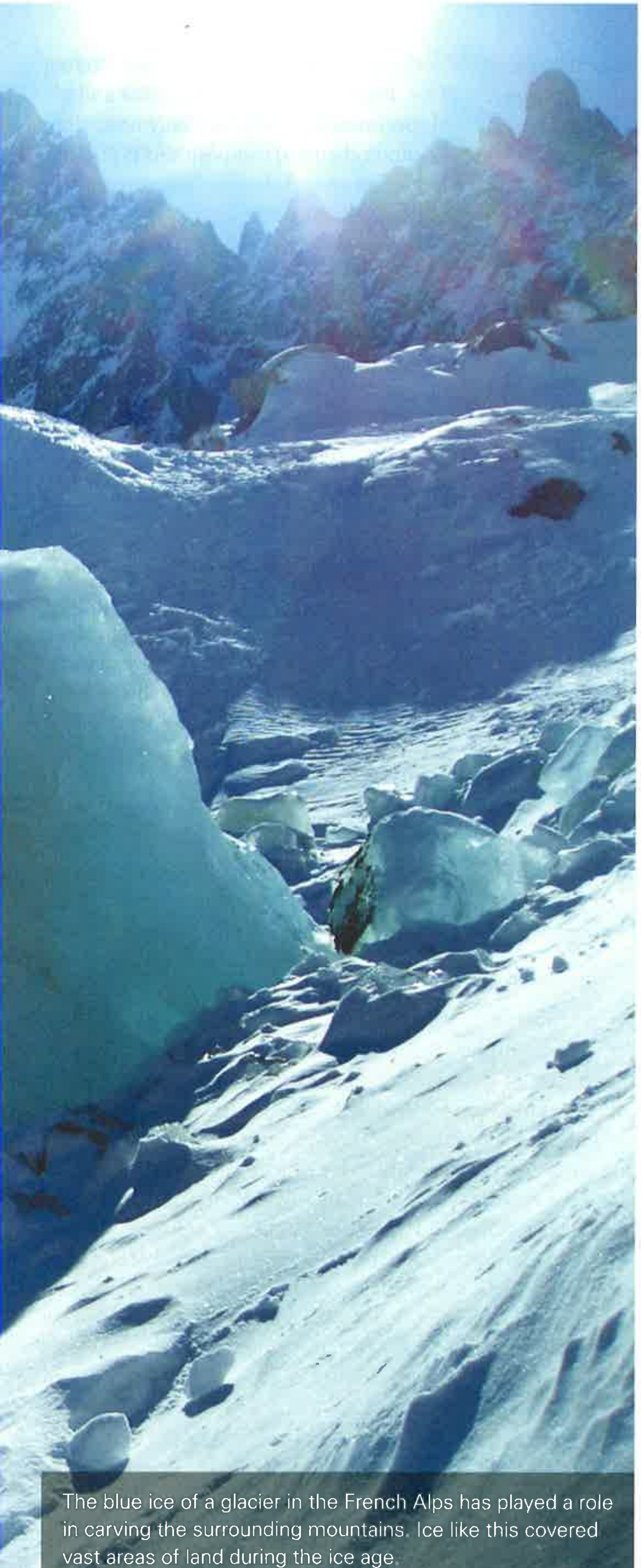


The blue ice of a glacier in the French Alps has played a role in carving the surrounding mountains. Ice like this covered vast areas of land during the ice age.

Chapter Objectives

By the end of this chapter you should know . . .

- how glacial ice forms and flows, and how to categorize various kinds of glaciers.
- how glaciers advance and retreat, and how their flow erodes the landscape.
- how to recognize sedimentary deposits and associated landforms left by glaciers.
- that glaciers covered large areas of continents and that sea level dropped during ice ages.
- why ice ages happen, and why glaciations during an ice age happen periodically.

I seemed to vow to myself that some day I would go to the region of ice and snow and go on and on till I came to one of the poles of the earth.

—Ernest Shackleton
(British polar explorer, 1874–1922)

18.1 Introduction

There's nothing like a good mystery, and one of the most puzzling in the annals of geology came to light in northern Europe early in the 19th century. When farmers of the region prepared their land for spring planting, they occasionally broke their plows by running them into boulders buried randomly through otherwise fine-grained sediment. Many of these boulders did not consist of local bedrock, but rather came from outcrops hundreds of kilometers away. Because the boulders had apparently traveled so far, they came to be known as **erratics** (from the Latin *errare*, to wander).

