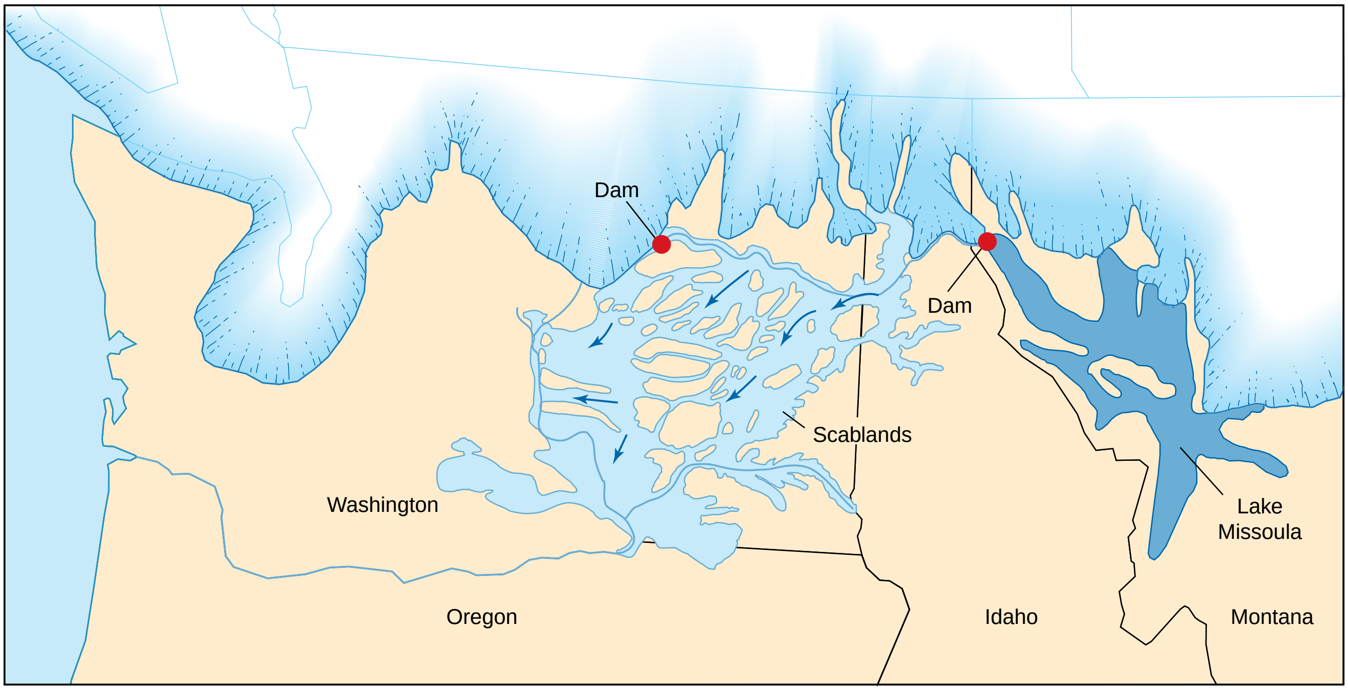
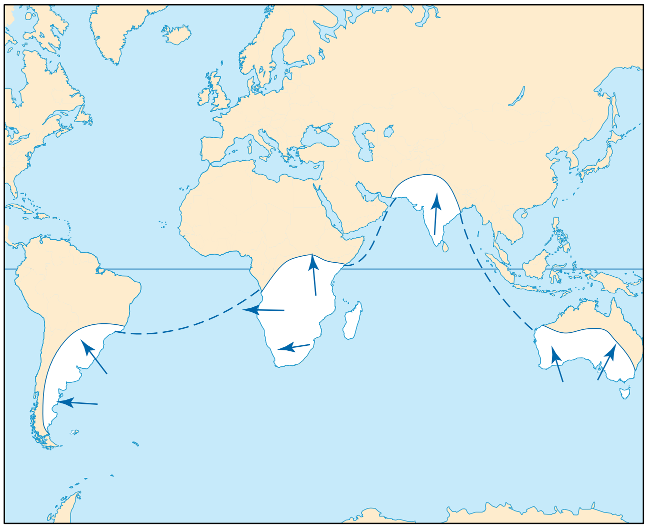


FIGURE 14.36 **The origin of the Channeled Scablands** is attributed to "catastrophic" flooding, on a magnitude apparently unique in Earth's history. The flood resulted when the ice dam that formed glacial Lake Missoula failed as the glacier receded. The ice sheet blocked the drainage of the northward-flowing Clark Fork River to form Lake Missoula, a long, deep lake in western Montana. As the glacier receded, the ice dam that formed Lake Missoula failed, and water from the lake quickly flowed across the Scablands, eroding deep channels. The glacier's repeated advance and retreat probably produced several ice dams that failed as the ice melted, each time causing catastrophic flooding.

viewed from the air, the surface has the appearance of great wounds or scars (Figure 14.35). Many of the channels have steep walls and dry waterfalls or cataracts. In addition, there are sediment deposits with giant ripple marks and huge bars of sand and gravel (Figure 14.35). These features attest to extreme erosion by running water—a catastrophic flooding by normal standards—yet, today the area does not have enough rainfall to maintain a single permanent stream.

The scablands were eroded by the following process. A large lobe of ice advanced southward across the Columbia Plateau and temporarily blocked the Clark Fork River, one of the major northward-flowing tributaries of the Columbia River (Figure 14.36). The impounded water backed up to form glacial Lake Missoula, a long, narrow lake extending diagonally across part of western Montana. Sediments deposited in this lake now partly fill the long, narrow valley. As the glacier receded, the ice dam failed, releasing a tremendous flood over the southwestward-sloping Columbia Plateau. The enormous discharge, barely diverted by the preexisting shallow valleys, spread over the basalt surface, scouring out channels and forming giant ripple marks, bars, and other sediment deposits. Estimates suggest that, during the flood, as much as 40 km^3 of water per hour may have been discharged from Lake Missoula. Because the glaciers advanced several times into the region, such catastrophic flooding probably occurred many times, perhaps as far back as 2.5 million years ago. Lake Missoula formed each time the ice front advanced past the Clark Fork River and then flooded the Scablands with each recession of the ice and subsequent dam failure.

