CHAPTER 12

# Glaciers and Glaciation



In chapters 9, 10, and 11, you have seen how the surface of the land is shaped by mass wasting, running water and, to some extent, ground water. Running water is regarded as the erosional agent most responsible for shaping Earth's land surface. Where glaciers exist, however, they are far more effective agents of erosion, transportation, and deposition. Geologic features characteristic of glaciation are distinctly different from the features formed by running water. Once recognized, they lead one to appreciate the great extent of glaciation during the recent geologic past (that age popularly known as the Ice Age).

Immense and extensive glaciers, covering as much as a third of Earth's land surface, had a profound effect on the landscape and our present civilization. Moreover, worldwide climatic changes during the glacial ages distinctively altered landscapes in areas far from the glacial boundaries.

Geologists' camp on a glacier in the Daniels Range, northern Victoria Land, Antarctica. *Photo by C. C. Plummer*

These episodes of glaciation took place within only the last couple million years, ending about 10,000 years ago. Preserved in the rock record, however, is evidence of extensive older glaciations. The record of a late Paleozoic glacial age is used as evidence for continental drift, as described in chapter 19 on plate tectonics.

## Relationships to Earth Systems

Glaciers, along with oceans, lakes, and rivers, are part of the hydrosphere. Most people are surprised to learn that most of the world's fresh water (approximately 75%) is in glaciers. Glaciers (and frozen sea ice) are part of a subsystem of the hydrosphere known as the *cryosphere*. Although glaciers exist in temperate climates, nearly all of the cryosphere is in polar regions.

The cryosphere affects the geosphere in that glaciers are very effective at eroding and transporting rock. Much of this chapter is about the unique landscapes produced by glacial activity. The cryosphere also has a profound influence on the atmosphere. Our climate and weather patterns are heavily influenced by air cooled by the ice in polar regions. Shrinking glaciers are often an indication of a warming climate.

The cryosphere also affects other parts of the hydrosphere. For instance, deep-ocean circulation takes place because dense, cold water from Antarctic oceans sinks beneath warmer waters from equatorial regions. Sea level changes when the world's glaciers grow or melt. During the most recent ice age, sea level was at least 100 meters lower than at present. The lower sea level meant that Asia and North America were joined at what is now the Bering Straits, permitting overland migration of humans from Asia to the Americas. Sea level rises when global warming takes place. If the current global warming continues, low-lying land will be submerged. (Almost all of Florida will be under water if a significant part of the Antarctic glaciers melts.)

The cryosphere also influences the biosphere. Water kept cool from melted glaciers and sea ice along the coast of Antarctica has the highest per-volume concentration of living organisms in the world. This is because colder water holds higher amounts of dissolved oxygen and other atmospheric gases, and a very diverse fauna (including penguins, whales, and tiny shrimp) have evolved into a unique ecosystem.

# INTRODUCTION

A **glacier** is a large, long-lasting mass of ice, formed on land, that moves under its own weight. It develops as snow is compacted and recrystallized. Glaciers can develop any place where, over a period of years, more snow accumulates than melts away or is otherwise lost.

There are two types of *glaciated* terrain on the Earth's surface. **Alpine glaciation** is found in mountainous regions, while **continental glaciation** exists where a large part of a continent (thousands of square kilometers) is covered by glacial ice. In both cases, the moving masses of ice profoundly and distinctively change the landscape.

The spectacularly scenic areas in many North American national parks owe much of their beauty to glacial action. Yosemite Valley in California might have been another nondescript valley if glaciers had not carved it into its present shape (figure 12.1). Unlike stream-carved valleys, Yosemite is straight for long stretches. Its sides are steep and the valley floor is flat (it is U-shaped rather than the characteristic V-shape of a stream-carved valley). The sediment beneath the vegetation in the valley floor is poorly sorted debris, unlike the sorted sediment deposited by a stream. All of these things are evidence that the Yosemite landscape has been carved by a glacier. But there is no glacier in Yosemite Valley. Yosemite indicates, as does overwhelming evidence elsewhere in the world, that glaciation was more extensive in the geologically recent past—that is, during the glacial ages.

Our lives and environment today have been profoundly influenced by the effects of past glaciation. For example, much of the fertile soil of the northern Great Plains of the United States developed on the loose debris transported and deposited

**FIGURE 12.1**

Yosemite Valley, as seen from Glacier Point, Yosemite National Park, California. Its U-shaped cross profile is typical of glacially carved valleys. *Photo by C. C. Plummer* by glaciers that moved southward from northern Canada. The thick blankets of sediment left in the Midwest store vast amounts of ground water. The Great Lakes and the thousands of lakes in Minnesota and neighboring states and provinces are the products of past glaciation.

Before we can understand how a continental glacier was responsible for much of the soil in the Midwest or how a glacier confined to a valley could carve a Yosemite, we must learn something about present-day glaciers.

# GLACIERS—WHERE THEY ARE, HOW THEY FORM AND MOVE

## Distribution of Glaciers

Glaciers occur in temperate as well as polar climates. They are found where more snow falls during the cold time of year than can be melted during warm months.

Washington has more glaciers than any other state except Alaska, because of the extensively glaciated mountains of western Washington. Washington's mountains have warmer winters but much more precipitation in the higher elevations than do the Rocky Mountains. There is more snow left after summer melting in Washington than in states to the east of it. Glaciers are common even near the equator in the very high mountains of South America and Africa because of the low temperatures at high altitudes.

Glaciation is most extensive in polar regions, where little melting takes place at any time of year. At present, about one-tenth of the land surface on Earth is covered by glaciers (compared with about one-third during the peak of the glacial ages). Approximately 85% of the present-day glacier ice is on the Antarctic continent, covering an area larger than the combined areas of western Europe and the United States; 10% is in Greenland. All the remaining glaciers of the world amount to only about 5% of the world's freshwater ice. This means that Antarctica is in fact storing most of Earth's fresh water in the form of ice. Some have suggested that ice from the Antarctic, towed as icebergs, could be brought to areas of dry climate to alleviate water shortages. It is worth noting that if all of Antarctica's ice were to melt, sea level around the world would rise over 70 meters (230 feet). This would flood the world's coastal cities and significantly decrease the land surface available for human habitation.

## Types of Glaciers

A simple criterion—whether or not a glacier is restricted to a valley—is the basis for classifying glaciers by form. A **valley glacier** is a glacier that is confined to a valley and flows from a higher to a lower elevation. Like streams, small valley glaciers may be tributaries to a larger trunk system. Valley glaciers

**FIGURE 12.2**
Valley glacier on the flanks of Mount Logan, Canada's highest mountain. *Photo by C. C. Plummer*

are prevalent in areas of alpine glaciation. As might be expected, most glaciers in the United States and Canada, being in mountains, are of the valley type (figure 12.2).

In contrast, an **ice sheet** is a mass of ice that is not restricted to a valley but covers a large area of land (over 50,000 square kilometers). Ice sheets are associated with continental glaciation. Only two places on Earth now have ice sheets: Greenland and Antarctica. A similar but smaller body is called an **ice cap.** Ice caps (and valley glaciers as well) are found in a few mountain highlands in Iceland and on islands in the Arctic Ocean, off Canada, Russia, and Scandinavia. An ice cap or ice sheet flows downward and outward from a central high point, as figure 12.3 shows.

## Formation and Growth of Glaciers

Snow converts to glacier ice in somewhat the same way that sediment turns into a sedimentary rock and then into metamorphic rock; figure 12.4 shows the process. A snowfall can be compared to sediment settling out of water. A new snowfall may be in the form of light "powder snow," which consists mostly of air trapped between many six-pointed snowflakes. In a short time, the snowflakes settle by compaction under their own weight, and much of the air between them is driven out. Meanwhile, the sharp points of the snowflakes are destroyed as flakes reconsolidate into granules. In warmer climates, partial thawing and refreezing result in coarse granules—the "corn snow" of spring skiing. In colder climates where little or no melting takes place, the snowflakes will recrystallize into fine granules. After the granular snow is buried by a new snowpack, usually during the following winter, the granules are

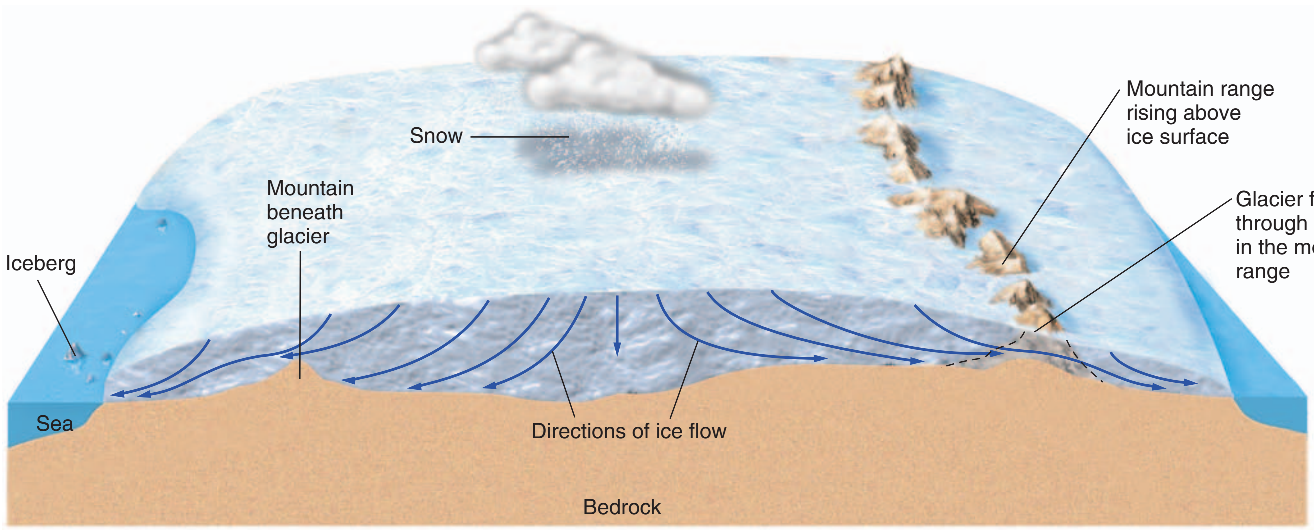



**FIGURE 12.3**

Diagrammatic cross section of an ice sheet. Vertical scale is highly exaggerated.

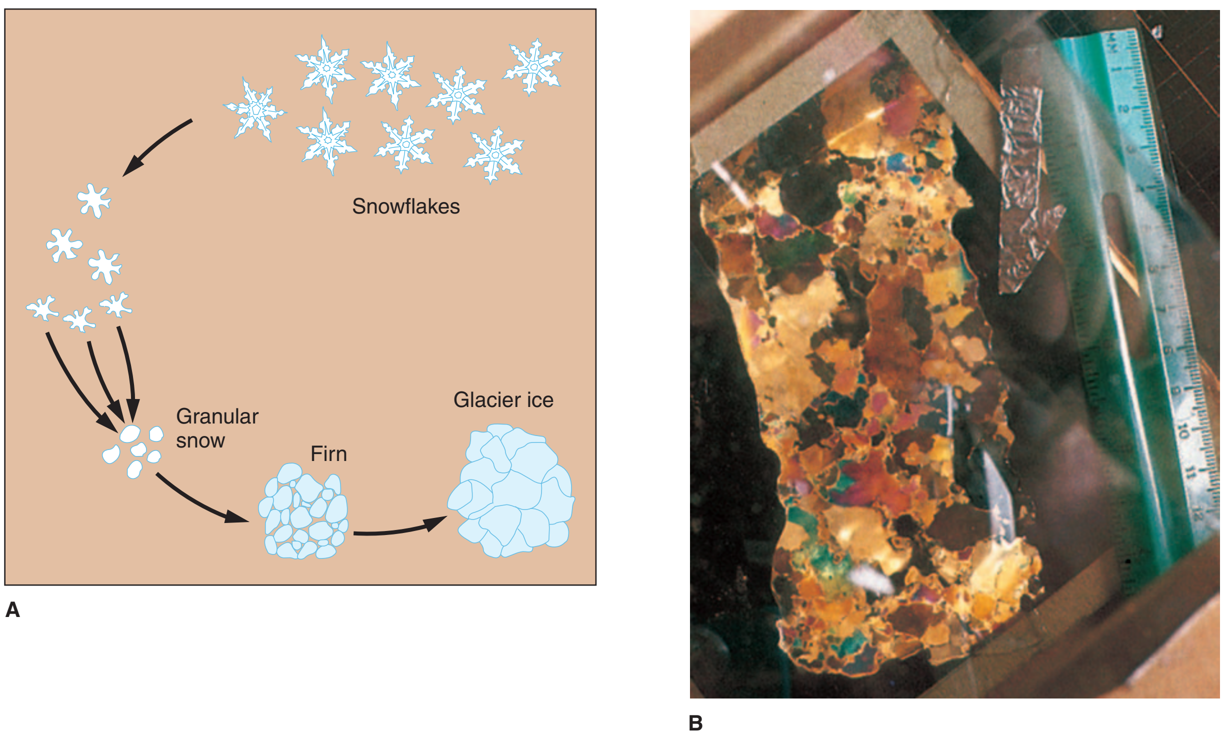



**FIGURE 12.4**

(*A*) Conversion of snow to glacier ice. (*B*) Thin slice of an ice core from a glacier (a core is shown in box 12.3, figure 1). The ice is between sheets of polarizing filters. In polarized light, the colors of individual ice grains vary depending on their crystallographic orientation. Without the polarizing filters, the ice would be transparent and clear. The ruler shows that many of the ice grains are over a centimeter in length. *Photo by C. C. Plummer* compacted and weakly “cemented” together by ice. The compacted mass of granular snow, transitional between snow and glacier ice, is called *firn*. Firn is analogous to a sedimentary rock such as a weakly cemented sandstone.

Through the years, the firn becomes more deeply buried as more snow accumulates. More air is expelled, the remaining pore space is greatly reduced, and granules forced together recrystallize into the tight, interlocking mosaic of *glacier ice* (figure 12.4*B*). The recrystallization process involves little or no melting and is comparable to metamorphism. Glacier ice is texturally similar to the metamorphic rock, quartzite.

Under the influence of gravity, glacier ice moves downward and is eventually **ablated,** or lost. For glaciers in all but the coldest parts of the world, ablation is due mostly to melting, although some ice evaporates directly into the atmosphere. If a moving glacier reaches a body of water, blocks of ice break off (or *calve*) and float free as **icebergs** (figure 12.5). In most of the Antarctic, ablation takes place largely through calving of icebergs and direct evaporation. Only along the coast does melting take place, and there for only a few weeks of the year.

**FIGURE 12.5**
An iceberg in southern Chile. *Photo by C. C. Plummer*

### *Glacial Budgets*

If, over a period of time, the amount of snow a glacier gains is greater than the amount of ice and water it loses, the glacier’s budget is *positive* and it expands. If the opposite occurs, the glacier decreases in volume and is said to have a *negative budget*. Glaciers with positive budgets push outward and downward at their edges; they are called **advancing glaciers.** Those with negative budgets grow smaller and their edges melt back; they are **receding glaciers.** Bear in mind that the glacial ice moves downvalley, as shown in figure 12.6, whether the glacier is advancing or receding. In a receding glacier, however, the rate of flow of ice is insufficient to replace all of the ice lost in the lower part of the glacier. If the amount of snow retained by the glacier equals the amount of ice and water lost, the glacier has a *balanced budget* and is neither advancing nor receding.

The upper part of a glacier, called the **zone of accumulation,** is the part of the glacier with a perennial snow cover (figure 12.6). The lower part is the **zone of ablation,** for there ice is lost, or ablated, by melting, evaporation, and calving.

The boundary between these two altitudinal zones of a glacier is an irregular line called the **equilibrium line** (sometimes called the *snow line* or the *firn line*), which marks the highest point at which the glacier’s winter snow cover is lost during a melt season (figure 12.7).