The mystery of the wandering boulders became a subject of great interest to early 19th-century geologists, who realized that such deposits of extremely *unsorted* sediment (sediment that contains a variety of clast sizes) could not be examples of typical stream alluvium, for running water sorts sediment by size. Most attributed the deposits to a vast flood that they imagined had been powerful enough to spread a slurry of boulders, sand, and mud across the continent. In 1837, however, a young Swiss geologist named Louis Agassiz proposed a radically different interpretation. Agassiz often hiked among **glaciers** (slowly flowing masses of ice that survive the summer melt) in the Alps near his home. He observed that glacial ice could carry enormous boulders as well as sand and mud, because ice is solid and has enough strength to support the weight of rock. Agassiz realized that, because solid ice does not sort sediment as it flows, glaciers leave behind unsorted sediment when they melt. On the basis of these observations, he proposed that the mysterious sediment and erratics of Europe were deposits left by ice sheets, vast glaciers that had once covered much of the continent (**Fig. 18.1**). In Agassiz's mind, Europe had once been in the grip of an **ice age**, a time when the climate was significantly colder and glaciers grew.

Agassiz's radical proposal faced intense criticism for the next two decades, but by the late 1850s, most doubters had changed their minds, and the geological community concluded that the notion that Europe once had Arctic-like climates was correct. Later in life, Agassiz traveled to the United States and documented many glacier-related features in North America's landscape, proving that an ice age had affected vast areas of the planet. Glaciers cover only about 10% of the land on Earth today, but during the most recent ice age, which ended only about 11,000 years ago, as much as 30% of continental land surface had a coating of ice. New York City, Montreal, and many of the great cities of Europe now occupy land that once lay beneath hundreds of meters to a few kilometers of ice.

The work of Louis Agassiz brought the subject of glaciers and ice ages into the realm of geologic study and led people to recognize that major climate changes happen in Earth history. In this chapter, after considering the nature of ice, we see how glaciers form, why they move, and how they modify landscapes by erosion and deposition. A substantial portion of the chapter concerns the most recent ice age, known as the Pleistocene Ice Age, for its impact on the landscape can still be seen today. But we briefly introduce ice ages that happened earlier in Earth history too. We conclude by considering hypotheses put forth to explain why ice ages happen.

18.2 Ice and the Nature of Glaciers

What Is Ice?

Ice consists of solid water, formed when liquid water cools below its freezing point. We can apply concepts introduced in our earlier discussions of rocks and minerals to distinguish among various occurrences of ice. For example, we can think of a single ice crystal as a mineral specimen, for it is a naturally occurring, inorganic solid, with a definite chemical composition (H_2O) and a regular crystal structure. Ice crystals have a hexagonal form, so snowflakes grow into six-pointed stars (**Fig. 18.2a**). We can picture a layer of fresh snow as a layer of sediment, and a layer of snow that has been compacted so that the grains stick together as a layer of sedimentary rock (**Fig. 18.2b**). We can also think of the ice that appears on the surface of a pond as an igneous rock, for it forms when molten ice (liquid water) solidifies. Glacial ice, in effect, is a metamorphic rock. It develops when preexisting ice recrystallizes in the solid state, meaning that the molecules in solid water rearrange to form new crystals (**Fig. 18.2c**).

FIGURE 18.1 Agassiz envisioned that the northern continents were covered by ice sheets similar to Antarctica's today.