Biological Effects of the Ice Age. The severe climatic changes during the ice age had a drastic impact on most life forms. With each advance of the ice, large areas of the continents (the areas beneath the ice) became totally depopulated, and plants and animals retreating southward in front of the advancing glacier were under tremendous stress. The most severe stresses resulted from drastic climatic changes, reduced living space, and a curtailed food supply. As the glaciers



(A) This map shows the areas covered by ice during the late Pennsylvanian and the Permian periods and the direction of ice movement.

(B) The glacially striated bedrock in southern Australia has been exposed by erosion of overlying sedimentary strata. The striations originally formed in the late Paleozoic.

FIGURE 14.37 **Late Paleozoic glaciation** is well documented in southern continents by deposits of glacial sedimentary rocks, striated bedrock surfaces, and other glacial features.

advanced, most species were displaced, along with their environments, across distances of approximately 3200 km. As the ice retreated, some new living space became available in deglaciated areas, but the formerly exposed continental shelves were inundated by the rising sea. During the major glacial advances, when sea level was lower, new routes of migration opened from Asia to North America, because much of Alaska and Siberia were not glaciated (see Figure 14.25), and from Southeast Asia to the islands of Indonesia. Land plants were forced to migrate with the climatic zones in front of the glaciers. As the glaciers pushed cold-weather belts southward, displaced storm tracks and changes in precipitation affected even the tropics.

Many life forms could not cope with the repeated and overwhelming environmental changes brought about by the cycles of advancing and retreating ice. Numerous species, particularly giant mammals, became extinct. During glaciation, the now-extinct imperial mammoth, 4.2 m high at the shoulders, roamed much of North America. The saber-toothed tiger became extinct about 14,000 years ago. Fossils of the giant beaver, as large as a black bear, and the giant ground sloth, which measured 6 m tall standing on its hind legs, have been found in Pleistocene sediments. In Africa, fossil sheep 2 m tall have been found, in addition to pigs as big as a present-day rhinoceros. In Australia, giant kangaroos and other marsupials thrived during the Pleistocene.

RECORDS OF PRE-PLEISTOCENE GLACIATION

Glaciation has been a rare event in Earth's history, but there is evidence of widespread glaciation during late Paleozoic time (200 to 300 million years ago) and during late Precambrian time (600 to 800 million years ago).

Before the great ice age, which began 2 to 3 million years ago, Earth's climate was typically mild and uniform for long periods of time. This climatic history is implied by the types of fossil plants and animals and by the characteristics of sediments preserved in the stratigraphic record. There are, however, widespread glacial deposits—unsorted, unstratified debris containing striated and faceted cobbles and

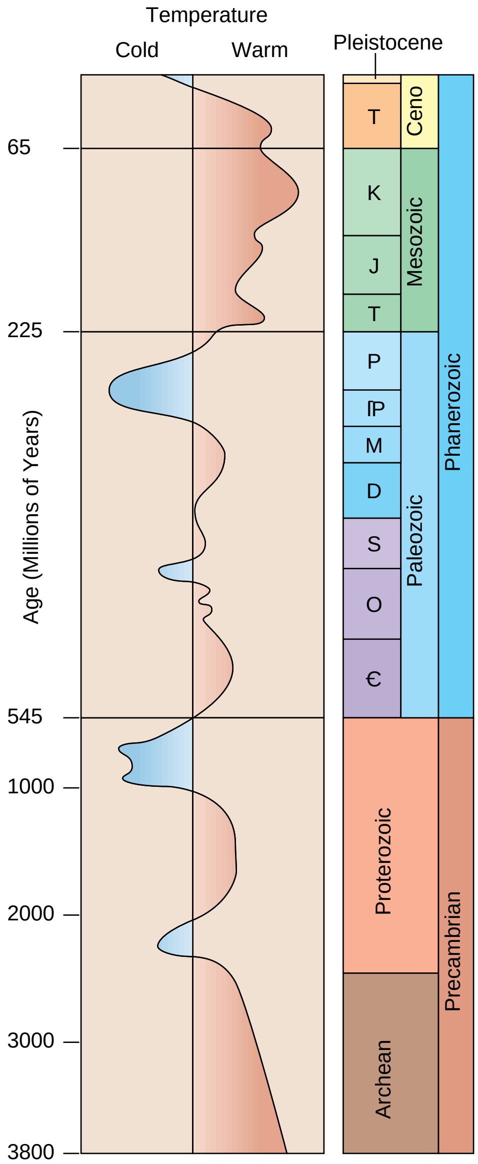


FIGURE 14.38 Several periods of glaciation have been identified in Earth's long history that may record changes in the surface temperature. The graph shows one estimate of relative temperature changes with time. The curve shows when temperatures were higher (to the right) or lower (to the left) than today.

boulders—recording several major periods of ancient glaciation in various parts of the geologic record. These glacial deposits commonly rest on striated and polished bedrock, and they are associated with varved shales and with sandstones and conglomerates that are typical of outwash deposits. Such evidence implies several major periods of glaciation prior to the last ice age.

The best-documented record of pre-Pleistocene glaciation is found in late Paleozoic rocks (formed 200 to 300 million years ago) in South Africa, India, South America, Antarctica, and Australia. Exposures of ancient glacial deposits are large and numerous in these areas, many resting on a striated surface of older rock (Figure 14.37). Deposits of even older glacial sediment exist on every continent but South America. These indicate that two other periods of widespread glaciation occurred during late Precambrian time (Figure 14.38).