The equilibrium line may shift up or down from year to year, depending on whether there has been more accumulation or more ablation. Its location therefore indicates whether a glacier has a positive or negative budget. An equilibrium line migrating upglacier over a period of years is a sign of a negative budget, whereas an equilibrium line migrating downglacier indicates that the glacier has a positive budget. If an equilibrium

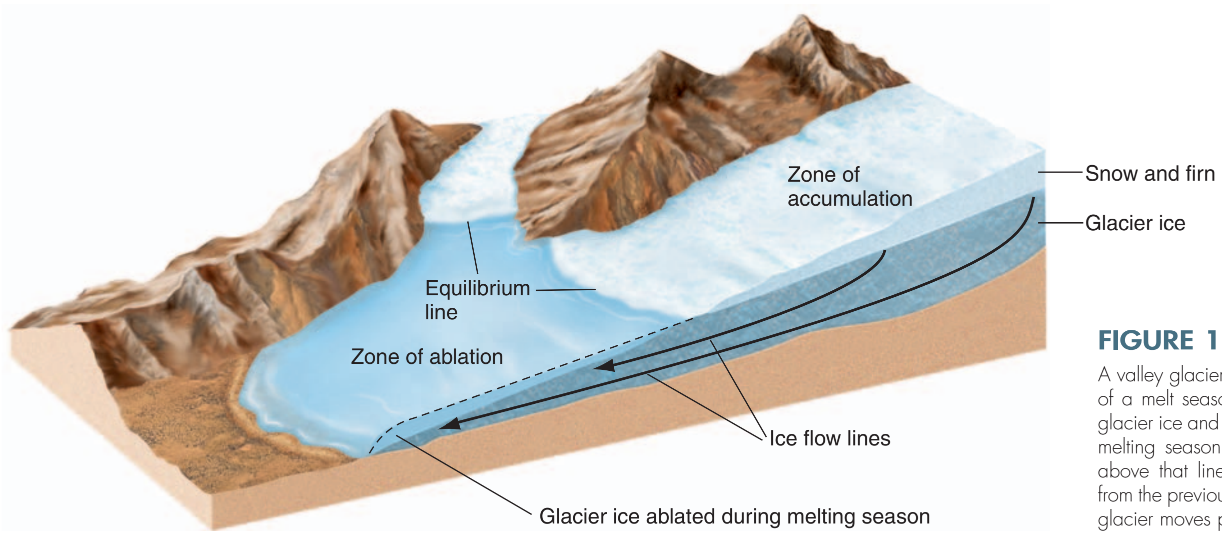



**FIGURE 12.6**
A valley glacier as it would appear at the end of a melt season. Below the equilibrium line, glacier ice and snow have been lost during the melting season. In the zone of accumulation above that line, firn is added to the glacier from the previous winter snowfall. Ice within the glacier moves parallel to the ice flow lines.

line remains essentially in the same place year after year, the glacier has a balanced budget.

The **terminus** is the lower edge of a glacier. Its position reflects the glacier's budget. For a valley glacier, a positive budget results in the terminus moving downvalley. In a receding glacier, the terminus melts back upvalley. Because glacial ice moves slowly, migration of the terminus tends to lag several years behind a change in the budget.

If the terminus of an ice sheet is on land, it will advance or retreat in response to a positive or negative budget, just as for a valley glacier. If the terminus is at the continent's shoreline (as it is for our Antarctic and Greenland ice sheets), a positive budget results in a greater volume of icebergs calving into the sea.

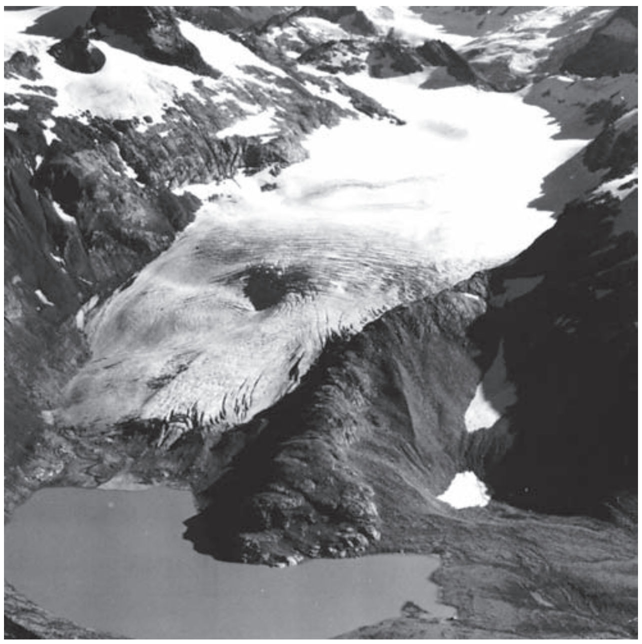
Advancing or receding glaciers are significant and sensitive indicators of climatic change. However, an advancing glacier does not necessarily indicate that the climate is getting colder. It may mean that the climate is getting wetter, more precipitation is falling during the winter months, or the summers are cloudier. It is estimated that a worldwide decrease in the mean annual temperature of about 5°C could bring about a new ice age. Conversely, global climate warming can significantly reduce the size and numbers of glaciers. In general, valley glaciers around the world have been receding during the past century. At present, glaciers at Glacier National Park in Montana and Mount Kilamanjaro in Africa are receding at a rate that, if sustained, will lead them to disappear in a few years. (Will Montana's park then be renamed Glacier-Free National Park?)

## Movement of Valley Glaciers

Valley glaciers move downslope under the influence of gravity at a variable rate, generally ranging from less than a few millimeters to 15 meters a day. Sometimes a glacier will move much faster for a brief period of time (see box 12.2). A glacier will flow faster where it is steeper. Also, the thicker parts of a glacier will flow faster than where it is thinner. The upper part of a glacier tends to be steeper than at lower levels. If a glacier has an even gradient, the glacier will be thickest near the equilibrium line. So, except for locally steeper stretches, we expect the fastest moving ice to be near the equilibrium line. Below the equilibrium line, the glacier usually becomes progressively thinner and slower.

Glaciers in temperate climates—where the temperature of the glacier is at or near the melting point for ice—tend to move faster than those in colder regions—where the ice temperature stays well below freezing.

**A**



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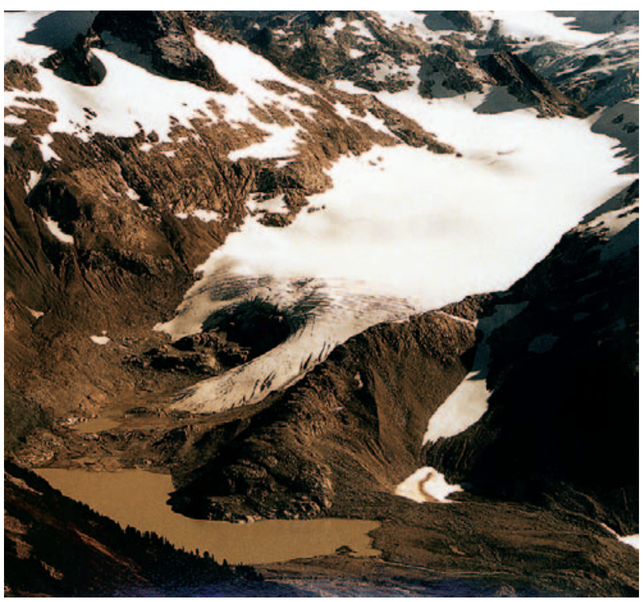


**C**

**FIGURE 12.7**

South Cascade glacier, Washington. If the photos were taken at the end of the melt season, the equilibrium line would be the boundary between white snow and darker glacier ice. Photo (*A*) was taken in 1957; note that the glacier extended into the lake and that small icebergs calved from it. Photo (*B*) was taken in 1980; notice that the glacier has shrunk and receded. During the 23-year interval, the glacier lost approximately 7.5 meters of ice averaged over its surface, or the equivalent of 18.7 million cubic meters of water for the entire glacier. Photo (*C*), taken in October 2000, shows that the glacier continued to recede. *Photos by U.S. Geological Survey*

ENVIRONMENTAL GEOLOGY 12.1

## Glaciers as a Water Resource

Few people think of glaciers as frozen reservoirs supplying water for irrigation, hydroelectric power, recreation, and industrial and domestic use. Yet, glacially derived water is an important resource in places such as Iceland, Norway, British Columbia, and the state of Washington. In Washington, streamflow from the approximately 800 glaciers there amounts to about 470 billion gallons of water during a summer, according to the U.S. Geological Survey. More water is stored in glacier ice in Washington than in all of the state's lakes, reservoirs, and rivers.

One important aspect of glacier-derived water is that it is available when needed most. Snow accumulates on glaciers during the wet winter months. During the winter, streams at lower elevations, where rain rather than snow falls, are full and provide plenty of water. During the summer, the climate in the Pacific Northwest is hotter and drier. Demand for water increases, especially for irrigation of crops. Streams that were fed by rainwater may have dried up. Yet, in the heat of summer, the period of peak demand, snow and ice on glaciers are melting, and streams draining glaciers are at their highest level.

Paradoxically, the greater the snowfall on a glacier during a winter, the smaller the amount of meltwater during the summer. A larger blanket of white snow reflects the sun's radiation more effectively than the darker, bare glacier ice, which absorbs more of the heat of the sun. Experiments have shown that melting can be greatly increased by darkening the snow surface, for instance, by sprinkling coal dust on it. Similarly, the melting of a glacier can be slowed artificially by covering it with highly reflective material. Such means of controlling glacial meltwater have been proposed to benefit power generating stations or to provide additional irrigation.

These ideas are appealing from a shortsighted point of view. However, the long-term effect of tampering with a glacier's natural regime can adversely affect the overall environment. It is conceivable, for example, that we could melt a glacier out of existence.

### Additional Resource

U.S. Geological Survey. 1973. *Glaciers, a water resource.* U.S. Geological Survey Information Pamphlet.

Velocity also varies within the glacier itself (figure 12.8). The central portion of a valley glacier moves faster than the sides (as water does in a stream), and the surface moves faster than the base. How ice moves within a valley glacier has been demonstrated by studies in which holes are drilled through the glacier ice and flexible pipes inserted. Changes in the shape and position of the pipes are measured periodically. The results of these studies are shown diagrammatically in figure 12.8.

Note in the diagram that the base of the pipe has moved downglacier. This indicates **basal sliding,** which is the sliding of the glacier as a single body over the underlying rock. A thin film of meltwater that develops along the base from the pressure of the overlying glacier facilitates basal sliding. Think of a large bar of wet soap sliding down an inclined board.

Note that the lower portion of the pipe is bent in a downglacier direction. The bent pipe indicates **plastic flow** of

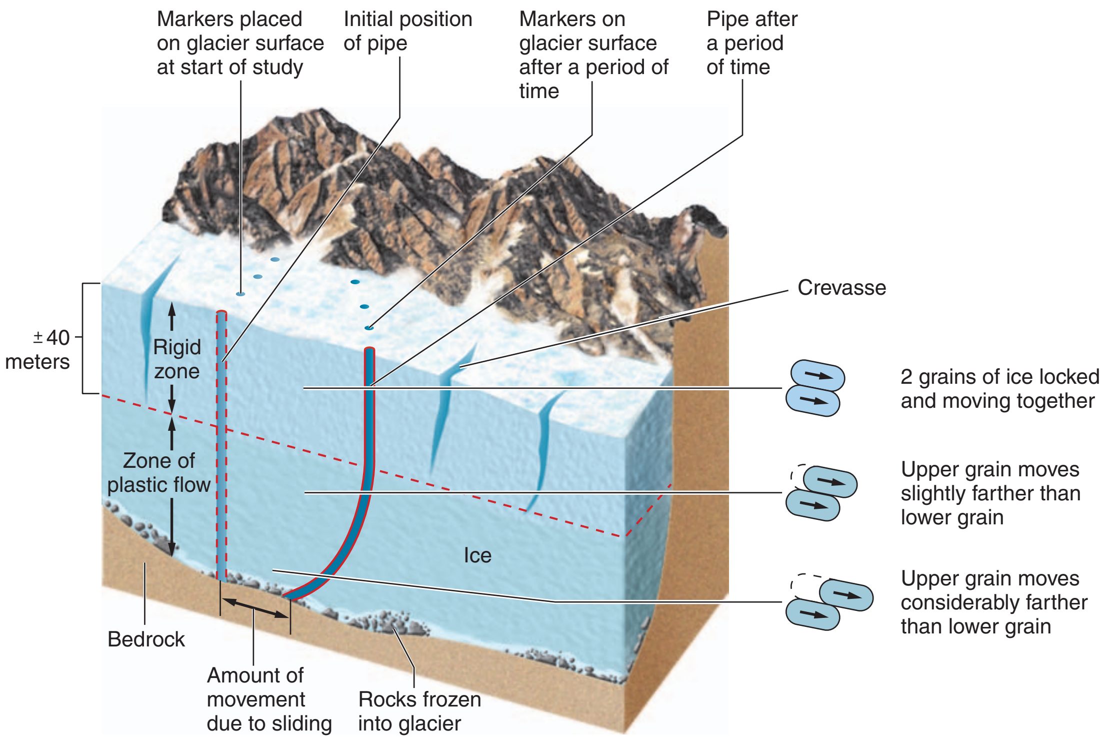
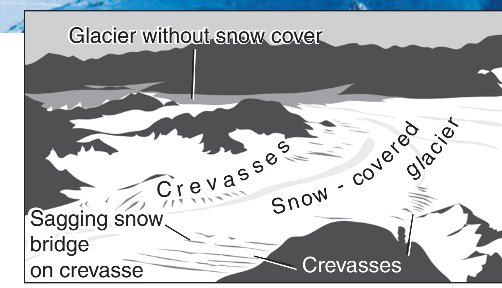
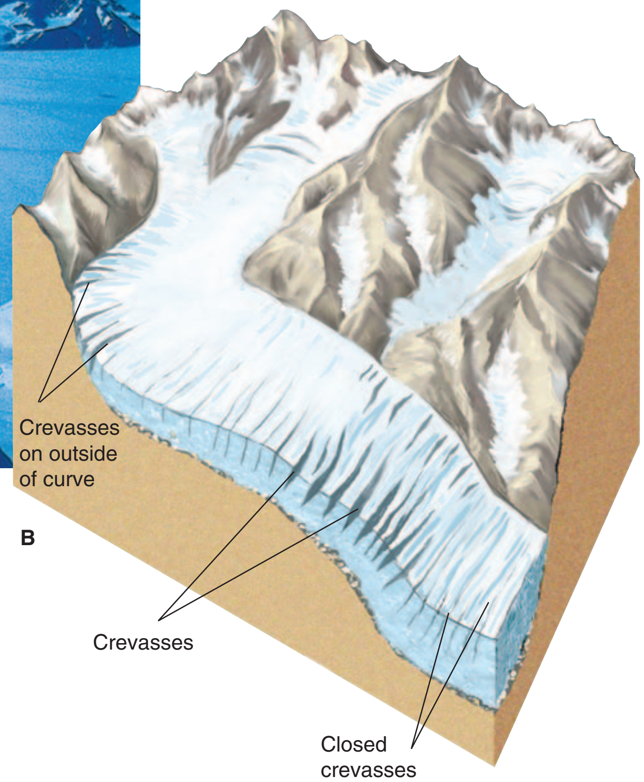



**FIGURE 12.8**
Movement of a glacier. Markers on the glacier indicate the center of the glacier moves faster than its side. Cross-sectional view shows movement within the glacier.

A




Geologist's View




B

**FIGURE 12.9**
(*A*) Crevasses on a glacier, looking down from Mount Logan, Yukon, Canada. (*B*) Crevasses along the course of a glacier. *Photo by C. C. Plummer*

ice, movement that occurs within the glacier due to the plastic or "deformable" nature of the ice itself. Visualize two neighboring grains of ice within the glacier, one over the other. Both are moving, carried along by the ice below them; however, the higher of the two ice grains slides over its underlying neighbor a bit further. The reason the pipe is bent more sharply near the base of the glacier is that pressure from overlying ice results in greater flowage with increasing depth. Deep in the glacier, ice grains are sliding past their underlying neighbors farther than similar ice grains higher up, where the pipe is less bent. We should point out that a glacier flows not only because ice grains slide past one another but also because ice grains deform and recrystallize.