How a Glacier Forms

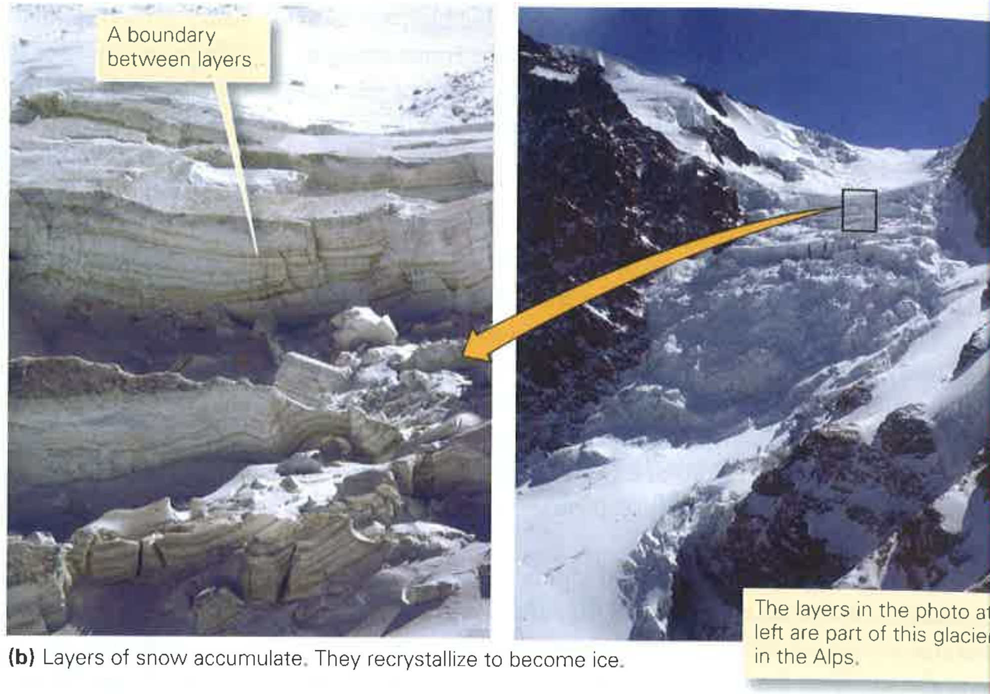
In order for a glacier to form, three conditions must be met. First, the local climate must be cold enough that winter snow does not melt entirely away during the summer. Second, there must be sufficient snowfall for a large amount of snow to accumulate. And third, the slope of the surface on which the snow accumulates must be gentle enough that the snow does not slide away in avalanches, and must be protected enough that the snow doesn't blow away.

Glaciers develop in polar regions because, even though relatively little snow falls today, temperatures remain so cold that most ice and snow survive all year. Glaciers develop in mountains, even at low latitudes, because temperature decreases with elevation; at high elevations, the mean temperature stays cold enough for ice and snow to survive all year. Since the temperature of a region depends on latitude, the specific elevation at which mountain glaciers form also depends on latitude. In Earth's present-day climate, glaciers form only at elevations above 5 km at the equator, but can flow down to sea level at latitudes of between 60° and 90°.

The transformation of snow to glacier ice takes place as younger snow progressively buries older snow. Freshly fallen snow consists of delicate hexagonal crystals with sharp points. The crystals do not fit together tightly, so fresh snow contains about 90% air. With time, the points of the snowflakes become blunt because they either sublimate (evaporate directly into vapor) or melt, and the snow packs more tightly. As snow becomes buried, the weight of the overlying snow increases pressure, which causes remaining points of contact between snowflakes to melt. Gradually, the snow transforms into a packed granular material called firn, which contains only about 25% air (**Fig. 18.2d**). Melting of firn grains at contact points produces water that crystallizes in the spaces between grains until eventually the firn transforms into a solid mass of glacial ice composed of interlocking ice crystals. Such glacial ice, which