Small bodies of glacial sediment from other geologic periods have been found in local areas, but they are not nearly as well documented or as widespread as the Precambrian and Late Paleozoic deposits. Glaciation, therefore, has been a relatively rare phenomenon and has not occurred in regular cycles throughout Earth's long history. Glacial epochs must require a special combination of conditions, which has occurred only a few times in the 4.5 billion years of Earth's history.

CAUSES OF GLACIATION

No completely satisfactory theory has been proposed to account for Earth's history of glaciation. The cause of glaciation may be related to several simultaneously occurring factors, such as astronomical cycles, plate tectonics, atmospheric composition, and ocean currents.

Although the history of Pleistocene glaciation is well established and the many effects of glaciation are clearly recognized, we do not know with complete certainty why Earth's climate changes and why glaciation takes place. For more than a century, geologists and climatologists have struggled with this problem, but it remains unsolved. An adequate theory of glaciation must account for the following facts:

1. During the last ice age, repeated advances of the ice in North America and northern Europe were separated by interglacial periods of warm climate (Figure 14.39).
2. Glaciation is an unusual event in Earth's history. Widespread glaciation also occurred at the end of the Paleozoic Era, 200 to 300 million years ago, and during late Precambrian time, approximately 700 million years ago (Figure 14.38).
3. Throughout most of Earth's history, the climate was milder and more uniform than it is now. Several lines of evidence suggest that the global average temperature was about 22°C throughout much of Earth's history. Today the global average is only about 14°C. A period of glaciation would require a lowering of Earth's present average surface temperature by about 5°C.
4. Continental glaciers grow on elevated or polar land masses that are situated so that storms bring moist, cold air to them. Glaciers can move into lower latitudes, but they originate in highlands or in high latitudes. Greenland and Antarctica provide favorable topographic conditions today, as do the Labrador Peninsula, the northern Rocky Mountains, Scandinavia, and parts of the Andes Mountains.
5. Precipitation is critical to the growth of glaciers. A number of areas are cold enough at present to produce glaciers but do not have sufficient snowfall to develop glacial systems.

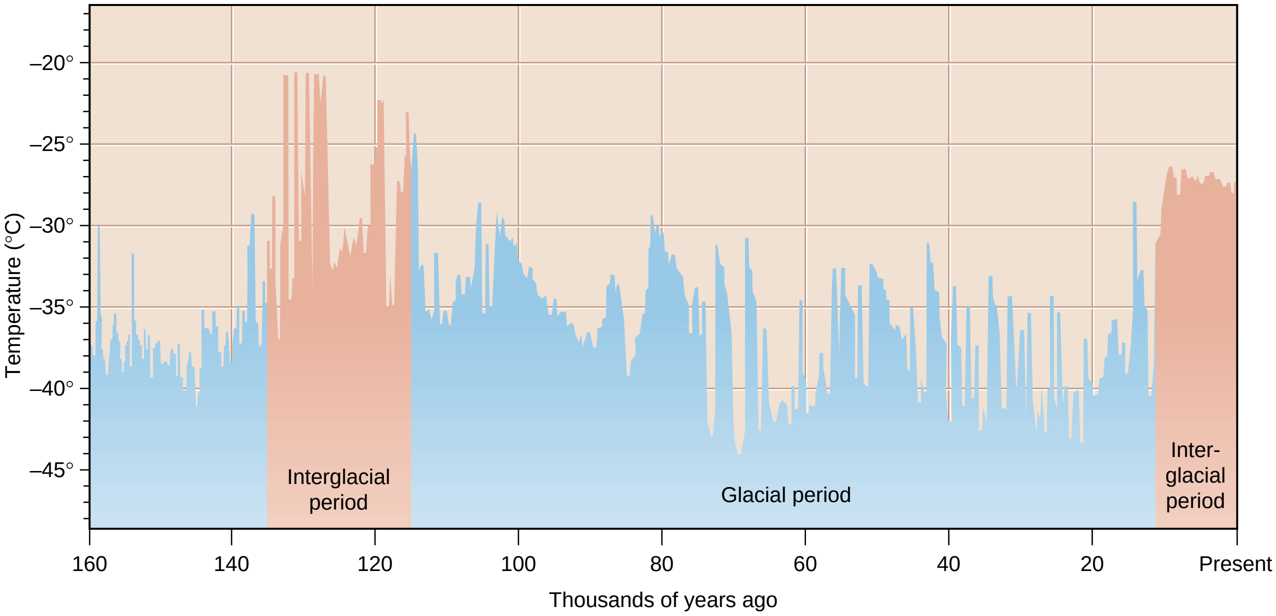


FIGURE 14.39 **A record of climatic change during the last 160,000 years** was assembled from studies of ice cores from Greenland's glacier. It shows that the normal pattern of change involves numerous rapid fluctuations in temperature—not only during glacial periods, but throughout interglacial periods as well. The stable warm temperature of the present interglacial period is distinctly abnormal.

Many hypotheses for the causes of climate change have been proposed. Some suggest that variations in the Sun's energy output could account for the ice ages. However, glaciation is cyclical and cannot be related to simple long-term cooling. Moreover, our present understanding of the Sun's luminosity holds that it should have progressively increased, not decreased, over the course of Earth's history. Still others argue that volcanic dust injected into the atmosphere shielded Earth from the Sun's rays and initiated an ice age. However, no correlation between volcanic activity and the start of the last ice age has been found.