In the **rigid zone,** or upper part of the glacier, the pipe has been moved downglacier; however, it has remained unbent. The ice nearer the top apparently rides along passively on the plastically moving ice closer to the base. In the rigid zone, grains of ice do not move relative to their neighbors.

### *Crevasses*

Along its length, a valley glacier moves at different rates in response to changes in the steepness of the underlying rock. Typically, a valley glacier rides over a series of rock steps. Where the glacier passes over a steep part of the valley floor, it moves faster. The upper rigid zone of ice, however, cannot stretch to move as rapidly as the underlying plastic-flowing ice. Being brittle, the ice of the rigid zone is broken by the tensional forces. Open fissures, or **crevasses,** develop (figure 12.9). Crevasses also form along the margins of glaciers in places where the path is curved, as shown in part of figure 12.9. This is because ice (like water) flows faster toward the outside of the curve. For glaciers in temperate climates, a crevasse should be no deeper than about 40 meters, the usual thickness of the rigid zone. If you are falling down a crevasse, it may be of some consolation that, as you are hurtling to death or injury, you realize on the way down that you will not fall more than 40 meters.

After the ice has passed over a steep portion of its course, it slows down, and compressive forces close the crevasses.

## Movement of Ice Sheets

An ice sheet or ice cap moves like a valley glacier except that it moves downward and outward from a central high area toward the edges of the glacier (as shown in figure 12.3).

Glaciological research in Antarctica has determined how ice sheets grow and move. Antarctica has two ice sheets: the West Antarctic Ice Sheet is separated by the Transantarctic Mountains from the much larger East Antarctic Ice Sheet (figure 12.10). The two ice sheets join in the low areas between mountain ranges. Both are nearly completely within a zone of accumulation because so little melting takes place (ablation is largely by calving of icebergs) and because occasional snowfalls nourish their high central parts. The ice sheets mostly overlie interior lowlands but also completely bury some mountain ranges. Much of the base of the West Antarctic Ice Sheet is on bedrock that is below sea level. At least one active volcano underlies the West Antarctic Ice Sheet (resulting in a depression in the ice sheet). Where mountain ranges are higher than the ice sheet, the ice flows between mountains as valley glaciers, known as *outlet glaciers.*

Although flowage in ice sheets is away from central highs where more snow accumulates, movement is not uniform. Most of the flowage in the East Antarctic Ice Sheet takes place in *ice streams,* zones where the movement is considerably faster than

ENVIRONMENTAL GEOLOGY 12.2

# Water Beneath Glaciers: Floods, Giant Lakes, and Galloping Glaciers

## A Galloping Glacier

Glacial motion is often used as a metaphor for slowness ("The trial proceeded at a glacial pace"). But, some glaciers will *surge*—that is, move very rapidly for short periods following years of barely moving at all. The most extensively documented surge (or "galloping glacier") was that of Alaska's Bering Glacier in 1993–94. The Bering Glacier is the largest glacier in continental North America, and it surges on a 20–30 year cycle. After its previous surge in 1967, its terminus retreated 10 kilometers. In August 1993, the latest surge began. Ice traveled at velocities up to 100 meters per day for short periods of time and sustained velocities of 35 meters per day over a period of several months. The terminus advanced 9 kilometers by the time the surge ended in November 1994. When glaciers surge, the previously slow moving, lower part of a glacier breaks into a chaotic mass of blocks (box figure 1). Surges are usually attributed to a buildup of water beneath part of a glacier, floating it above its bed. In July 1994, a large flood of water burst from Bering Glacier's terminus, carrying with it blocks of ice up to 25 meters across.

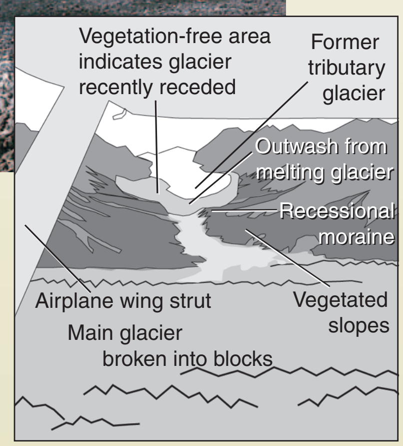
## A Flood

Glacial outburst floods are not always associated with surges. In October 1996, a volcano erupted beneath a glacier in Iceland. The glacier, which is up to 500 meters thick, covers one-tenth of Iceland. Emergency teams prepared for the flood that geologists predicted would follow the eruption. The expected flood took place early in November with a peak flow of 45,000 cubic meters per second (over 1.5 million cubic feet per second)! The flood lasted only a few hours; however, it caused between $10 and 15 million worth of damage. Three major bridges were destroyed or damaged, and 10 kilometers of roads were washed away. Because people had been kept away from the expected flood path, there were no casualties.

## A Giant Lake

One of the world's largest lakes was only recently discovered. But don't expect to take a dip in it or go windsurfing on it. It lies below the thickest part of the East Antarctic Ice Sheet and is named after the Russian research station, Vostok, which is 4,000 meters above the lake at the coldest and most remote part of Antarctica. Lake Vostok was discovered in the 1970s through ice-penetrating radar; however, its extent was unknown until 1996, when satellite-borne radar revealed how large it is. Studies indicate that the lake is 200 kilometers long and 50 kilometers wide—about the size of Lake Ontario. At its deepest, it is 510 meters, placing it among the ten deepest lakes in the world. Recently, more, but smaller, lakes beneath the East Antarctic Ice Sheet have been discovered.

The lake has been sealed off from the rest of the world for around a million years, and it likely contains organisms, such as microbes, dating back to that time. These organisms (and their genes) would not have been affected by modern pollution or nuclear bomb fallout. By coincidence, the world's deepest ice hole (over 3 kilometers) was being drilled from Vostok Station above the lake when the size of Lake Vostok was being determined. The ice core from this hole should add to the findings from the Greenland drilling projects (box 12.3) and provide an even greater picture of Earth's climate during the ice ages. When the hole was completed in 1997, drilling was halted short of reaching the lake due to fear of contaminating it and harming whatever living organisms might be in the very old water.




Geologist's View

**BOX 12.2 ■ FIGURE 1**
Part of a glacier after a surge (lower part of photo). The debris-covered ice has been broken up into a chaotic mass of blocks. In the background is a small glacier that has retreated up its valley. Photo taken near the Canadian-Alaskan border. *Photo by C. C. Plummer*

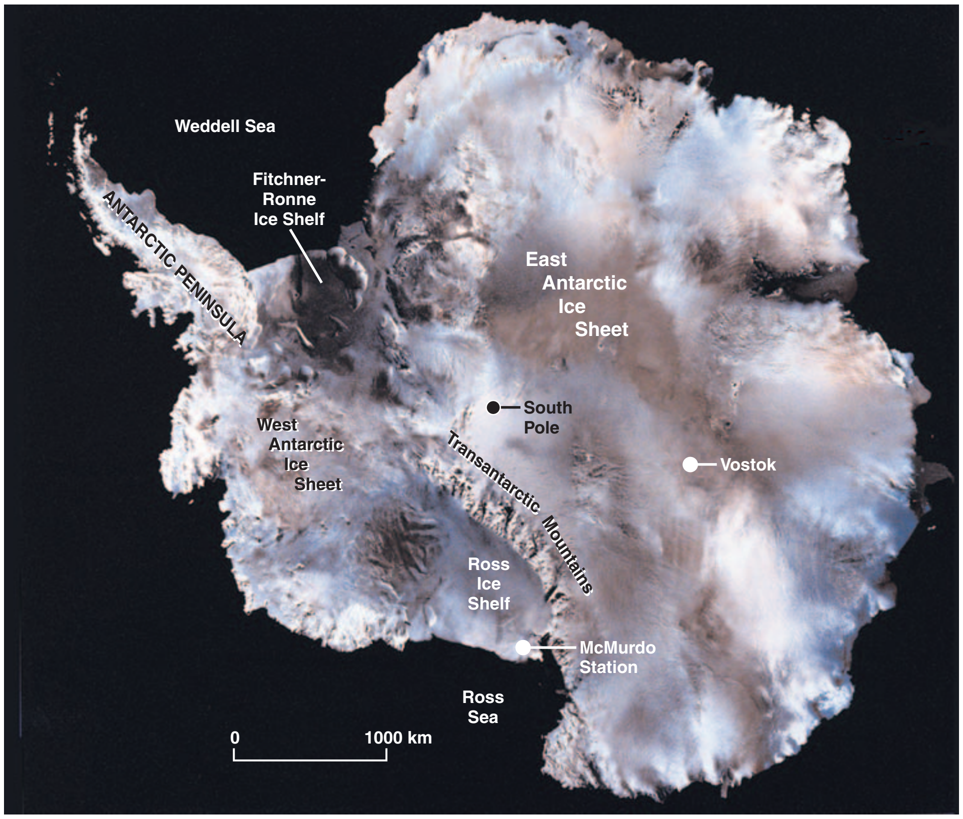



**FIGURE 12.10**

The Antarctic continent and its ice sheets. Vostok is at the highest part of the East Antarctic Ice Sheet. (False coloring is used to show variations among snow, ice, blue ice, and exposed rock.) *Photo by U.S. Geological Survey/NASA*

in adjoining ice, which is frozen to its bed. An ice stream is often heavily crevassed and its boundaries are determinable by the transition from crevassed to crevasse-free ice.

At the South Pole (figures 12.10 and 12.11)—neither the thickest part nor the center of the East Antarctic Ice Sheet—the ice is 2,700 meters thick. The thickest part of the East Antarctic Ice Sheet is 4,776 meters. Research at ice sheets has yielded important information regarding past climates (see box 12.3).

Most of the movement of the East Antarctic Ice Sheet is by means of plastic flow. It has been thought that most of the ice sheet is frozen to the underlying rocks and basal sliding takes place only locally. But the recent discovery of a giant lake and other lakes beneath the thickest part of the East Antarctic Ice Sheet (see box 12.2) indicates that liquid water at its base is more widespread and basal sliding might be more important than previously regarded.

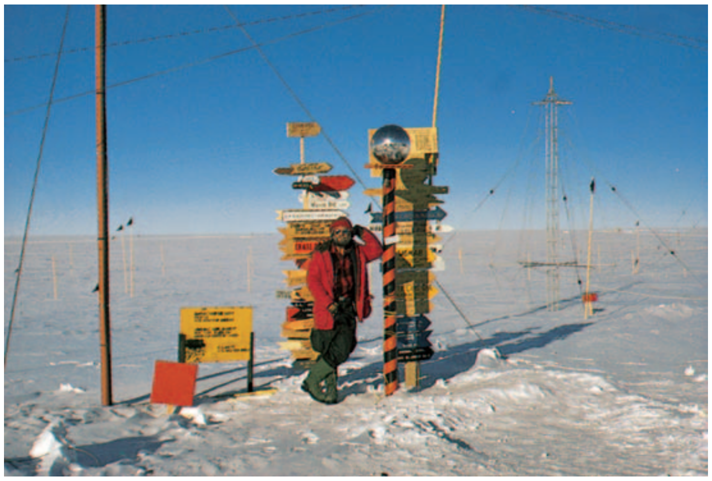


**FIGURE 12.11**

The South Pole. Actually, the true South Pole is several kilometers from here. The moving ice sheet has carried the striped pole away from the site of the true South Pole, where the pole was erected in 1956. *Photo by C. C. Plummer*

## GLACIAL EROSION

Wherever basal sliding takes place, the rock beneath the glacier is abraded and modified. As meltwater works into cracks in bedrock and refreezes, pieces of the rock are broken loose and frozen into the base of the moving glacier, a process known as *plucking*. While being dragged along by the moving ice, the rock within the glacier grinds away at the underlying rock (figure 12.12). The thicker the glacier, the more pressure on the rocks and the more effective the grinding and crushing.

Pebbles and boulders that are dragged along are *faceted,* that is, given a flat surface by abrasion. Bedrock underlying a glacier is *polished* by fine particles and *striated* (scratched) by sharp-edged, larger particles. Striations and grooves on bedrock indicate the direction of ice movement (figure 12.13).

The grinding of rock across rock produces a powder called **rock flour.** Rock flour is composed largely of very fine (silt- and clay-sized) particles of unaltered minerals (pulverized from chemically unweathered bedrock). When *meltwater* washes rock flour from a glacier, the streams draining the

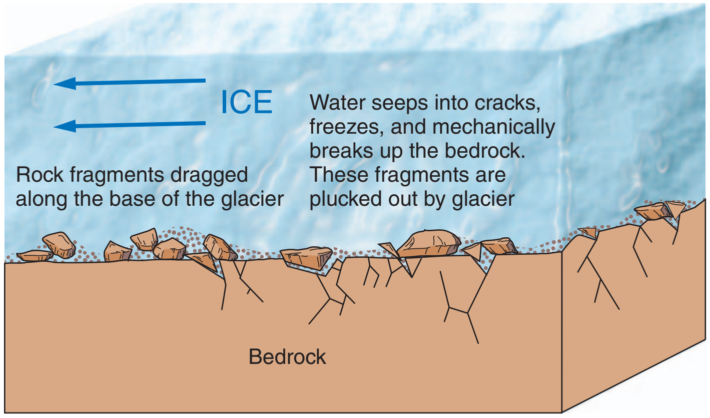



**FIGURE 12.12**

Plucking and abrasion beneath a glacier.

**FIGURE 12.13**

Striated and polished bedrock surface in south Australia. Unlike glacial striations commonly found in North America, these were caused by late Paleozoic glaciation. *Photo by C. C. Plummer*

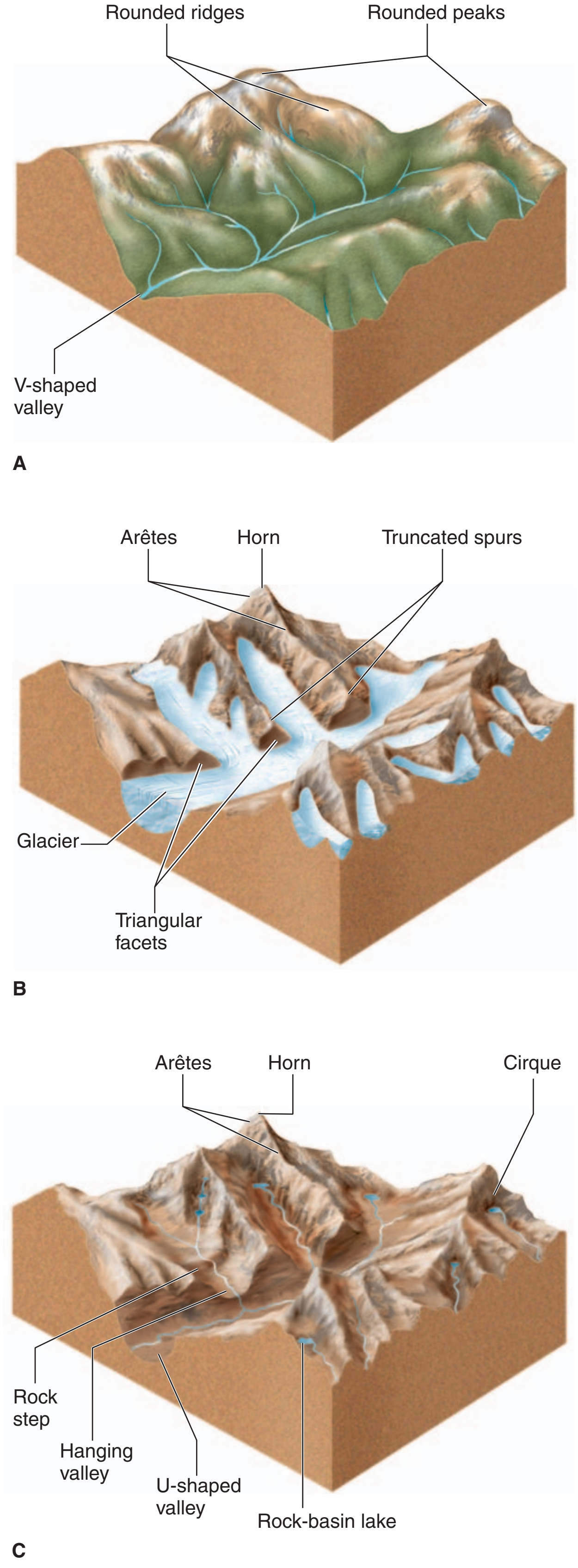



**FIGURE 12.14**

(*A*) A stream-carved mountain landscape before glaciation. (*B*) The same area during glaciation. Ridges and peaks become sharper due to frost wedging. (*C*) The same area after glaciation.

glacier appear milky, and lakes into which glacial meltwater flows often appear a milky green color.