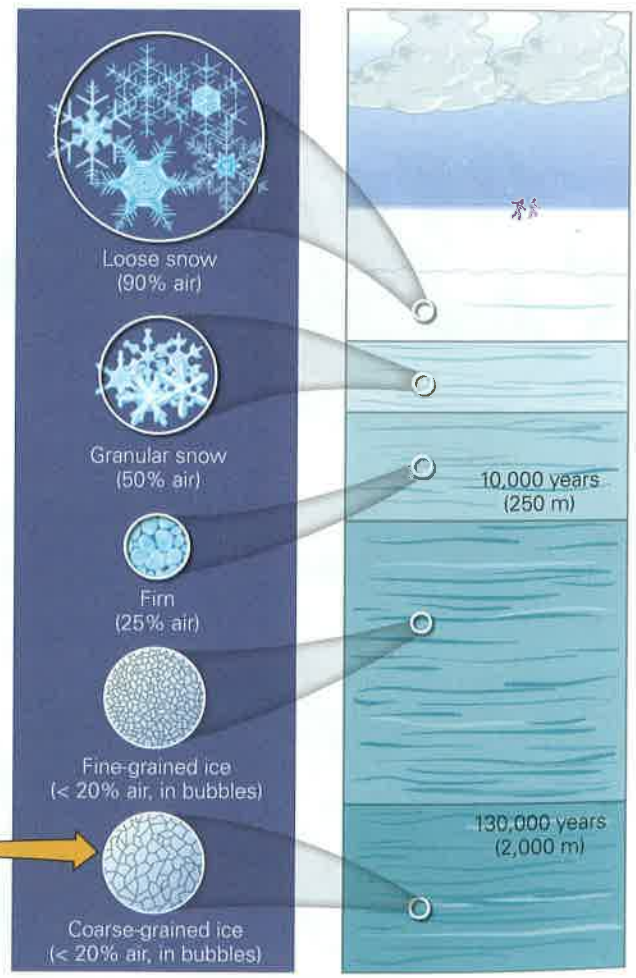
FIGURE 18.2 The nature of ice and the formation of glaciers. Snow falls like sediment and metamorphoses to ice when buried.

(a) The hexagonal shape of snowflakes. No two are alike.



(b) Layers of snow accumulate. They recrystallize to become ice.

(c) Glacial ice is blue. As revealed by a microscope, the ice has coarse grains and contains air bubbles.



(d) Snow compacts and melts to form firn, which recrystallizes into ice. Crystal size increases with depth.

may still contain up to 20% air trapped in bubbles, tends to absorb red light and thus has a bluish color. The transformation of fresh snow to glacier ice can take as little as tens of years in regions with abundant snowfall, or as long as thousands of years in regions with little snowfall.

Categories of Glaciers

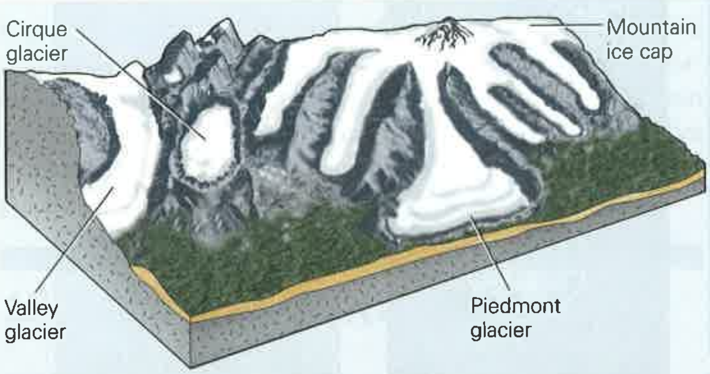
Glaciers are streams or sheets of recrystallized ice that stay frozen all year long and flow under the influence of gravity. Today, they highlight coastal and mountain scenery in Alaska, the Cordillera of western North America, the Alps of Europe, the Southern Alps of New Zealand, the Himalayas of Asia, and the Andes of South America, and they cover most of Greenland and Antarctica (**See for Yourself R**). Geologists distinguish between two main categories: mountain glaciers and continental glaciers.

Mountain glaciers (also called alpine glaciers) exist in or adjacent to mountainous regions (**Fig. 18.3a**). Topographical features of the mountains control their shape; overall, mountain glaciers flow from higher elevations to lower elevations. Mountain glaciers include *cirque glaciers*, which fill bowl-shaped depressions, or *cirques*, on the flank of a mountain; *valley glaciers*, rivers of ice that flow down valleys; mountain *ice caps*, mounds of ice that submerge peaks and ridges at the crest of a mountain range; and *piedmont glaciers*, fans or lobes of ice that form where a valley glacier emerges from a valley and spreads out into the adjacent plain (**Fig. 18.3b–d**). Mountain glaciers range in size from a few hundred meters to a few hundred kilometers long.