It has been known for some time that Earth's orbit around the Sun changes periodically, cyclically affecting the amount of solar radiation that reaches Earth. The role of Earth's orbital changes in controlling climate was first advanced by James Croll in the late 1800s. Later, Milutin Milankovitch, a Serbian geophysicist, elaborated on the theory and convincingly calculated that these irregularities in Earth's orbit could cause the climatic cycles now known as **Milankovitch cycles.** They are the result of the additive behavior of several types of cyclical changes in Earth's orbital properties. Changes in the *eccentricity* (a measure of the noncircularity) of Earth's orbit occur in a cycle about 96,000 years long. The *inclination,* or tilt, of Earth's axis varies periodically between 22° and 24.5°. The tilt of Earth's axis, of course, causes the seasons: The greater the tilt, the greater the contrast between summer and winter temperatures. Changes in the tilt occur in a cycle 41,000 years long. Also, Earth wobbles on its spin axis and completes one wobble, or *precession,* every 21,700 years. According to the Milankovitch theory, these astronomical factors cause a periodic cooling of Earth, with the coldest part in the cycle occurring about every 40,000 years (Figure 14.40). The main effect of the Milankovitch cycles is to change the contrast between the seasons and not to change the amount of solar heat delivered to Earth. These cycles within cycles predict that during maximum glacial advances, winter temperatures are milder but so too are summer temperatures. As a result, less ice is melted than is received and a glacier may build up.

Milankovitch worked out the ideas of climatic cycles in the 1920s and 1930s, but it was not until the 1970s that a sufficiently long and detailed chronology of the Pleistocene temperature changes was worked out to test the theory adequately. A correspondence between astronomical cycles and late Cenozoic climate fluctuations

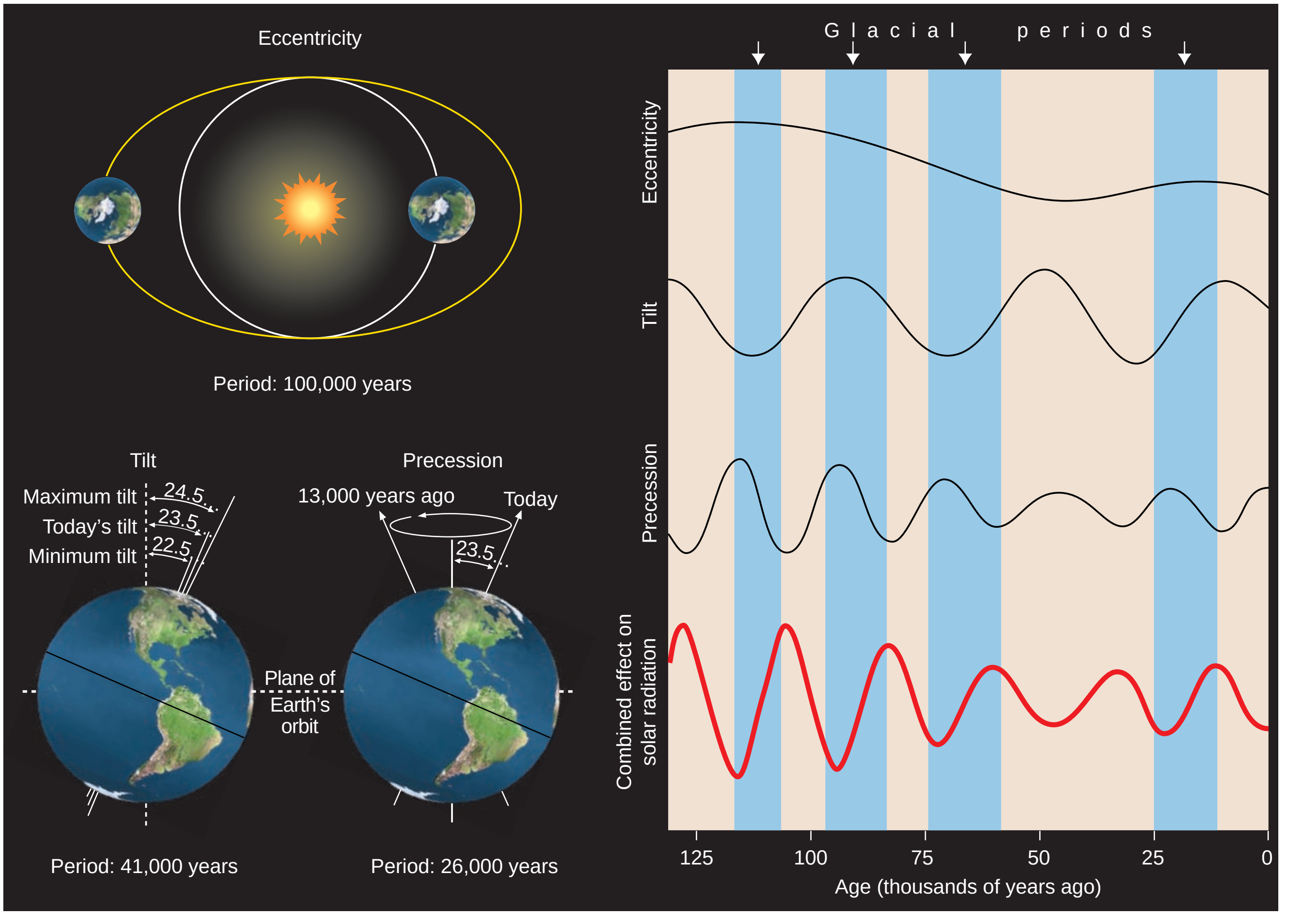


FIGURE 14.40 **Milankovitch climate cycles** are caused by periodic changes with time in Earth's orbital elements, including orbital eccentricity, obliquity or tilt of the spin axis, and precession or wobble of the spin axis. When all of these cycles are added together, they affect the seasonal differences in temperature on Earth. The total solar radiation at 65° N is shown as an example. The principal periods of glaciation as defined from the continents, seafloor sediments, and polar ice cores are also shown.

now seems clear. Furthermore, studies of deep-sea cores, and the fossils contained in them (see page 140), indicate that the fluctuation of climate during the last few hundred thousand years is remarkably close to that predicted by Milankovitch.