Not all glacier-associated erosion is caused directly by glaciers. Mass wasting takes place on steep slopes created by downcutting glaciers. Frost wedging breaks up bedrock ridges and cliffs above a glacier, causing frequent rockfalls. Snow avalanches bring down loose rocks onto the glacier. If rocks collect in the zone of accumulation, they may be incorporated into the body of the glacier. If rock falls onto the zone of ablation, they will ride on the glacial ice surface. Debris may also fall into crevasses to be transported within or at the base of a glacier, as shown in figure 12.19.

## Erosional Landscapes Associated with Alpine Glaciation

We are in debt to glaciers for the rugged and spectacular scenery of high mountain ranges. Figure 12.14 shows how glaciation has radically changed a previously unglaciated

EARTH SYSTEMS 12.3

# Global Warming and Glaciers

Most of Earth's glaciers have been receding for a century (see figure 12.7). This is generally regarded as a consequence of global warming. That Earth's climate is warming is now clearly established. But some questions arise with regard to global warming: How does it compare to past episodes of warming? Is it part of a natural cycle? How much of it is anthropogenic (caused by humans)? What are the consequences of continued global warming on Earth systems? Can we do anything to reduce the global warming?

Glaciers, particularly the Antarctic and Greenland ice sheets, provide us with a means to answer these questions. Glaciers preserve records of precipitation, air temperatures, atmospheric dust, volcanic ash, carbon dioxide, and other atmospheric gases.

When snow becomes converted to glacier ice, some of the air that was mixed with the snowflakes becomes bubbles trapped in the glacier ice. By analyzing the air in these bubbles, we are analyzing the air that prevailed when an ancient ice layer formed. Drilling into glaciers and retrieving ice cores allows scientists to sample the environment at the time of ancient snowfalls. A cylindrical core of ice is extracted from a hollow drill after it has penetrated a glacier. The layers in an ice core represent the different layers of snow that converted to glacier ice (box figure 1). Each layer, when analyzed, can reveal information about conditions of the atmosphere at the time the snow accumulated and turned into ice.

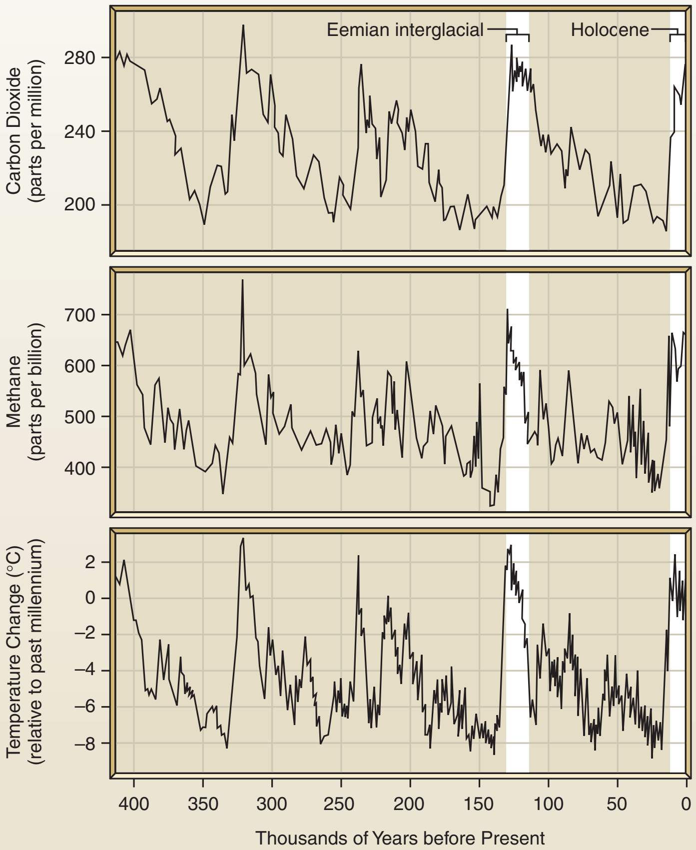
The most ambitious drilling project in Antarctica was completed in December 2004 by the European Project for Ice Coring in Antarctica (EPICA). Drilling retrieved ice core to a depth of 3,270 meters (10,728 feet), stopping 5 meters above the base of the ice sheet. EPICA scientists estimate that, when analyzed, the ice core will give us a record of the climate extending back an estimated 900,000 years. The next-largest core was drilled at Vostok (described in box 12.2) in Antarctica in the 1990s.

The Vostok core reached a depth of over 3 kilometers and yielded a climate and atmospheric history of the past 420,000 years. Graphs derived from the research project are shown in box figure 2. The temperature variation is relative to the ice sheet's temperature during the past millennium. The team determined the temperature by studying hydrogen isotope variation (see chapter 2) within the ice layers. Methane and carbon dioxide are greenhouse gases. Note how the greenhouse gases correlate closely with the temperature variations. Also note the five periods when the temperature was warmest. These are the *interglacial* periods during which the North American and European ice sheets disappeared. Two of the five warm periods are emphasized for comparison—the Holocene interglacial epoch (which began about 12,000 years ago and is ongoing) and the previous interglacial (the Eemian).

Compare the Holocene temperature pattern to that of the Eemian. From this, you can understand why scientists infer that we

**BOX 12.3 ■ FIGURE 1**

An ice core being examined in a cold laboratory. *Photo by Mark Twickler, University of New Hampshire/National Oceanic and Atmospheric Administration Paleoclimatology Program/Department of Commerce*




**BOX 12.3 ■ FIGURE 2**

Temperature, carbon dioxide, and methane content of air at Vostok on the East Antarctic Ice Sheet for the last 420,000 years. See text for explanation. Also note the rapid rising of temperature at the beginning of interglacial periods.

should be in a period of declining temperatures leading into the next glacial age. Instead, we have ongoing global warming. Further, there is now strong evidence that the global warming is due to anthropogenic contribution of greenhouse gases to our atmosphere. The two biggest culprits are methane and carbon dioxide. If these gases are not controlled, their levels will rise to the naturally derived levels reached during the warmer Eemian interglacial. Sea level worldwide during that time was several meters higher than at present. (This was caused by the expansion of the ocean waters due to heating, as well as melting of polar ice at a higher rate than at present.)

If computer models projecting higher rates of global warming are correct, we can expect the hydrosphere to be affected by gases in the atmosphere, and sea level will rise significantly. One group of researchers calculated that sea level could rise several tens of centimeters during this century. But this prediction is based mainly on expansion of the oceans due to being heated. If the higher temperatures also trigger disintegration of large parts of the ice sheets, sea levels could rise even higher. A higher sea level affects the biosphere, notably humans. A major proportion of the world's population lives at or close to a coastline. Houses would be destroyed by coastal erosion. Major cities, such as New York, would have to erect dikes to keep water out of buildings that are below sea level.

Can anything be done to stop or slow down global warming? James Hansen (see Additional Resources) thinks so. The rate at which methane and carbon dioxide are produced would have to be reduced. The rate of carbon dioxide production, mainly from burning of fossil fuels, is rising. However, the rate of production of methane has been declining for two decades. Methane is a fuel and it makes economic sense to capture it where it is produced at landfills, mines, and oil fields. Reducing the production of carbon dioxide is more problematic. Additional things that could be done include using more fuel-efficient vehicles and moving toward alternate forms of energy. Cutting back the production of carbon dioxide and other pollutants has the additional benefit of decreasing health risks.

### Additional Resources

For more on ice sheet drilling, go to this book's website at

- www.mhhe.com/plummer12e.

The Greenland Ice Sheet Project 2 (GISP 2) report on the paleoclimate highlights. Includes a description of how they determined climate variation using oxygen isotope ratios ($^{18}O/^{16}O$) in air bubbles trapped in the ice core.

- www.agu.org/revgeophys/mayews01/mayews01.html

For more on the topic of global warming and its relationship to glaciation, read James Hansen, Defusing the Global Warming Time Bomb. *Scientific American,* March 2004, pp. 68–77. For a more detailed version of that article, go to

- www.sciam.com/media/pdf/hansen.pdf.

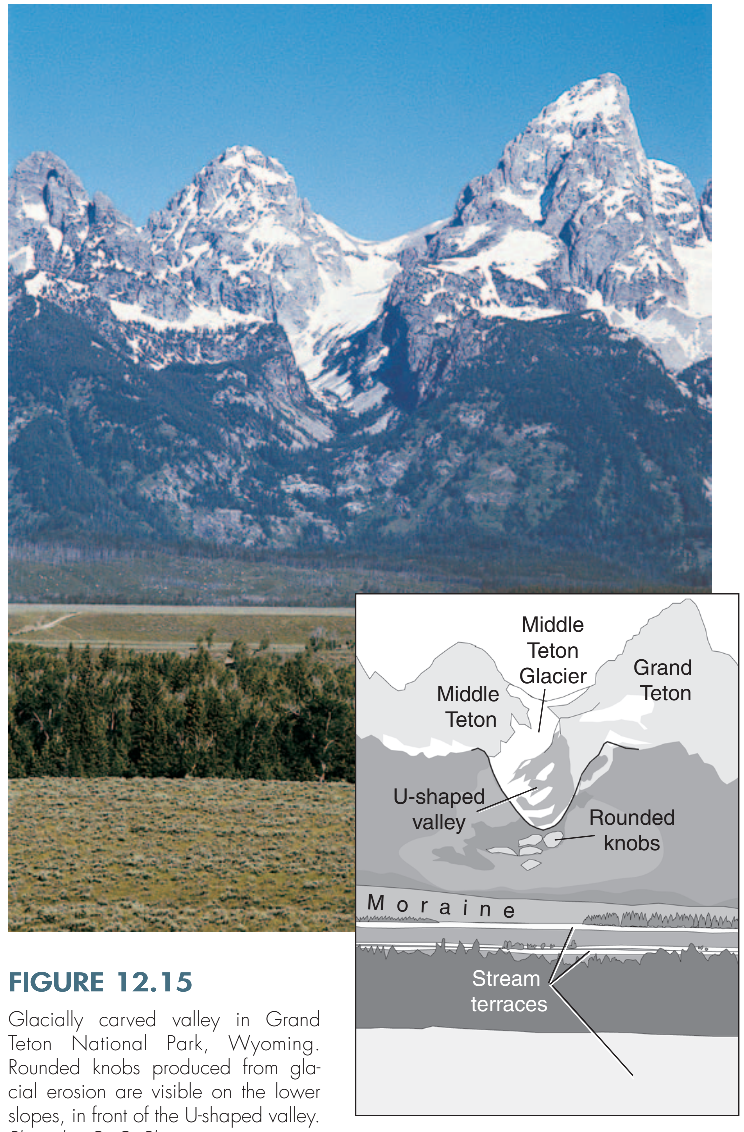



**FIGURE 12.15**

Glacially carved valley in Grand Teton National Park, Wyoming. Rounded knobs produced from glacial erosion are visible on the lower slopes, in front of the U-shaped valley. *Photo by C. C. Plummer*

***Geologist's View***

mountainous region. The striking and unique features associated with mountain glaciation, described next, are due to the erosional effects of glaciers as well as frost wedging on exposed rock.

### *Glacial Valleys*

Glacially carved valleys are easy to recognize. A **U-shaped valley** (in cross profile) is characteristic of glacial erosion (figure 12.15), just as a V-shaped valley is characteristic of stream erosion.

The thicker a glacier is, the more erosive force it exerts on the underlying valley floor, and the more bedrock is ground away. For this reason, a large trunk glacier erodes downward more rapidly and carves a deeper valley than do the smaller tributary glaciers that join it. After the glaciers disappear, these tributaries remain as **hanging valleys** high above the main valley (figure 12.16).

**FIGURE 12.16**

A hanging valley in Yosemite National Park, California. *Photo by C. C. Plummer*

Valley glaciers, which usually occupy valleys formerly carved by streams, tend to straighten the curves formed by running water. This is because the mass of ice of a glacier is too sluggish and inflexible to move easily around the curves. In the process of carving the sides of its valley, a glacier erodes or "truncates" the lower ends of ridges that extended to the valley. **Truncated spurs** are ridges that have *triangular facets* produced by glacial erosion at their lower ends (figure 12.14*B*).

Although a glacier tends to straighten and smooth the side walls of its valley, ice action often leaves the surface of the underlying bedrock carved into a series of steps. This is due to the variable resistance of bedrock to glacial erosion. Figure 12.17 shows what happens when a glacier abrades a relatively weak rock with closely spaced fractures. Water seeps into cracks in the bedrock, freezes there, and enlarges fractures or makes new ones. Rock frozen into the base of the glacier grinds and loosens more pieces. After the ice has

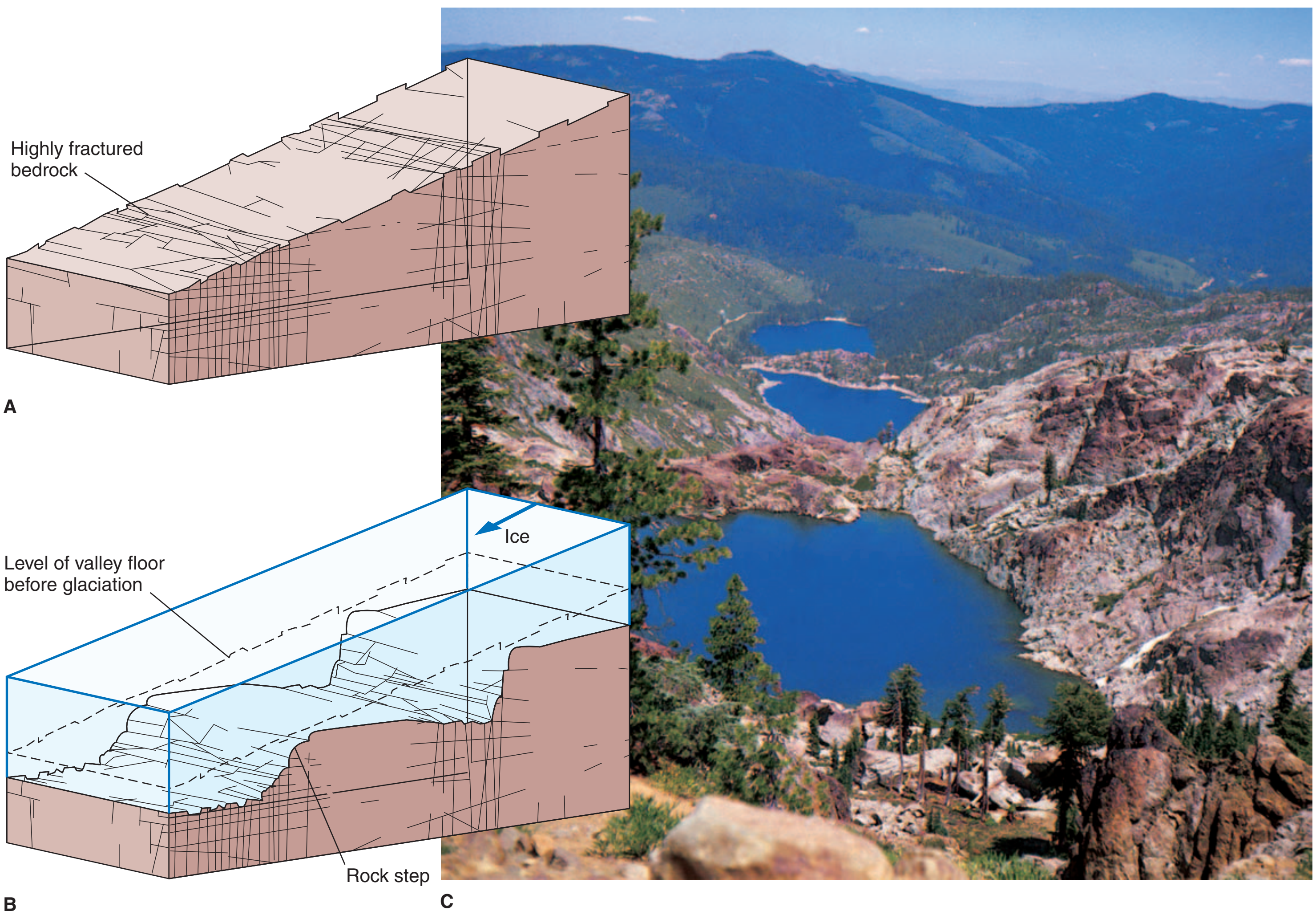



**FIGURE 12.17**

Development of rock steps. (*A*) Valley floor before glaciation. (*B*) During glaciation. (*C*) Rock steps and rock-basin lakes. Sierra Nevada, California. *A and B after F. E. Matthes, 1930, U.S. Geological Survey; photo by C. C. Plummer* melted back, a chain of **rock-basin lakes** (also known as **tarns**) may occupy the depressions carved out of the weaker rock. A series of such lakes, reminiscent of a string of prayer beads, is sometimes called *paternoster lakes.*

Areas where the bedrock is more resistant to erosion stand out after glaciation as *rounded knobs* (see figures 12.15 and 12.22), usually elongated parallel to the direction of glacier flow. These are also known as *roches moutonnées.* (In French, *roche* is rock and *moutonnée* means fleecy or curled.*)

### *Cirques, Horns, and Arêtes*

A **cirque** is a steep-sided, half-bowl-shaped recess carved into a mountain at the head of a valley carved by a glacier (figure 12.18). In this unique, often spectacular, topographic feature, a large percentage of the snow accumulates that eventually converts to glacier ice and spills over the threshold as the valley glacier starts its downward course.