Continental glaciers are vast ice sheets that spread over thousands of square kilometers of continental crust. Continental glaciers now exist only on Antarctica and Greenland (**Fig. 18.4a, b**). Antarctica is a continent, so the ice beneath the South Pole rests mostly on solid ground. Locally, however, lakes of liquid water exist at the base of continental glaciers. In 2012, Russian geologists drilled into one of these lakes, Lake Vostock, 3.7 km below the surface of the Antarctic ice sheet. Continental glaciers flow outward from their thickest point (up to 3.5 km thick) and thin toward their margins, where they may be only a few hundred meters thick.

Geologists also find it valuable to distinguish between types of glaciers on the basis of the thermal conditions in which the glaciers exist. **Temperate glaciers** occur in regions where atmospheric temperatures become warm enough for the glacial ice to

FIGURE 18.3 A great variety of glaciers form in mountainous areas.



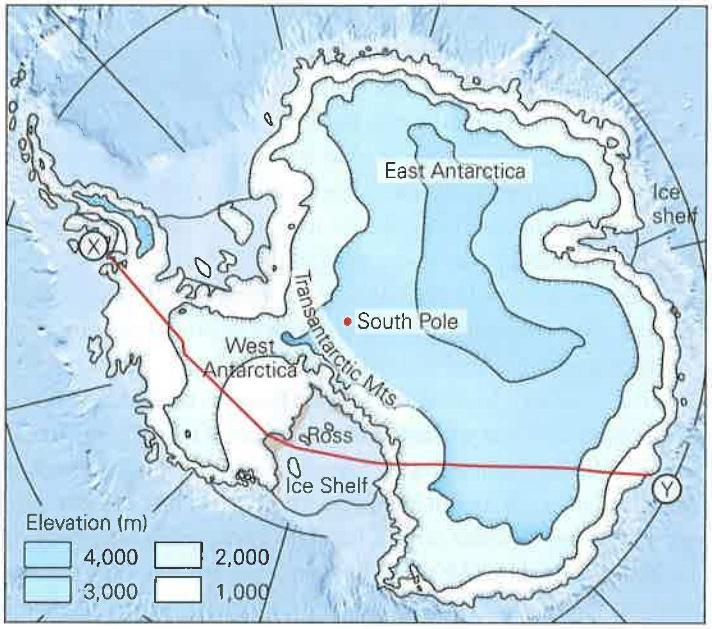
(a) Mountain glaciers are classified based on shape and position.

(b) A valley glacier and cirque glaciers in Switzerland.

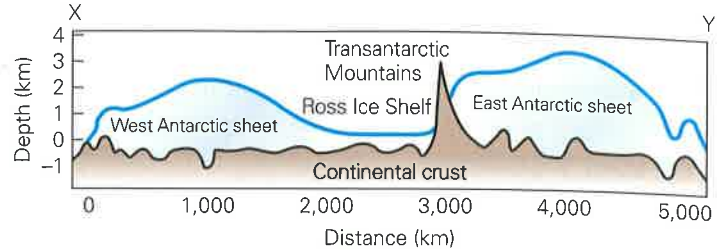
(c) Valley glaciers draining a mountain ice cap in Alaska.

(d) A piedmont glacier near the coast of Greenland.

FIGURE 18.4 Antarctica is an ice-covered continent.



(a) A contour map of the Antarctic ice sheet. Valley glaciers carry ice from the ice sheet of East Antarctica down to the Ross Ice Shelf.



(b) A cross section X to Y of the Antarctic ice sheet. The Transantarctic Mountains separate East Antarctica from West Antarctica.

be at or near its melting temperature during part or all of the year. **Polar glaciers** occur in regions where atmospheric temperatures stay so cold all year long that the glacial ice remains below melting temperature throughout the year. Of note, Earth is not alone in hosting polar glaciers—Mars has them too (**Box 18.1**).