A problem with this theory is that the astronomical cycles have been in existence for billions of years. We might expect that glaciation would have been a cyclic event throughout geologic time, instead of a rare occurrence (Figure 14.38). Other factors must also be involved that caused Earth's temperature to drop below a critical threshold. Once the temperature is low enough, Milankovitch cyclicity will act as an ice age pacemaker, forcing the planet into and out of glacial epochs.

An attractive theory holds that decreases in atmospheric carbon dioxide, an important greenhouse gas, started the long-term cooling trend that eventually led to glaciation. Recent studies of the carbon dioxide content of gas bubbles preserved in the Greenland ice cap lend support to this idea. High carbon dioxide contents correspond to warm interglacial periods, and low carbon dioxide to glacial epochs. Similarly, conclusions drawn from our current understanding of the geochemical cycle of carbon indicate a greater than 10-fold decrease in atmospheric carbon dioxide since the middle of the Mesozoic Era (Figure 14.41). However, we must still ask: Is this decline the cause of global cooling or is it the result? What caused the carbon dioxide levels to decline?

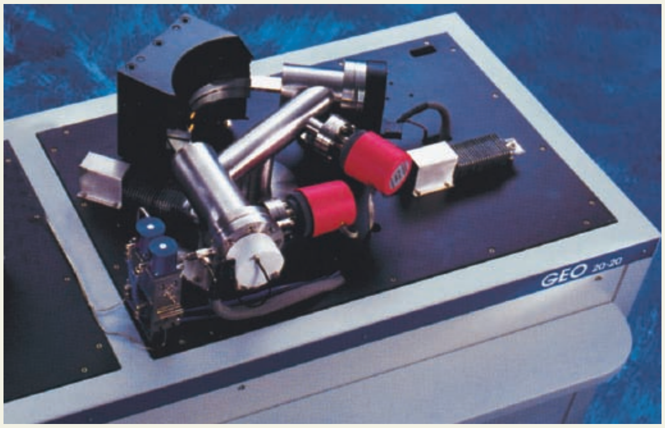
Another important component of the cause for the long-term temperature drop (Figure 14.38) may be related to the positions of the continents, relative to the

STATE OF THE ART — Mass Spectrometry and Earth's Climate

Many of the speculations about the cause of climate variations are rooted in highly specialized geochemical studies. Earth's changing climate has been tracked using tiny marine fossils and a sophisticated instrument called a mass spectrometer. Tiny marine animals secrete shells made of calcium carbonate ($CaCO_3$) by extracting ions of Ca^{+2} and CO_3^{-2} from seawater. The oxygen in the carbonate is in equilibrium with the oxygen isotopic ratio of the surrounding seawater. The isotopic composition of seawater is in turn controlled by the amount of ice on the continents. This is so because light isotopes of oxygen are preferentially evaporated from the ocean to enter the atmosphere and eventually fall as snow on the continents. Thus, during periods of glaciation, the light isotopes of oxygen are extracted and locked into ice. Consequently, the remaining seawater becomes richer in the heavy isotopes of oxygen during periods of glaciation. By analyzing the ratio of the heavy (^{18}O) to light (^{16}O) oxygen isotopes in the fossils, geologists are able to estimate the amount of ice on the continents—a neat trick indeed. The higher the $^{18}O/^{16}O$ ratio in the fossils, the higher the amount of ice on the continents and the lower the paleotemperature.

Samples containing these tiny fossils are collected from the seafloor when researchers on a ship drill cores through the uppermost layers of sediment. Paleontologists carefully extract the fossil shells from each layer. They are able to determine the age of each layer using the principle of faunal succession. In the laboratory, the shells from each layer are treated to release carbon dioxide gas. This gas is collected in a glass tube and then released into a mass spectrometer, which measures the ratio of the oxygen isotopes to one another.

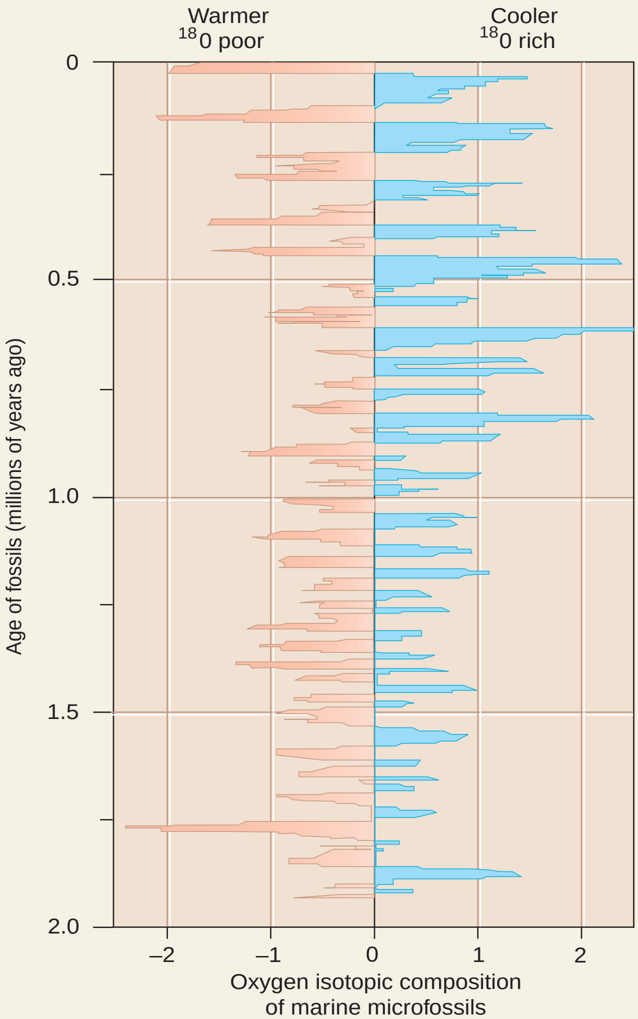
As the name implies, a mass spectrometer is able to separate the isotopes in the gas sample according to their masses (atomic mass is the sum of the protons and neutrons). Specifically, it measures the ratio of the heavy to the light isotopes of oxygen. This ratio is exactly what we need to know to reconstruct Earth's glacial history.