A cirque is not entirely carved by the glacier itself but is also shaped by the weathering and erosion of the rock walls above the surface of the ice. Frost wedging and avalanches break up the rock and steepen the slopes above the glacier. Broken rock tumbles onto the valley glacier and becomes part of its load, and some rock may fall into a crevasse that develops where the glacier is pulling away from the cirque wall (figure 12.19).

The headward erosional processes that enlarge a cirque also help create the sharp peaks and ridges characteristic of glaciated mountain ranges. A **horn** is the sharp peak that remains after cirques have cut back into a mountain on several sides (figure 12.20).

Frost wedging works on the rock exposed above the glacier, steepening and cutting back the side walls of the valley. Sharp ridges called **arêtes** separate adjacent glacially carved valleys (figure 12.21).

## Erosional Landscapes Associated with Continental Glaciation

In contrast to the rugged and angular nature of glaciated mountains, an ice sheet tends to produce rounded topography. The rock underneath an ice sheet is eroded in much the same way as the rock beneath a valley glacier; however, the weight and thickness of the ice sheet may produce more pronounced effects. Rounded knobs are common (figure 12.22), as are grooved and striated bedrock. Some grooves are actually channels several meters deep and many kilometers long. The orientation of grooves and striations indicates the direction of movement of a former ice sheet.

An ice sheet may be thick enough to bury mountain ranges, rounding off the ridges and summits and perhaps streamlining them in the direction of ice movement. Much of northeastern Canada, with its rounded mountains and grooved and striated bedrock surface, shows the erosional effects of

**FIGURE 12.18**

A cirque occupied by a small glacier in the Canadian Rocky Mountains. The glacier was much larger during the ice ages. *Photo by C. C. Plummer*

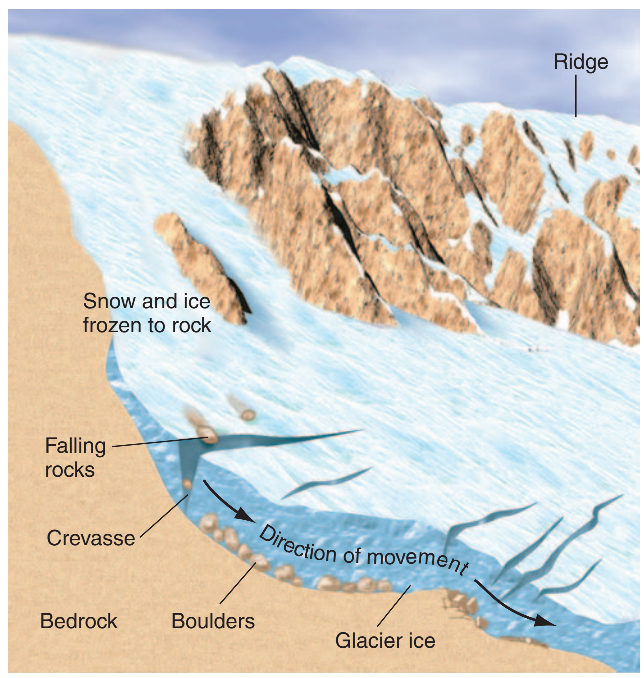



**FIGURE 12.19**

Cutaway view of a cirque.

*The term was first used in the 1780s to describe an assemblage of rounded knobs in the Swiss Alps. It alluded to a fleecy wig called a *moutonné,* popular at that time, that was slicked down with sheep tallow. Later, the term came to refer to individual rounded knobs that resembled sheep—*mouton* is French for sheep.

**FIGURE 12.20**
Ama Dablan, a horn in the Mount Everest region of the Himalaya in Nepal. Note the cirque below the peak. *Photo by C. C. Plummer*

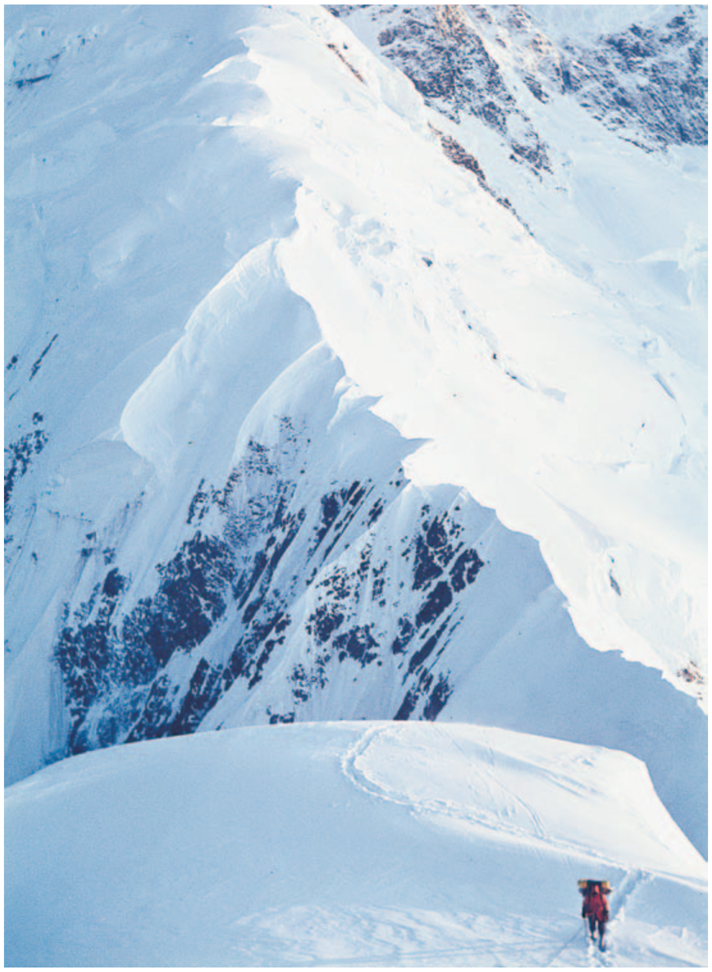


**FIGURE 12.21**
An arête on Mount Logan, Yukon, Canada. *Photo by C. C. Plummer*

ice sheets that formerly covered that part of North America (figure 12.23).

## GLACIAL DEPOSITION

The rock fragments scraped and plucked from the underlying bedrock and carried along at the base of the ice make up most of the load carried by an ice sheet but only part of a valley glacier's load. Much of a valley glacier's load comes from rocks broken from the valley walls.

Most of the rock fragments carried by glaciers are angular, as the pieces have not been tumbled around enough for the edges and corners to be rounded. The debris is unsorted, and clay-sized to boulder-sized particles are mixed


**FIGURE 12.22**
Rounded knob (*roche moutonnée*) with an erratic (the boulder) on it in Central Park, New York City. *Photo by Charles Merguerian*

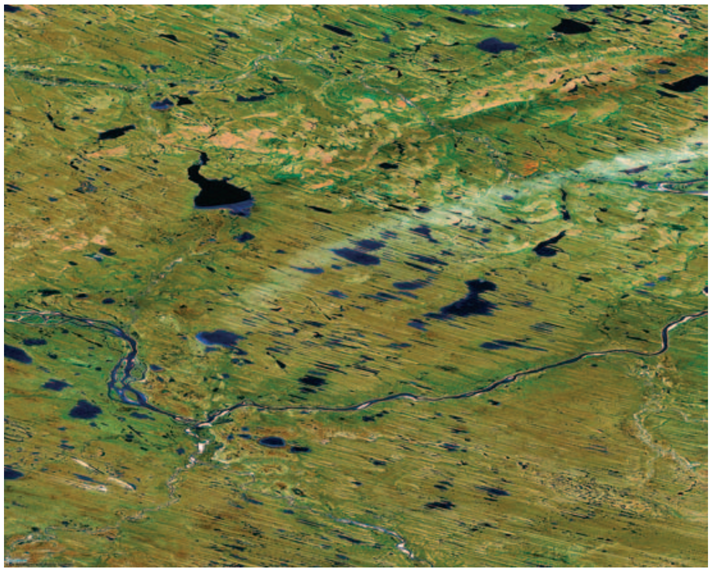


**FIGURE 12.23**

Glacially scoured terrain near Baker Lake, Northwest Territories, Canada. *Satellite Imagery Provided by GlobeXplorer.com. © 2005*

together (figure 12.24). The unsorted and unlayered rock debris carried or deposited by a glacier is called **till.**

Glaciers are capable of carrying virtually any size of rock fragment, even boulders as large as a house. An **erratic** is an ice-transported boulder that has not been derived from underlying bedrock (figure 12.22). If its bedrock source can be found, the erratic indicates the direction of movement of the glacier that carried it.

## Moraines

When till occurs as a body of unsorted and unlayered debris either on a glacier or left behind by a glacier, the body is regarded as one of several types of **moraines. Lateral moraines** are elongate, low mounds of till that form along the sides of a valley glacier (figures 12.24, 12.25, 12.26, and 12.27). Rockfall debris from the steep cliffs that border valley glaciers accumulates along the edges of the ice to form lateral moraines.

Where tributary glaciers come together, the adjacent lateral moraines join and are carried downglacier as a single long

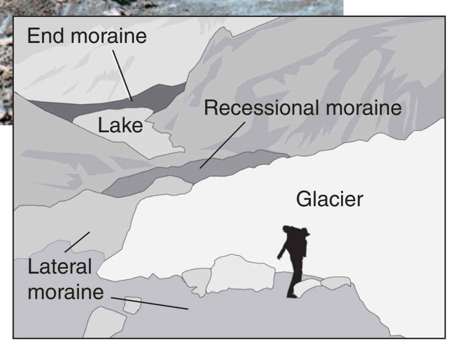



**FIGURE 12.24**

Till transported on top of and alongside a glacier in Peru. View is downglacier. The lake is dammed by an end moraine at its far end. *Photo by C. C. Plummer*

**Geologist's View**

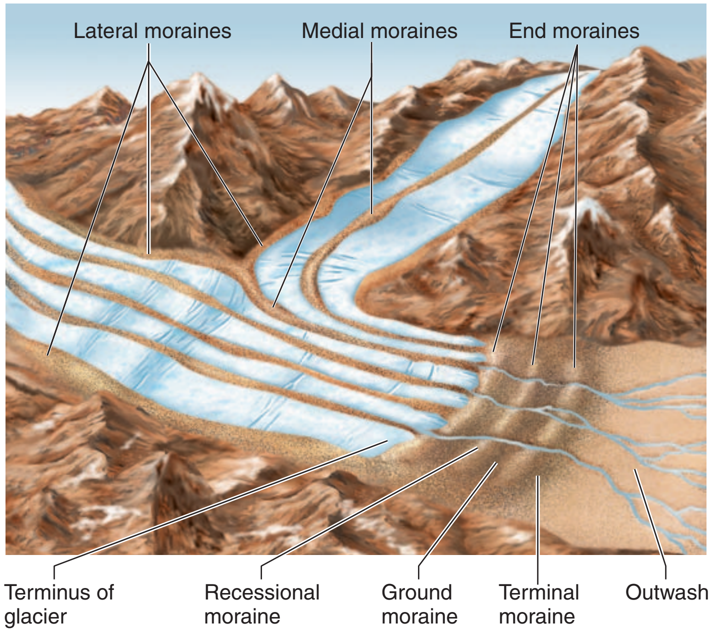



**FIGURE 12.25**
Moraines associated with valley glaciers.

ridge of till known as a **medial moraine.** In a large trunk glacier that has formed from many tributaries, the numerous medial moraines give the glacier the appearance from the air of a multilane highway (figures 12.25 and 12.26).

An actively flowing glacier brings debris to its terminus. If the terminus remains stationary for a few years or advances, a distinct **end moraine,** a ridge of till, piles up along the front edge of the ice. Valley glaciers build end moraines that are crescent-shaped or sometimes horseshoe-shaped (figures 12.25 and 12.27). The end moraine of an ice sheet takes a similar lobate form but is much longer and more irregular than that of a valley glacier (figure 12.28).

Geologists distinguish two special kinds of end moraines. A *terminal moraine* is the end moraine marking the farthest advance of a glacier. A *recessional moraine* is an end moraine built while the terminus of a receding glacier remains temporarily stationary. A single receding glacier can build several recessional moraines (as in figures 12.24, 12.25, 12.27, and 12.28).

As ice melts, rock debris that has been carried by a glacier is deposited to form a **ground moraine,** a fairly thin, extensive layer or blanket of till (figures 12.25 and 12.28). Very large areas that were once covered by an ice sheet now have the gently rolling surface characteristic of ground moraine deposits.