The Movement of Glacial Ice

How do glaciers move? Let's consider the two mechanisms that allow glaciers to move—plastic deformation and basal sliding. At conditions found below depths of about 60 m in a glacier, ice deforms by *plastic deformation*, meaning that the

CONSIDER THIS . . . **BOX 18.1**

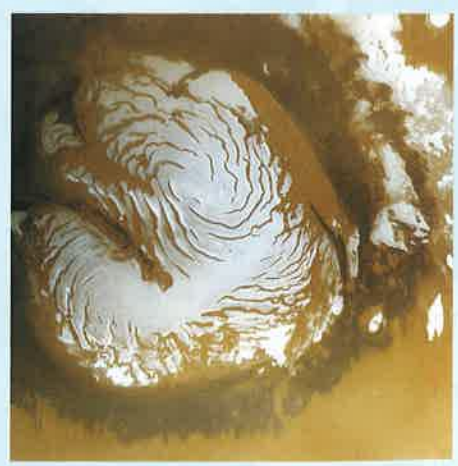
Polar Ice Caps on Mars

Mars has white polar ice caps that change in area with the season, suggesting that they partially melt and then refreeze (**Fig. Bx18.1a, b**). The question of what the ice caps consist of remained a puzzle until fairly recently. It now appears that the Martian ice caps consist mostly of water (H_2O) ice mixed with a small amount of dust. The ice caps attain a maximum thickness of 3 km. During the winter, atmospheric carbon dioxide freezes and covers the north polar cap with a 1-m-thick layer of frozen CO_2 (dry ice). During the summer, this layer melts away. The south polar cap has a dry-ice blanket that is 8 m thick and doesn't melt away entirely in the summer. The difference between the north and south poles may reflect elevation, for the south pole is 6 km higher and therefore remains colder.

High-resolution photographs reveal that distinctive canyons, up to 10 km wide and 1 km deep, spiral outward from the center of the north polar ice cap. Why did this pattern form? Recent calculations suggest that if the ice sublimates (transforms into gas) on the sunny side of a crack and refreezes on the shady side, the crack will migrate sideways over time. If the cracks migrate more slowly closer to the pole, where it's colder, than they do farther away, they will naturally evolve into spirals.

FIGURE Bx18.1 The ice caps of Mars.

(a) During the winter, the ice caps expand to lower latitudes.



(b) A close-up of the northern polar cap in summer.

grains within it change shape very slowly, and new grains grow while old ones disappear. We can picture such changes to be a consequence of the rearrangement of water molecules within ice grains. If ice is warm enough for thin water films to form along grain boundaries, plastic deformation may also involve the microscopic slip of ice grains past their neighbors along the water films. In cases where significant quantities of meltwater accumulate at the base of a glacier, forming a layer either of liquid or of slurry-like wet sediment, glaciers can move by *basal sliding*. During this process, the liquid water or water-saturated slurry layer holds the glacial ice above bedrock and thereby decreases friction; effectively, the glacier glides along on a wet cushion.

Did you ever wonder . . .
how a glacier moves?

As we noted earlier, plastic deformation takes place only at depths of greater than about 60 m in a glacier—above this depth, known as the brittle–plastic transition, ice is too brittle to flow. As a glacier overall undergoes movement, its upper 60 m of ice deforms predominantly by cracking. A crack that develops by brittle deformation of a glacier is called a **crevasse** (**Fig. 18.5**). In large glaciers, crevasses can be hundreds of meters long, and they can open up to form open gashes up to 15 m across.

Why do glaciers move? Ultimately, because the pull of gravity is strong enough to make ice flow (**Fig. 18.6a, b**). A glacier flows in the direction in which its top surface slopes. Thus, valley glaciers flow down their valleys, and continental ice sheets spread outward from their thickest point. To picture the movement of a continental ice sheet, imagine pouring honey on a tabletop. The honey spreads out until the puddle reaches an even thickness. In the case of a continental ice sheet, a thick pile of ice builds up, and gravity causes the top of the pile to push down on the ice at the base. Eventually, the basal ice can no longer support the weight of the overlying ice and begins to deform plastically. When this happens, the basal ice starts squeezing out to the side, carrying the overlying ice with it. The greater the volume of ice that builds up, the wider the ice sheet can become.

Glaciers generally flow at rates of between 10 and 300 m per year. Not all parts of a glacier move at the same rate. For example, friction between rock and ice slows a glacier, so the center of a valley glacier moves faster than its margins, and the top of a glacier moves faster than its base (**Fig. 18.7a, b**). If water builds up beneath a valley glacier to the point where it lifts the glacier off its substrate, basal sliding starts and the glacier undergoes a *glacial surge*. During surges, glaciers have been clocked at speeds of 10 to 110 m per day! Sudden surges may generate ice quakes, whose seismic vibrations travel through the glacier and through the rock below.