(Courtesy PDZ Europa Ltd.)

But how does the mass spectrometer do this? In our case, the carbon dioxide gas is heated so that it ionizes—loses an electron and becomes charged. Once the ion is charged, it is accelerated by a magnetic field down a curved metal tube less than one meter long. Magnets along the tube bend the path of the individual ionized particles. The paths of the heavy isotopes are not as easily bent as the paths of the light isotopes, and separation occurs. Ion detectors are placed at the end of the tube and record the numbers of each ion that strike it. By comparing the counts on two detectors, the isotope ratio is calculated.

We now have the information needed to construct a climate variation curve. By plotting (1) the age of the fossil and (2) its isotopic composition, we create a curve that shows the changing amount of ice on the continents. Each bend to the right is a cool period with much ice on the continent; a bend to the left is a warmer interglacial period with little ice on the continents. We can verify these climate curves by performing the same kind of analysis in widely separated parts of the ocean. What a story is told by the isotope ratios in these tiny fossils.



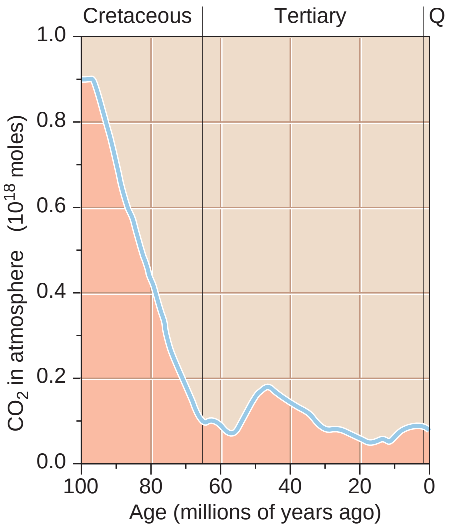


FIGURE 14.41 The abundance of carbon dioxide in Earth's atmosphere has declined dramatically during the last 100 million years. Loss of this important greenhouse gas may have allowed Earth to cool enough for glaciers to accumulate.

poles. This relation can control the circulation of the oceans and atmosphere, affecting how ocean currents carry heat to high latitudes. Here again, the theory of plate tectonics helps to explain how Earth's systems operate. Throughout most of geologic time, the North Pole appears to have been in a broad, open ocean that allowed major ocean currents to move unrestricted. Equatorial waters flowed into the polar regions, warming them with water from more temperate latitudes. This unrestricted circulation produced mild, uniform climates that persisted throughout most of geologic time.

Throughout the Cenozoic Era, the large North American and South American continental plates moved westward from the Eurasian plate. This drift culminated in the development of the Atlantic Ocean, trending north–south, with the North Pole in the small, nearly landlocked basin of the Arctic Ocean. The Isthmus of Panama developed at a convergent plate margin about 4 million years ago, and further separated oceanic circulation and created the Pacific and Atlantic oceans. Meanwhile, Antarctica had drifted over the South Pole and a strong circumpolar current developed in the surrounding ocean. This current prevented Antarctica from exchanging heat with the tropics. By about 40 million years ago, dramatic cooling started in Antarctica and by about 20 million years ago, glaciation began on that continent. The ages of volcanoes on glaciated basement rocks, and evidence from deep-sea cores in the southern oceans, strongly suggest that glaciation in the Antarctic began long before the Pleistocene and has continued ever since.

Plate tectonics may have also caused other important changes in Earth's climate. While the Arctic Ocean became enclosed and surrounded by continents, the Rocky Mountains and the Himalayas rose. These mountains may have altered the flow of the atmosphere and, according to computer models, could have created a colder climate in the Northern Hemisphere. Plate tectonics may even provide an explanation for the drop in the abundance of carbon dioxide during the last 60 million years. The process may have begun with the rise of the high Himalaya mountains. Uplift and erosion exposed large volumes of rock to weathering. As weathering attacked the silicates, many ions went into solution. When feldspar weathers, calcium ions go into solution and are carried by rivers to the oceans. Once in the oceans, calcium may have combined with dissolved carbon dioxide to make limestone; in essence fossilizing part of the atmosphere's carbon dioxide. Over the course of millions of years of weathering and carbonate deposition, the carbon dioxide levels may have dropped (Figure 14.41). As carbon dioxide was cleared from the air, the greenhouse effect was also diminished and Earth's climate cooled.

As can be seen, there are many variables in the interactions of climate, atmospheric composition, the circulation of the oceans, and plate tectonics that could have helped cause the ice ages. No single causative agent has been identified. Apparently, an ice age occurs because of several simultaneously occurring factors. The Pleistocene glaciation appears to have had two major underlying causes. One is related to a gradual long-term drop in global temperature. The most likely causes may be plate tectonic movements and a drop in atmospheric carbon dioxide, but the two may be intertwined. A second cause is needed to explain the waxing and waning of the glacial epochs on short time scales. Milankovitch cycles seem to provide appropriately timed changes.

When Will the Next Ice Age Start?