**FIGURE 12.26**
Medial and lateral moraines on valley glaciers, Yukon, Canada. Ice is flowing toward viewer and to lower right. *Photo by C. C. Plummer*

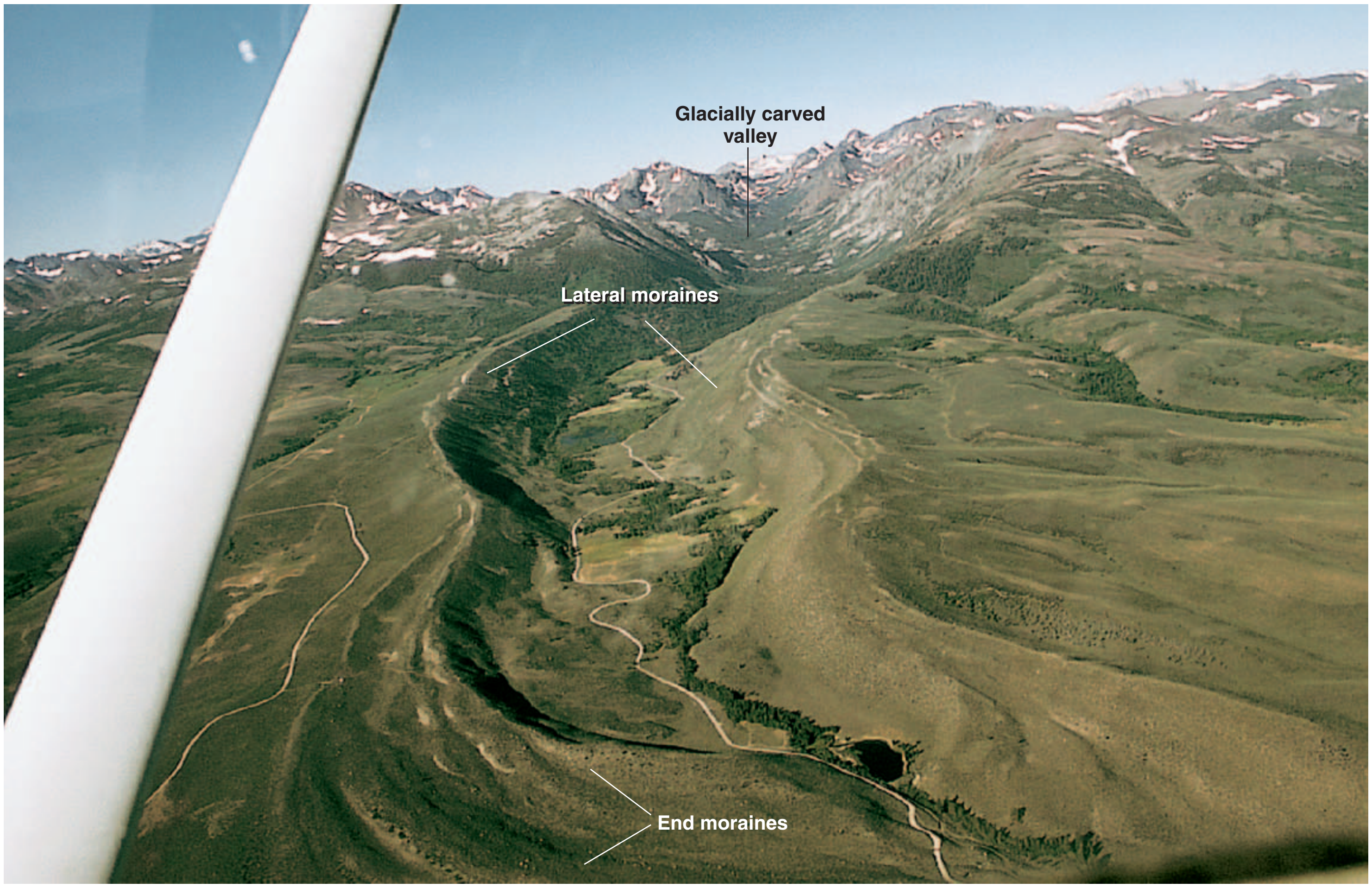



**FIGURE 12.27**

End moraines (recessional moraines) in the foreground, curve into two long, lateral moraines. The two lateral moraines extend back to a glacially carved valley in the Sierra Nevada, California. *Photo by C. C. Plummer*

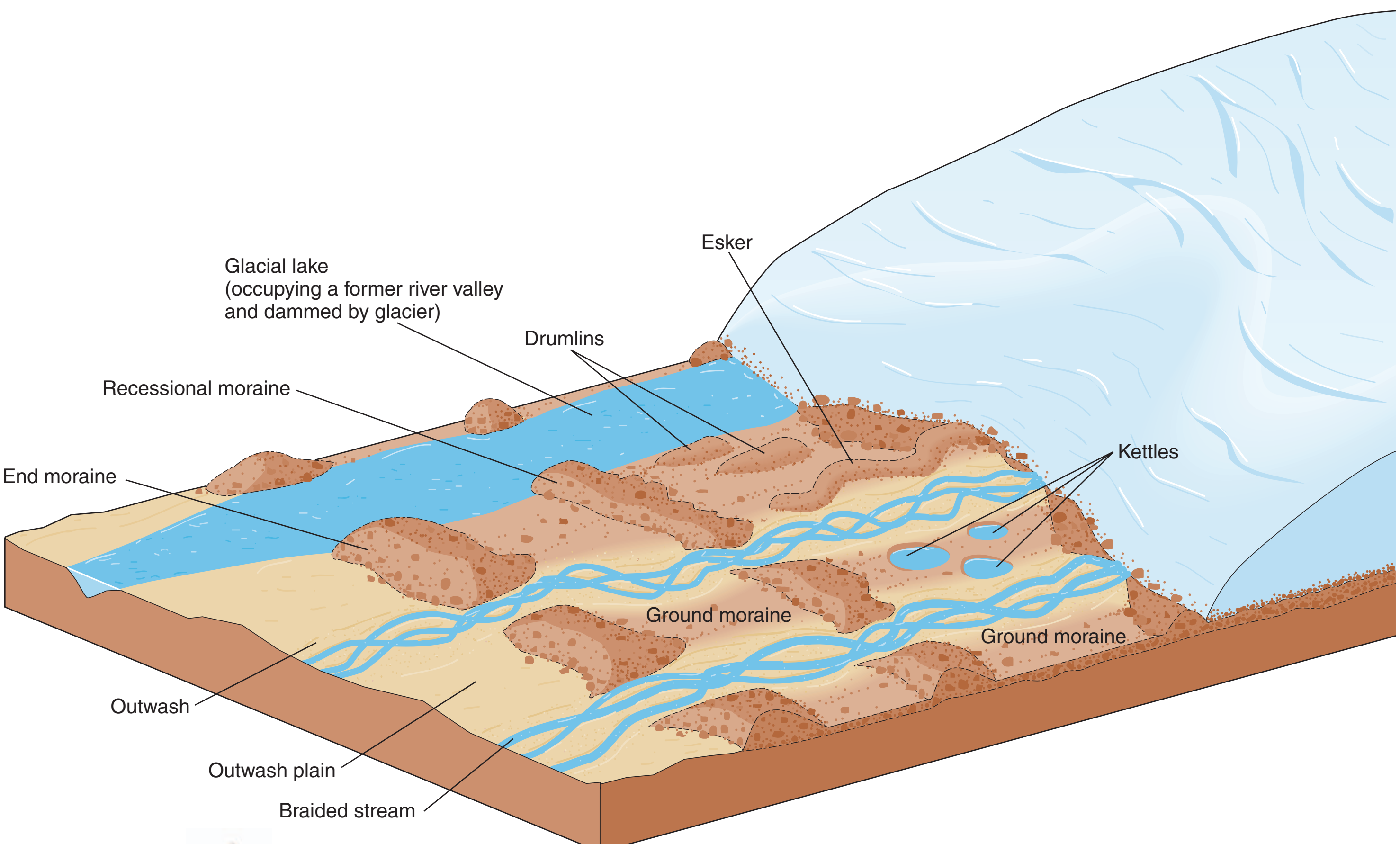



**FIGURE 12.28**

Depositional features in front of a receding ice sheet.

**FIGURE 12.29**

Drumlins in Wisconsin. They are lined up parallel to the direction of movement of the ice sheet. *Photo © Tom Bean*

In some areas of past continental glaciation, there are bodies of till shaped into streamlined hills called **drumlins** (figures 12.28 and 12.29). A drumlin is shaped like an inverted spoon aligned parallel to the direction of ice movement of the former glacier. Its gentler end points in the downglacier direction. Because we cannot observe drumlins forming beneath present ice sheets, we are not certain how till becomes shaped into these streamlined hills.

## Outwash

In the zone of ablation, large quantities of meltwater usually run over, beneath, and away from the ice. The material deposited by the debris-laden meltwater is called **outwash.** Because it has the characteristic layering and sorting of stream-deposited sediment, outwash can be distinguished easily from the unlayered and unsorted deposits of till. Because outwash is fairly well sorted and the particles generally are not chemically weathered, it is an excellent source of aggregate for building roadways and for mixing with cement to make concrete.

An outwash feature of unusual shape associated with former ice sheets and some very large valley glaciers is an **esker,** a long, sinuous ridge of water-deposited sediment (figures 12.28 and 12.30). Eskers can be up to 10 meters high and are formed of cross-bedded and well-sorted sediment. Evidently eskers are deposited in tunnels within or under glaciers, where meltwater loaded with sediment flows under and out of the ice.

As meltwater builds thick deposits of outwash alongside and in front of a retreating glacier, blocks of stagnant ice may be surrounded and buried by sediment. When the ice block finally melts (sometimes years later), a depression called a **kettle** forms (figures 12.28 and 12.31). Many of the small scenic lakes in the

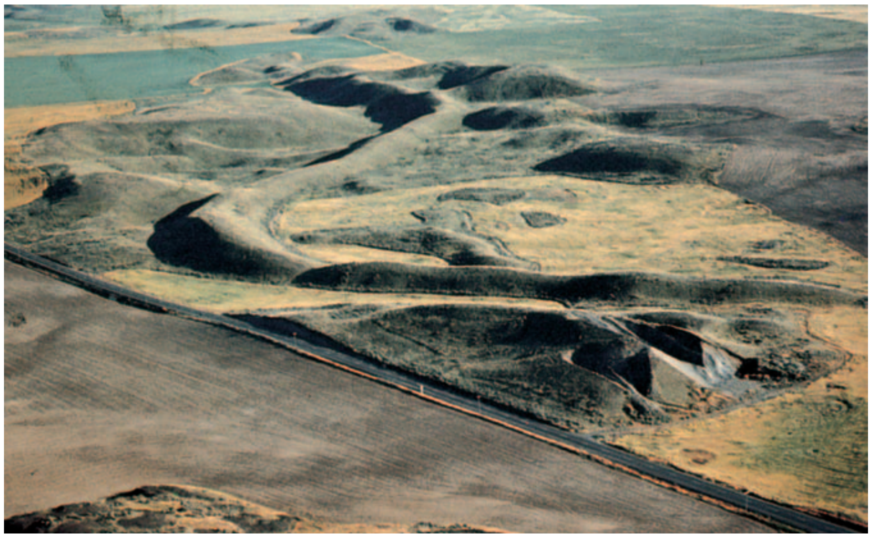


**FIGURE 12.30**

An esker in northeastern Washington. *Photo by D. A. Rahm, courtesy of Rahm Memorial Collection, Western Washington University* upper middle west of the United States are kettle lakes. A *kame* is a low mound or irregular ridge formed of outwash deposits on a stagnating glacier. Sediment accumulates in depressions or troughs on a glacier's surface. When the ice melts, the sediment remains as irregular, moundlike hills. The irregular, bumpy landscape of hills and depressions associated with many moraines is known as *kame and kettle topography.*

The streams that drain glaciers tend to be very heavily loaded with sediment, particularly during the melt season. As they come off the glacial ice and spread out over the outwash deposits, the streams form a braided pattern (see chapter 10 on streams).

The large amount of rock flour that these streams carry in suspension settles out in quieter waters. In dry seasons or drought, the water may dry up, and the rock flour deposits may be picked up by the wind and carried long distances. Some of the best agricultural soil in the United States has been formed by rock flour that has been redeposited by wind. Such fine-grained, wind-blown deposits of dust are called *loess* (see chapter 13).

## Glacial Lakes and Varves

Lakes often occupy depressions carved by glacial erosion but can also form behind dams built by glacial deposition. Commonly, a lake forms between a retreating glacier and an earlier end moraine (see figure 12.24).

In the still water of the lake, clay and silt settle on the bottom in two thin layers—one light-colored, one dark—that are characteristic of glacial lakes. Two layers of sediment representing one year's deposition in a lake are called a **varve** (figure 12.32). The light-colored layer consists of slightly coarser sediment (silt) deposited during the warmer part of the year when the nearby glacier is melting and sediment is transported to the lake. The silt settles within a few weeks or so after reaching the lake. The dark layer is finer sediment (clay)—material that sinks down more slowly during the winter after the lake surface freezes and the supply of fresh, coarser sediment stops due to lack of meltwater. The dark color is attributed to fine organic matter mixed with the clay.

Because each varve represents a year's deposit, varves are like tree rings and indicate how long a glacial lake existed.

# PAST GLACIATION

In the early 1800s, the hypothesis of past extensive continental glaciation of Europe was proposed. Among the many people who regarded the hypothesis as outrageous was the Swiss naturalist Louis Agassiz. But, after studying the evidence in

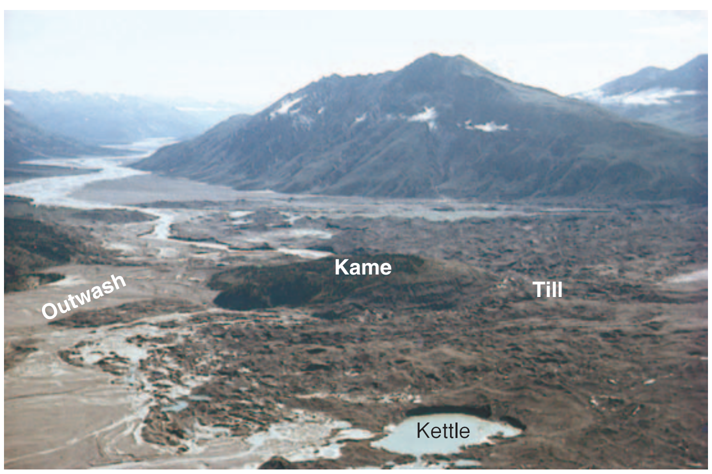



**FIGURE 12.31**

A kettle, a kame, and outwash (*background* and *left*) from a glacier, Yukon, Canada. Stagnant ice underlies much of the till. *Photo by C. C. Plummer*

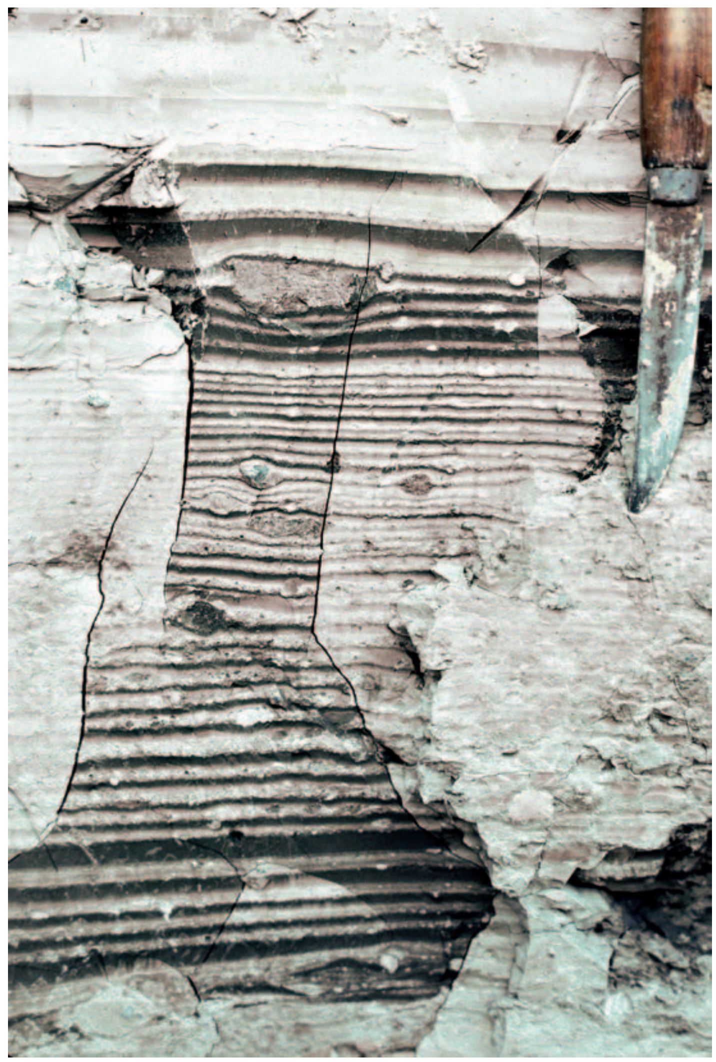


**FIGURE 12.32**

Varves from a former glacial lake. Each pair of light and dark layers represents a year's deposition. *Photo © Nick Eyles, University of Toronto, Scarborough*

PLANETARY GEOLOGY 12.4

# Mars on a Glacier

*Meteorites* are extraterrestrial rocks—fragments of material from space that have managed to penetrate Earth's atmosphere and land on Earth's surface. They are of interest not only to astronomers but to geologists, for they help us date Earth (chapter 8) and give us clues to what Earth's interior is like (see chapter 17) because many of the meteorites are thought to represent fragments of destroyed minor planets. Meteorites are rarely found; they usually do not look very different from Earth's rocks with which they are mixed.