The next ice age seemed imminent, when paleoclimatologists met in 1972 to discuss this question. The previous interglacial periods seemed to have lasted about 10,000 years each. Assuming that the present interglacial period would be just as long, they concluded that "it is likely that the present-day warm epoch will terminate relatively soon *if man does not intervene*." Since 1972 our understanding of the climate system has improved. We know now that not all interglacial periods are of the same length and that solar heating varies in an irregular fashion forced by Milankovitch orbital changes. But we also know that greenhouse gases are increasing in concentration with each passing year. What will be their effect on the onset of the next ice age? Predicting next week's weather is so hard you may think predicting temperatures thousands of years in the future is impossible. But based on the variations in solar heating and on the amount of carbon dioxide in the atmosphere, some calculations of future temperatures have been made (Figure 14.42) According to these estimates, the interglacial period we are in now may persist for another 50,000 years. That is, if carbon dioxide levels increase to 750 ppm. Right now, the concentration of carbon dioxide in the atmosphere is only about 370 ppm, but it is rising rapidly as people continue to burn fossil fuels (Chapter 9). If carbon dioxide in the atmosphere drops instead, then the next glacial epoch may be only 15,00 years away.

In addition, recent studies of seafloor sediments and cores from glaciers around the world, especially the Greenland glacier, indicate that climatic change is anything but smooth. The long cores drilled from the ice yield information about atmospheric gases, temperature, precipitation, wind, and volcanic activity. Scientists can count the annual layers of ice, just as tree rings are counted, but the ice layers contain much more information than do tree rings. They can preserve elemental carbon from forest fires and datable layers of ash from volcanic eruptions. But the unique feature of ice cores is that they contain actual samples of Earth's ancient atmosphere. According to studies of the oxygen isotopic composition of the ice in these cores, the change from warm to frigid temperatures can occur in a decade or two. Moreover, the ice cores show that an ice age is not uniformly cold, nor are interglacial periods uniformly warm. Analysis of ice cores of the entire thickness of the Greenland Glacier shows that the climate over the last 250,000 years has changed frequently and abruptly (Figure 14.39). The present interglacial period (the last 8000 to 10,000 years) has been fairly stable and warm, but the previous one was interrupted by numerous frigid spells lasting hundreds of years. If the previous period was more typical than the present one, the period of stable climate in which humans flourished—inventing agriculture and thus civilization—may have been possible only because of a highly unusual period of stable temperature.

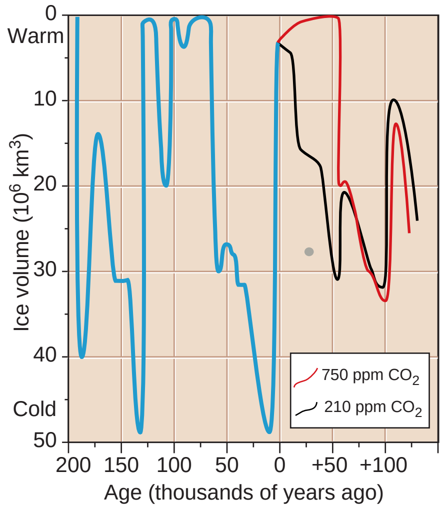
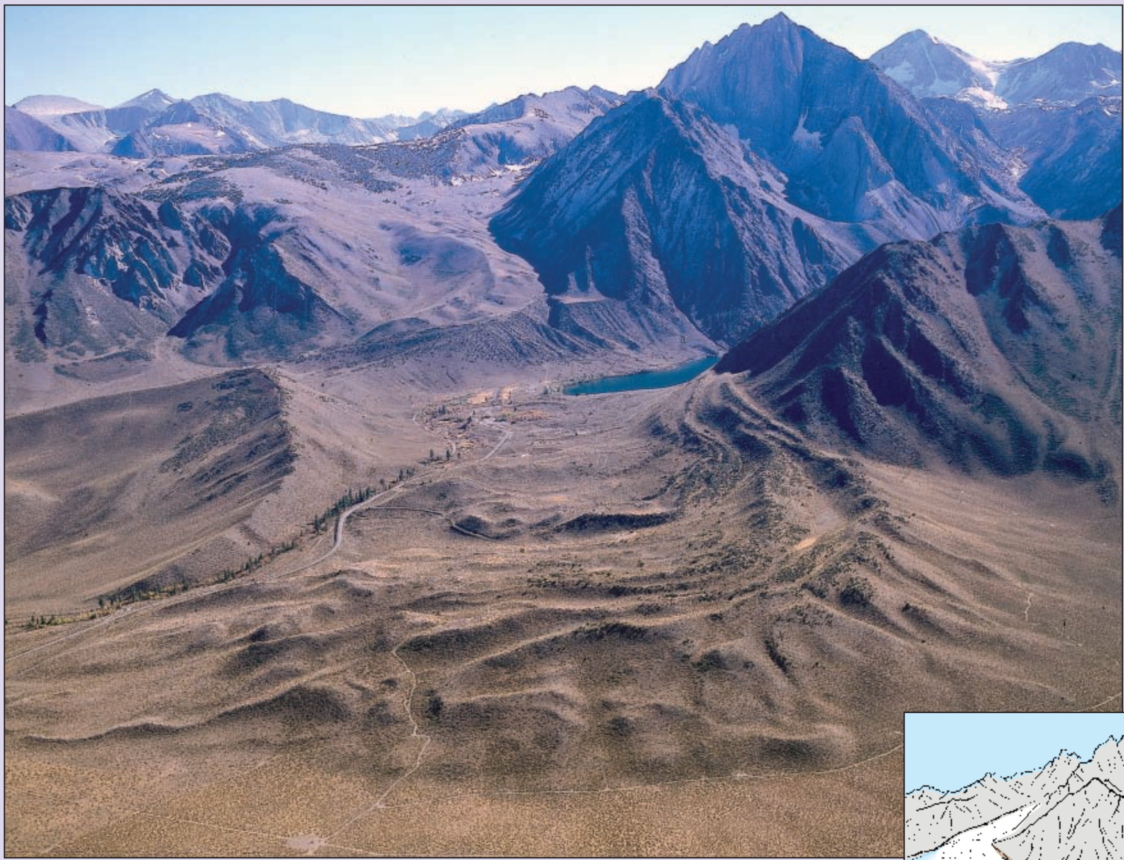
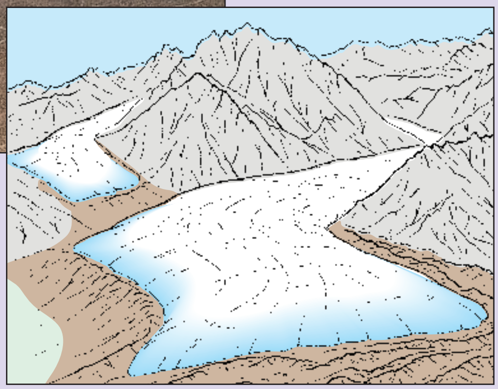