The international Antarctic meteorite program has recovered 30,000 specimens during the last three decades. This far exceeds the total collected elsewhere in the past two centuries. Over a thousand meteorites have been collected from one small area where the ice sheet abuts against the Transantarctic Mountains. The reason for this heavy concentration is that meteorites landing on the surface of the ice over a vast area have been incorporated into the glacier and transported to where ablation takes place. The process is illustrated in box figure 1.

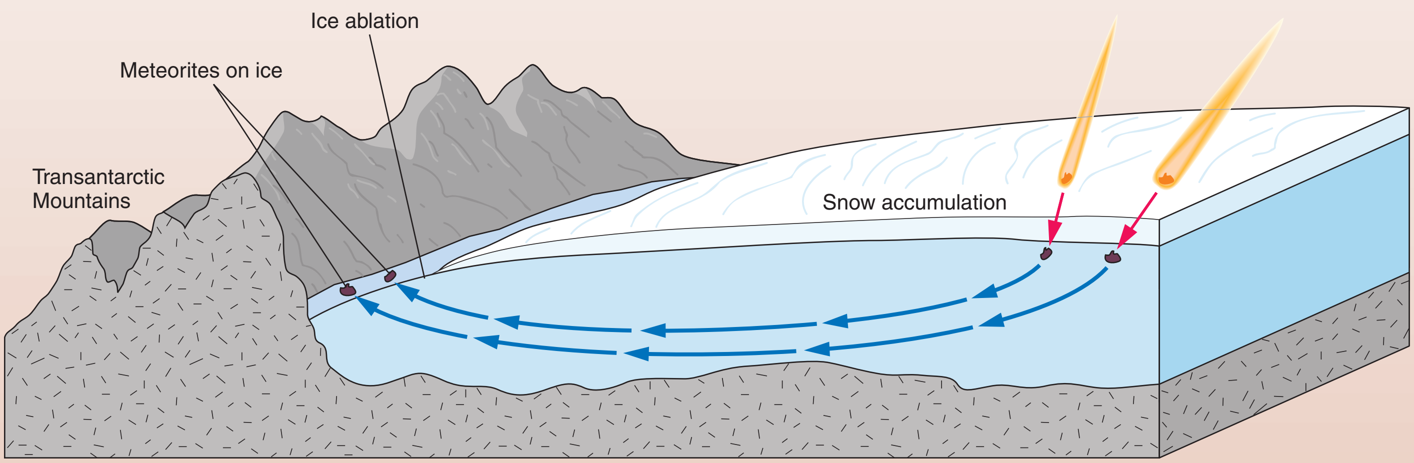
A few of the meteorites are especially intriguing. Some almost certainly are rocks from the moon, while several others apparently came from Mars. Their chemistry and physical properties match what we would expect of a Martian rock. But how could a rock escape Mars and travel to Earth? Scientists suggest that a meteorite hit Mars with such force that fragments of that planet were launched into space. Eventually, some of the fragments reached Earth.

In 1996, researchers announced that they found what could be signs of former life on Mars in one of the meteorites collected twelve years earlier in Antarctica. The evidence included carbon-containing molecules that might have been produced by living organisms as well as microscopic blobs that could be fossil alien bacteria. But there are alternate explanations for each line of evidence, and a hot debate has ensued between scientists with opposing viewpoints.

## Additional Resource

**Antarctic Meteorite Program**

- www-curator.jsc.nasa.gov/antmet/index.cfm




**BOX 12.4 ■ FIGURE 1**

Diagram showing the way in which meteorites are concentrated in a narrow zone of wastage along the Transantarctic Mountains. Two meteorites are shown as well as the paths they would have taken from the time they hit the ice sheet until they reached the zone of ablation. The vertical scale is greatly exaggerated. *Source: Antarctic Journal of the United States*

Switzerland, he changed his mind. In 1837, he published a discourse arguing that Switzerland was, in the past, entirely glaciated. Subsequently, he, along with the eminent English geologist William Buckland, found the same evidence in the British Isles for past glaciation that was found in Switzerland. Presently, there are no glaciers in Britain or Ireland. Agassiz, after further studies in northern Europe, concluded that a great glacier had covered most or all of Europe. Agassiz had to overcome skepticism over past climates being quite different from those of today. At the time, the hypothesis seemed to many geologists to be a violation of the principle of uniformitarianism. Agassiz later came to North America and worked with American geologists who had found similar indications of large-scale past glaciation on this continent.

As more evidence accumulated, the hypothesis became accepted as a theory that today is seldom questioned. The **theory of glacial ages** states that at times in the past, colder climates prevailed during which much more of the land surface of Earth was glaciated than at present (box 12.5).

As the glacial theory gained general acceptance during the latter part of the nineteenth century, it became clear that much of northern Europe and the northern United States as well as most of Canada had been covered by great ice sheets during the so-called Ice Age. It also became evident that even areas not covered by ice had been affected because of the changes in climate and the redistribution of large amounts of water.

We now know that the last of the great North American ice sheets melted away from Canada less than 10,000 years ago. In many places, however, till from that ice sheet overlies older tills, deposited by earlier glaciations. The older till is distinguishable from the newer till because the older till was deeply weathered during times of warmer climate between glacial episodes.

Geologists can reconstruct with considerable accuracy the last episode of extensive glaciation, which covered large parts of North America and Europe and was at its peak about 18,000 years ago (figure 12.33). There has not been enough time for weathering and erosion to alter significantly the effects of glaciation. Less evidence is preserved for each successively older glacial episode, because (1) weathering and erosion occurred during warm interglacial periods and (2) later ice sheets and valley glaciers overrode and obliterated many of the features of earlier glaciation. However, from piecing together the evidence, geologists can see that earlier glaciers covered approximately the same region as the more recent ones.

Ironically, we know more about when the numerous glacial ages began and ended not from glacial deposits but from deep-ocean sediment. As described in chapter 2, oxygen isotope studies ($^{18}O/^{16}O$ ratios in microfossil shells) have delineated changes in temperature of near-surface ocean water. The changes of temperature of the seas have been correlated with periods of extensive worldwide glaciation and intervening, interglacial warm climates. Studies of ice cores from Antarctica and Greenland have also provided important information on climate change (see box 12.3).

Although the glacial ages are generally associated with the Pleistocene Epoch (see chapter 8), cooling actually began earlier. Recent work indicates that worldwide climate changes necessary for northern continental glaciation probably began at least 3 million years ago, late in the Tertiary Period, at least a million years before the Pleistocene. Moreover, Antarctica has been glaciated for 14 million years.

Earth has undergone episodic changes in climate during the last 2 to 3 million years. Actually, the climate changes necessary for a glacial age to occur are not so great as one might imagine. During the height of a glacial age, the worldwide average of annual temperatures was probably only about 5°C cooler than at present. Some of the intervening interglacial periods were probably a bit warmer worldwide than present-day average temperatures.


**FIGURE 12.33**

Maximum glaciation during the Pleistocene in the Northern Hemisphere. Small glaciated areas are in mountains. Note that ice sheets extended beyond present continental shorelines. This is because sea level was lower than at present. Note that the North Pole (center of map), which is in the Arctic Ocean, was not glaciated. *After J. Ehlers and P. L. Gibbard, 2004, Quaternary glaciations—extent and chronology, Parts I–III. Elsevier.*

EARTH SYSTEMS 12.5

## Causes of Glacial Ages

Go to the book's website at www.mhhe.com/plummer12e for a more in-depth presentation of this summary.

The question of what caused the glacial ages has not been completely answered since the theory of glacial ages was accepted over a century ago. Only in the last few decades have climatologists thought they were beginning to provide acceptable answers.

The primary control on the Pleistocene glacial and interglacial episodes seems to be variations in Earth's orbit and inclination to the Sun. The amount of heat from solar radiation received by any particular portion of Earth is related to the angle of the incoming Sun's rays and, to a lesser degree, the distance to the Sun. The angle of Earth's poles relative to the plane of Earth's orbit about the Sun also changes periodically. Variations in orbital relationships and "wobble" of Earth's axis are largely responsible for glacial and interglacial episodes. These provide variations in incoming solar radiation cycles of 21,000, 41,000, and 100,000 years, as calculated by Milutin Milankovitch, a Serbian mathematician, in 1921. Support for Milankovitch's cycles came from cores of deep sediment taken by oceanographic research ships. Deep-sea sediment provides a fairly precise record of climatic variations over the past few hundred thousand years. The cycles of cooling and warming determined from the marine sediments closely match the times predicted by Milankovitch.

But the theory fails to explain the absence of glaciation over most of geologic time. Thus, one or more of the other mechanisms in the following list (and described in the website) may have contributed to climate change resulting in glacial ages.

- **Changes in the atmosphere.** These changes include the amount of carbon dioxide in the atmosphere. Carbon dioxide has a "greenhouse effect," whereby the more of the gas in the atmosphere, the warmer the global climate. Large volcanic eruptions are known to lower temperature worldwide by placing $SO_2$ gas and fine dust in the high atmosphere. A series of large, volcanic eruptions might help trigger an ice age.
- **Changes in the positions of continents.** Plate-tectonic movement of continents closer to the poles increases the likelihood of glaciation. Movement of Northern Hemisphere continents closer to the North Pole has placed landmasses in a position more favorable for glaciation.
- **Changes in circulation of sea water.** The surface of the Arctic Ocean freezes during the winter because bordering landmasses block its circulation with the warmer Atlantic Ocean. One hypothesis speculates that an ice age might have begun at a time when there was free circulation between the oceans. The Arctic Ocean surface would not have frozen over, and the increased moisture in the air would have resulted in greater snowfall to the adjacent continents.

## Direct Effects of Past Glaciation in North America

Moving ice abraded vast areas of northern and eastern Canada during the growth of the North American ice sheets. Most of the soil and sedimentary rock was scraped off, and underlying crystalline bedrock was scoured. Many thousands of future lake basins were gouged out of the bedrock.

The directions of ice flow can be determined from the orientation of striations and grooves in the bedrock and from elongate, rounded knobs. The largest ice sheet (the Laurentide Ice Sheet) moved outward from the general area now occupied by Hudson Bay, which is where the ice sheet was thickest. The present generally barren surface of the Hudson Bay area contrasts markedly with the Great Plains surface of southern Canada and northern United States, where vast amounts of till were deposited.

Most of the till was deposited as ground moraine, which, along with outwash deposits, has partially weathered to yield excellent soil for agriculture. Rock flour that originally washed out of ice sheets has been redistributed by wind, as *loess,* over large parts of the Midwest and eastern Washington to contribute to especially good agricultural land (see chapter 13). In many areas along the southern boundaries of land covered by ground moraines, broad and complex end moraines extend for many kilometers, indicating that the ice margin must have been close to stationary for a long time (figure 12.34). Numerous drumlins are preserved in areas such as Ontario, New England, and upstate New York. New York's Long Island is made of terminal and recessional moraines and outwash deposits. Erratics there come from metamorphic rock in New England. Cape Cod in Massachusetts was also formed from moraines.

Glaciers have a tremendous capability for forming lakes through both erosion and deposition. Most states and provinces that were glaciated have thousands of lakes. By contrast, Virginia, which was not glaciated, has only two natural lakes. Minnesota bills itself as "the land of 10,000 lakes." Most of those lakes are kettle lakes. The Finger Lakes in New York (figure 12.35) are in long, north-south glacially modified valleys that are dammed by recessional moraines at their southern ends. The Great Lakes are, at least in part, a legacy of continental glaciation. Former stream valleys were widened by the ice sheet eroding weak layers of sedimentary rock into the present lake basins. End moraines border the Great Lakes, as shown in figure 12.34. Large regions of Manitoba, Saskatchewan, North Dakota, and Minnesota were covered by ice-dammed lakes. The largest of these is called Lake Agassiz. The former lake beds are now rich farmland.

Alpine glaciation was much more extensive throughout the world during the glacial ages than it is now. For example, small glaciers in the Rocky Mountains that now barely extend beyond their cirques were then valley glaciers 10, 50, or 100 kilometers in length. Yosemite Valley, which is no longer glaciated, was filled by a glacier about a kilometer thick. Its terminus was at an elevation of about 1,300 meters above sea level. Furthermore, cirques and other features typical of valley glaciers can be found in regions that at present have no glaciers, such as the northern Appalachians—notably in the White Mountains of New Hampshire.

## Indirect Effects of Past Glaciation

As the last continental ice sheet wasted away, what effects did the tremendous volume of meltwater have on American rivers? Rivers that now contain only a trickle of water were huge in the glacial ages. Other river courses were blocked by the ice sheet or clogged with morainal debris. Large dry stream channels have been found that were preglacial tributaries to the Mississippi and other river systems.

### *Glacial Lakes*

During the ice ages, the retreating Laurentide Ice Sheet was a dam for an enormous lake—Glacial Lake Agassiz (figure 12.34). Canada's Lake Winnipeg is the largest remnant of Lake Agassiz.

Another noteworthy glacial lake was Glacial Lake Missoula. This lake formed when the ice sheet advanced into Montana. Ice dammed up a river system creating a large lake. Eventually, the lake overtopped and destroyed the ice dam resulting in a giant flood (box 12.6).

### *Pluvial Lakes*

During the glacial ages, the climate in North America, beyond the glaciated parts, was more humid than it is now. Most of the presently arid regions of the western United States had moderate rainfall, as traces or remnants of numerous lakes indicate. These **pluvial lakes** (formed in a period of abundant rainfall) once existed in Utah, Nevada, and eastern California (figure 12.34). Some may have been fed by meltwater from


**FIGURE 12.34**

End moraines in the contiguous United States and Canada (shown by brown lines), and glacial lakes Agassiz and Missoula, as well as pluvial lakes in the western United States (magenta). *After C. S. Denny, U.S. Geological Survey, and the Geological Map of North America, Geological Society of America, and the Geological Survey of Canada*

**FIGURE 12.35**

Satellite image of Finger Lakes in New York. Part of Lake Ontario is at the top. *Photo © Advanced Satellite Productions, Inc.*

mountain glaciers, but most were simply the result of a wetter climate.

Great Salt Lake in Utah is but a small remnant of a much larger body of fresh water called Lake Bonneville, which, at its maximum size, was nearly as large as Lake Michigan is today. Ancient beaches and wave-cut terraces on hillsides indicate the depth and extent of ancient Lake Bonneville. As the climate became more arid, lake levels lowered, outlets were cut off, and the water became salty, eventually leaving behind the Bonneville salt flats and the present very saline Great Salt Lake.

Even Death Valley in California—now the driest and hottest place in the United States—was occupied by a deep lake during the Pleistocene. The salt flats (see figure 6.24) that were left when this lake dried include rare boron salts that were mined during the pioneer days of the American West.

### *Lowering and Rising of Sea Level*

All of the water for the great glaciers had to come from somewhere. The water was "borrowed" from the oceans, such that sea level worldwide was lower than it is today—at least 130 meters lower, according to scientific estimates. Figure 12.36 shows the present shoreline for part of North America and the position of the inferred coastline during the height of Pleistocene glaciation. It also shows where the shoreline would be if the Antarctic and Greenland ice sheets were to disappear.

Recall that if today's ice sheets were to melt, sea level worldwide would rise by over 60 meters, and shorelines would be considerably further inland. It's important to realize that our present shorelines are not fixed and are very much controlled by climate changes. We should also realize that we are still in a cooler than usual (relative to most of Earth's history) time, perhaps the lingering effects of the last ice age.

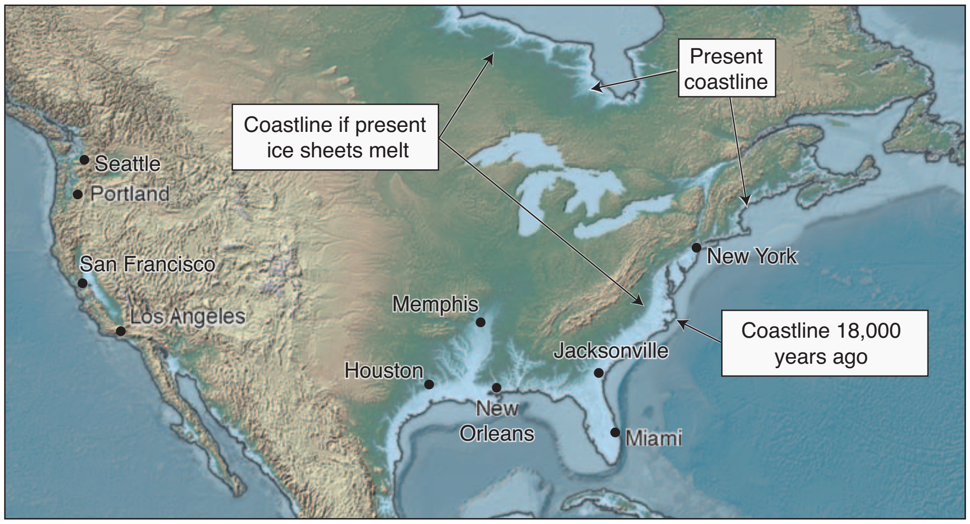



**FIGURE 12.36**

Map of North America showing the present coastline as well as the coastline at the height of the last glacial age, around 18,000 years ago. The map also shows the coastline we could expect if the Greenland and Antarctic ice sheets melt.