FIGURE 14.42 An exceptionally long interglacial period may be in store if these calculations are correct. Computer models using the amount of solar heating (as controlled by Milankovitch orbital variations) and the amount of carbon dioxide, predict that the next glacial period may begin about 50,000 years from now (red line assuming a concentration of 750 ppm CO_2) or as soon as 15,000 years from now (if CO_2 drops to 210 ppm, black line).

GeoLogic Glaciation in the Sierra Nevada





John Muir (1838-1914) was the one of the first to suggest that the Sierra Nevada range of eastern California had been extensively glaciated. Originally, his claims were met with skepticism, especially by J.D. Whitney, then the state geologist of California. How could the sunny state of California have sustained glaciers? Now 130 years later, few doubt Muir's claims. Look at this photograph to see what evidence you can find of a former period of glaciation.

Observations

1. A U-shaped mountain valley set amid a distinctive mountainous terrain marked by horns and hanging valleys.
2. Linear trails of sediment along the valley walls join arcuate ridges of sediment at the mouth of the canyon.
3. The sedimentary deposits are made of till–unstratified and poorly sorted.

Interpretations

The logical conclusion that glaciers shaped this landscape was made by comparing it with modern glaciated regions. Horns and hanging valleys flank U-shaped valleys that are still filled with flowing masses of glacial ice. Mounds of till have accumulated at the end of the glaciers. In Muir's words, *"The main lateral moraines that extend from the jaws of the amphitheater...are continued in straggling masses along the walls of the amphitheater, while separate boulders, hundreds of tons in weight, are left stranded here and there out in the middle of the channel."* All that was missing was the ice.

Here, we have reconstructed an ancient glacier that carved this valley in the Sierra Nevada Mountains of California, then transported the material and dropped it in arcuate ridges at the terminus of the glacier. Such evidence helps to show that Earth is coming out of a frigid glacial epoch that peaked 18,000 years ago.

KEY TERMS

abrasion (p. 381)
arête (p. 388)
Channeled Scablands (p. 409)
cirque (p. 388)
compressing flow (p. 378)
continental glacier (p. 375)
crevasse (p. 379)
drumlin (p. 397)
end moraine (p. 388)
erratic (p. 397)
esker (p. 397)
extending flow (p. 378)
glacial plucking (p. 381)
glacial striation (p. 382)
ground moraine (p. 397)
hanging valley (p. 388)
horn (p. 388)
kettle (p. 397)
lateral moraine (p. 384)
loess (p. 407)
medial moraine (p. 384)
Milankovitch cycles (p. 413)
moraine (p. 384)
outlet glacier (p. 392)
outwash plain (p. 388)
Pleistocene Epoch (p. 399)
pluvial lake (p. 405)
recessional moraine (p. 388)
roche moutonnée (p. 382)
snow line (p. 374)
terminal moraine (p. 388)
till (p. 397)
valley glacier (p. 375)
varve (p. 397)
zone of ablation (p. 374)
zone of accumulation (p. 374)

REVIEW QUESTIONS

1. Describe the processes by which snow is transformed into glacial ice.
2. Draw a cross section of a typical valley glacier, and explain how a valley glacial system operates.
3. Contrast compressing and extending flow in a glacier. What part of a glacier is dominated by each type of flow?
4. Which moves faster, the base of a glacier or the ice near the surface? Why? What evidence supports your answer?
5. Why is the flow of glacial ice laminar instead of turbulent as the flow of water in streams?
6. Sketch a model of a continental glacial system and explain how it operates.
7. Explain the processes by which glaciers erode the surface over which they flow.
8. Name and describe landforms produced by valley glaciers.
9. Make a sketch map of North America showing the extent of the ice sheet during Pleistocene time.
10. Briefly describe the major effects, both direct and indirect, of Pleistocene glaciation.
11. Explain the origin of the Channeled Scablands.
12. Compare and contrast the origins of Lake Michigan and the Great Salt Lake.
13. List several hypotheses for the causes of continental glaciation.
14. Explain the origin of Hudson Bay.
15. Why did sea level change during each period of advance and retreat of the ice?
16. Explain the origin of the present course of the Missouri River.
17. Study Figure 14.26 and explain why the terminal moraines occur in a series of lobate patterns rather than in a straight line.
18. How do geologists measure isostatic adjustments of the crust that result from glaciation?
19. Why did a large number of lakes develop in the arid part of the western United States during each major advance of the ice during the Pleistocene ice age?
20. List the periods of major pre-Pleistocene glaciation that are well documented in the geologic record.

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MULTIMEDIA TOOLS

Earth's Dynamic Systems Website
The Companion Website at **www.prenhall.com/hamblin** provides you with an on-line study guide and additional resources for each chapter, including:

- On-line Quizzes (Chapter Review, Visualizing Geology, Quick Review, Vocabulary Flash Cards) with instant feedback
- Quantitative Problems
- Critical Thinking Exercises
- Web Resources

Earth's Dynamic Systems CD
Examine the CD that came with your text. It is designed to help you visualize and thus understand the concepts in this chapter. It includes:

- Animations of the flow of glacial ice
- Video clips of glacial processes
- Slide shows with examples glacial landforms
- A direct link to the Companion Website