IN GREATER DEPTH 12.6

## The Channeled Scablands

In chapter 4, we described how the Columbia plateau in the Pacific Northwest (see figure 4.27) was built by a series of successive lava floods. The northeastern part of the plateau features a unique landscape, known as the channeled scablands, where the basalt bedrock has been carved into a series of large, interweaving valleys. From the air, the pattern looks like that of a giant braided stream. The channels, however, which range up to 30 kilometers wide and are usually 15 to 30 meters deep, are mostly dry.

The scablands are believed to have been carved by gigantic floods of water. Huge ripples in gravel bars (box figure 1) support this idea. To create these ripples, a flood would have to be about 10 times the combined discharge of all the world's rivers. This is much larger than any flood in recorded history.

What seems to have occurred is that, during the ice ages, a lobe of the ice sheet extended southward into northern Washington, Montana, and Idaho, blocking the head of the valley occupied by the Clark Fork River. The ice provided a natural dam for what is now known as Glacial Lake Missoula. Lake Missoula drowned a system of valleys in western Montana that extended hundreds of kilometers into the Rocky Mountains.

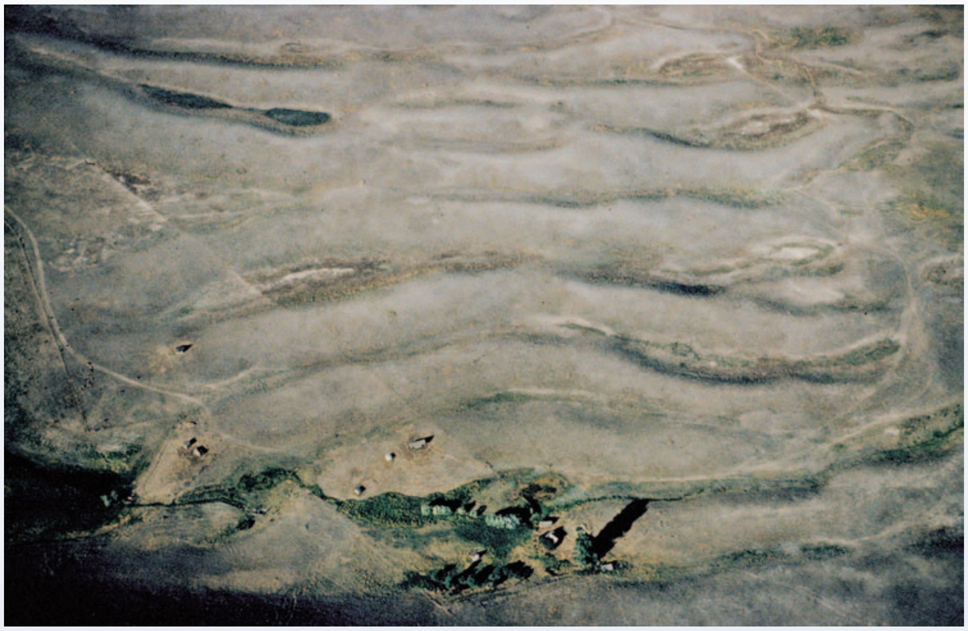
Ice is not ideal for building dams. Upon failure of the glacial dam, the contents of Lake Missoula became the torrential flood that scoured the Columbia plateau. There were dozens of giant floods. Advancing ice from Canada would reestablish the dam, only to be destroyed after the reservoir refilled.

Mars has what appear to be giant outflow channels that are similar to those of the channeled scablands. At present, Mars has no liquid water, but the channels suggest that there must have been a huge amount of water in the distant past.

### Additional Resource

**Ice Age Flood Home Site**

- www.iceagefloodsinstitute.org/



**BOX 12.6 ■ FIGURE 1**

Giant ripples of gravel from the draining of Lake Missoula, Montana. For scale, see farm buildings in lower middle of photo. *Photo by P. Weiss, U.S. Geological Survey*

**FIGURE 12.37**

Lysenfjord, a fiord in Norway. Underwater it is a deep, U-shaped valley. *Photo © Jan Stromme/Alamy*

What is the evidence for lower sea level? Stream channels have been charted in the present continental shelves, the gently inclined, now submerged edges of the continents (described in chapter 18 on the sea floor). These submerged channels are continuations of today's major rivers and had to have been above sea level for stream erosion to take place. Bones and teeth from now-extinct mammoths and mastodons have been dredged up from the Atlantic continental shelf, indicating that these relatives of elephants roamed over what must have been dry land at the time.

A **fiord** (also spelled fjord) is a coastal inlet that is a drowned glacially carved valley (figure 12.37). Fiords are common along the mountainous coastlines of Alaska, British Columbia, Chile, New Zealand, and Norway. Surprisingly, the lower reach of the Hudson River, just north of New York City, is a fiord. Fiords are evidence that valleys eroded by past glaciers were later partly submerged by rising sea level.

### *Crustal Rebound*

The weight of an ice sheet several thousand meters thick depresses the crust of Earth much as the weight of a person depresses a mattress. A land surface bearing the weight of a continental ice sheet may be depressed several hundred meters.

Once the glacier is gone, the land begins to rebound slowly to its previous height (see chapter 17 and figures 17.13 and 17.14). Uplifted and tilted shorelines along lakes are an indication of this process. The Great Lakes region is still rebounding as the crust slowly adjusts to the removal of the last ice sheet.

## Evidence for Older Glaciation

Throughout most of geologic time, the climate has been warmer and more uniform than it is today. We think that the late Cenozoic Era is unusual because of the periodic fluctuations of climate and the widespread glaciations. However, glacial ages are not restricted to the late Cenozoic.

Evidence of older glaciation comes from rocks called tillites. A **tillite** is lithified till (figure 12.38). Unsorted rock particles, including angular, striated, and faceted boulders, have been consolidated into a sedimentary rock. In some places, tillite layers overlie surfaces of older rock that have been polished and striated. Tillites of the late Paleozoic and tillites representing a minor part of the late Precambrian crop out in parts of the southern continents. (The striated surface in Australia, shown in figure 12.13, is overlain in places by late Paleozoic tillite.)

The oldest glaciation, for which we have evidence, appears to have taken place in what is now Ontario around 2.3 billion years ago.

Support is growing for the idea that a late Precambrian Ice Age was so extensive that the surfaces of the world's oceans were frozen. Although the concept was first proposed in the early twentieth century, scientists in the 1990s began taking it seriously and called it the *snowball Earth hypothesis*. Evidence for the hypothesis includes tillites that must, at the time, have been deposited near the equator. The hypothesis proposes that the extreme cold was due to the Sun being weaker at the time and the absence of carbon dioxide and other greenhouse gases in the atmosphere. For more, go to www.snowballearth.org/.

Paleozoic glaciation provides strong support for plate tectonics. The late Paleozoic tillites in the southern continents (South Africa, Australia, Antarctica, South America) indicate that these landmasses were once joined (see chapter 19 on plate tectonics). Directions of striations show that an ice sheet flowed onto South America from what is now the South Atlantic Ocean. Because an ice sheet can build up only on land, it is reasonable to conclude that the former ice sheet was centered on the ancient supercontinent.

**FIGURE 12.38**

The Dwyka tillite in South Africa. It is of Permian (late Paleozoic) age. Similar Permian tillites found in South America, Australia, and India are used as evidence for the existence of a super continent and continental drift (see figure 19.4). *Photo by Robert J. Stull*

## Summary

A *glacier* is a large, long-lasting mass of ice that forms on land and moves under its own weight. A glacier can form wherever more snow accumulates than is lost. *Ice sheets* and *valley glaciers* are the two most common types of glaciers. Glaciers move downward from where the most snow accumulates toward where the most ice is ablated.

A glacier moves by both basal sliding and internal flow. The upper portion of a glacier tends to remain rigid and is carried along by the ice flowing beneath it.

Glaciers advance and recede in response to changes in climate. A receding glacier has a *negative budget,* and an advancing one has a *positive budget.* A glacier's budget for the year can be determined by noting the relative position of the *equilibrium line,* which separates the *zone of accumulation* from the *zone of ablation.*

Snow recrystallizes into firn, which eventually becomes converted to glacier ice. Glacier ice is lost (or ablated) by melting, breaking off as icebergs, and direct evaporation of the ice into the air.

A glacier erodes by plucking and the grinding action of the rock it carries. The grinding produces rock flour and faceted and polished rock fragments. Bedrock over which a glacier moves is generally polished, striated, and grooved.

A mountain area showing the erosional effects of alpine glaciation possesses relatively straight valleys with U-shaped cross profiles. The floor of a glacial valley usually has a *cirque* at its head and descends as a series of rock steps. Small *rock-basin lakes* are commonly found along the steps and in cirques.

A *hanging valley* indicates that a smaller tributary joined the main glacier. A *horn* is a peak between several cirques. *Arêtes* usually separate adjacent glacial valleys.

A glacier deposits unsorted rock debris or *till,* which contrasts sharply with the sorted and layered deposits of glacial *outwash.* Till forms various types of *moraines.*

Fine silt and clay may settle as *varves* in a lake in front of a glacier, each pair of layers representing a year's accumulation.

Multiple till deposits and other glacial features indicate several major episodes of glaciation during the late Cenozoic Era. During each of these episodes, large ice sheets covered most of northern Europe and northern North America, and glaciation in mountain areas of the world was much more extensive than at present. At the peak of glaciation, about a third of Earth's land surface was glaciated (in contrast to the 10% of the land surface presently under glaciers). Warmer climates prevailed during interglacial episodes.

The glacial ages also affected regions never covered by ice. Because of wetter climate in the past, large lakes formed in now-arid regions of the United States. Sea level was considerably lower.

Glacial ages also occurred in the more distant geologic past, as indicated by late Paleozoic and Precambrian tillites.

## Terms to Remember

ablation 311
advancing glacier 311
alpine glaciation 308
arête 321
basal sliding 313
cirque 321
continental glaciation 308
crevasse 314
drumlin 326
end moraine 324
equilibrium line 311
erratic 323
esker 326
fiord 334
glacier 308
ground moraine 324
hanging valley 319
horn 321
iceberg 311
ice cap 309
ice sheet 309
kettle 326
lateral moraine 323
medial moraine 324
moraine 323
outwash 326
plastic flow 313
pluvial lake 331
receding glacier 311
rigid zone 314
rock-basin lake 321
rock flour 316
tarns 321
terminus 312
theory of glacial ages 329
till 323
tillite 334
truncated spur 320
U-shaped valley 319
valley glacier 309
varve 327
zone of ablation 311
zone of accumulation 311

## Testing Your Knowledge

Use the following questions to prepare for exams based on this chapter.

1. How do erosional landscapes formed beneath glaciers differ from those that developed in rock exposed above glaciers?
2. How do features caused by stream erosion differ from features caused by glacial erosion?
3. How does material deposited by glaciers differ from material deposited by streams?
4. Why is the North Pole not glaciated?
5. How do arêtes, cirques, and horns form?
6. How does the glacial budget control the migration of the equilibrium line?
7. How do recessional moraines differ from terminal moraines?
8. Alpine glaciation
   a. is found in mountainous regions
   b. exists where a large part of a continent is covered by glacial ice
   c. is a type of glacier
   d. none of the preceding
9. Continental glaciation
   a. is found in mountainous regions
   b. exists where a large part of a continent is covered by glacial ice
   c. is a glacier found in the subtropics of continents
   d. none of the preceding

10. At present, about _____% of the land surface of the Earth is covered by glaciers.
    a. 1/2 b. 1
    c. 2 d. 10
    e. 33 f. 50
11. Which is not a type of glacier?
    a. valley glacier b. ice sheet
    c. ice cap d. sea ice
12. The boundary between the zone of accumulation and the zone of ablation of a glacier is called the
    a. firn
    b. equilibrium line
    c. ablation zone
    d. moraine
13. In a receding glacier
    a. ice flows from lower elevations to higher elevations
    b. the terminus moves upvalley
    c. the equilibrium line moves to a lower elevation
    d. all of the preceding
14. Recently, geologists have been drilling through ice sheets for clues about
    a. ancient mammals
    b. astronomical events
    c. extinctions
    d. past climates
15. Glacially carved valleys are usually _____ shaped.
    a. V b. U
    c. Y d. all of the preceding
16. Which is not a type of moraine?
    a. medial b. end
    c. terminal d. recessional
    e. ground f. esker
17. The last episode of extensive glaciation in North America was at its peak about _____ years ago.
    a. 2,000 b. 5,000
    c. 10,000 d. 18,000
18. How fast does the central part of a valley glacier move compared to the sides of the glacier?
    a. faster b. slower
    c. at the same rate
19. During the Ice Ages, much of Nevada, Utah, and eastern California was covered by
    a. ice b. huge lakes
    c. deserts d. the sea

## *Expanding Your Knowledge*

1. How might a warming trend cause increased glaciation?
2. How do, or do not, the Pleistocene glacial ages fit in with the principle of uniformitarianism?
3. Is ice within a glacier a mineral? Is a glacier a rock?
4. Could a rock that looks like a tillite have been formed by any agent other than glaciation?
5. What is the likelihood of a future glacial age? What effect might human activity have on causing or preventing a glacial age?

## Exploring Web Resources

**www.mhhe.com/plummer12e**

McGraw-Hill's ARIS website for *Physical Geology* 12th edition features a wide variety of study aids, such as animations, quizzes, answers to the Testing Your Knowledge questions, additional readings and media resources, Internet exercises, and much more. The URLs listed in this book are given as links in chapter web pages, making it easy to go to a website without typing in its URL. The ARIS website can also be used by instructors to create and share course materials and assignments with students.

**http://dir.yahoo.com/science/earth_sciences/geology_and_geophysics/glaciology/**

*Glaciers and Glaciology—list of sites*. This site provides links and descriptions of numerous icy websites.

**www.glacier.rice.edu/**

*Glacier.* Explore Antarctica on Rice University's site. Go to "Ice." There are many topics you can go to for information that expands on that covered in this book. Examples are "How Do Glaciers Move?" "How Do Glaciers Change the Land?" and "What Causes Ice Ages?"

**www.crevassezone.org/**

*Glacier movement studies on the Juneau Icefield, Alaska*. Go to "Photo Gallery" to view photos of glacial features and other aspects of the project.

**www.museum.state.il.us/exhibits/ice_ages/**

*Ice Ages*. Illinois State Museum's virtual ice ages exhibit. The site features a tape clip showing the retreat of glaciers during the last ice age. You can download the video clip by going to:
**www.museum.state.il.us/exhibits/ice_ages/laurentide_deglaciation.html**

**http://nsidc.org/cryosphere/index.html**

*The Cryosphere*. General information on snow and ice. You can link to pages on glaciers, avalanches, and icebergs.

**www.swisseduc.ch/glaciers/**

*Swiss Educ: Glaciers Online*. A very nice website with stunning photographs illustrating a wide range of glacial features and processes. By glaciologists Jürg Alean (Swiss) and Michael Hambrey (British), authors of the book *Glaciers*.

## Animations

This chapter includes the following animations on the book's ARIS website at **www.mhhe.com/plummer12e**.

12.6 Dynamics of glacial advance and retreat
12.9 Crevasse formation in glaciers
12.28 Formation of glacial features by deposition at a wasting ice front
12.33 Glacial maximum and deglaciation