Glacial Advance and Retreat

Glaciers resemble bank accounts: snowfall accumulates and adds to the account, while **ablation**—the removal of ice by sublimation (the evaporation of ice into water vapor), melting (the transformation of ice into liquid water, which flows away), and calving (the breaking off of chunks of ice)—subtracts from the account. Snowfall adds to the glacier in

FIGURE 18.5 Crevasses form in the upper layer of a glacier, in which the ice is brittle. Commonly, cracking takes place where the glacier bends while flowing over steps or ridges in its substrate.

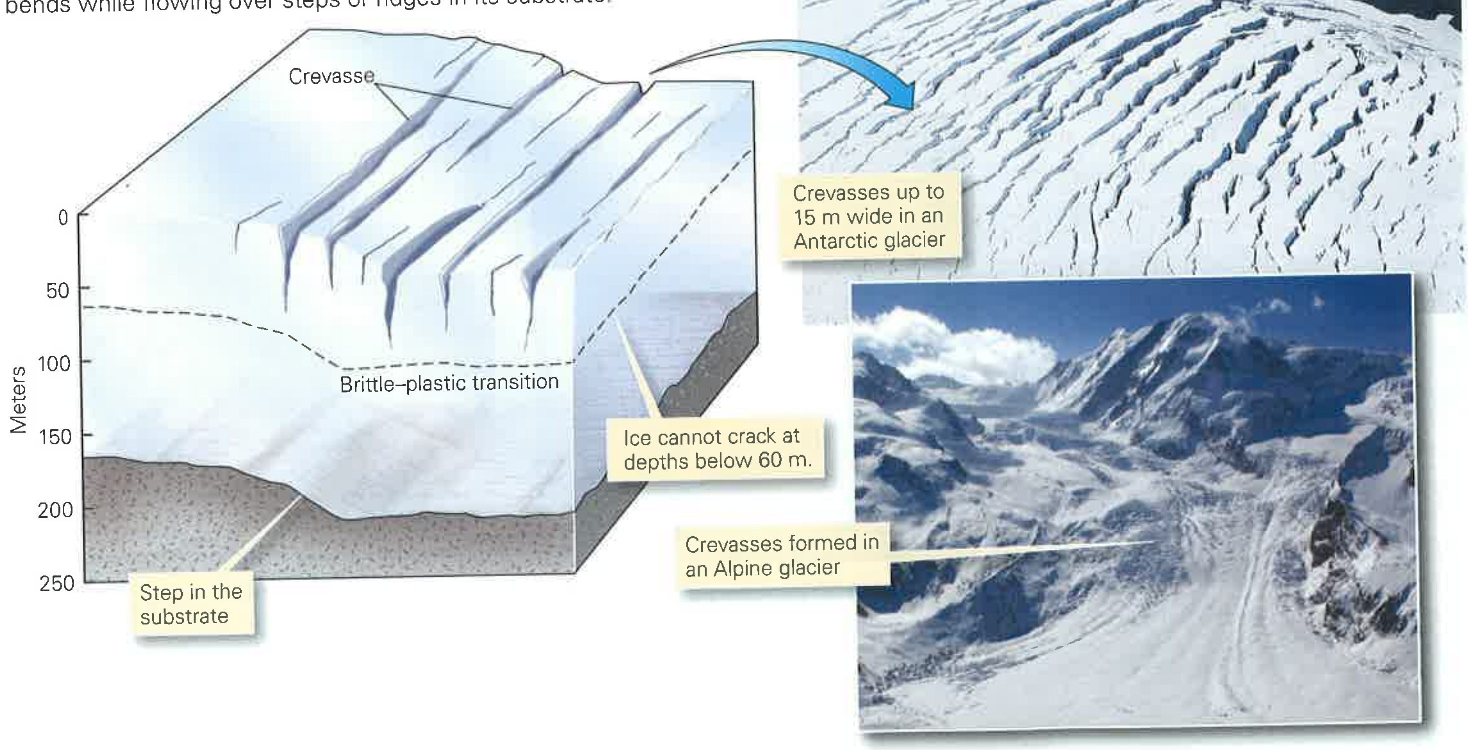
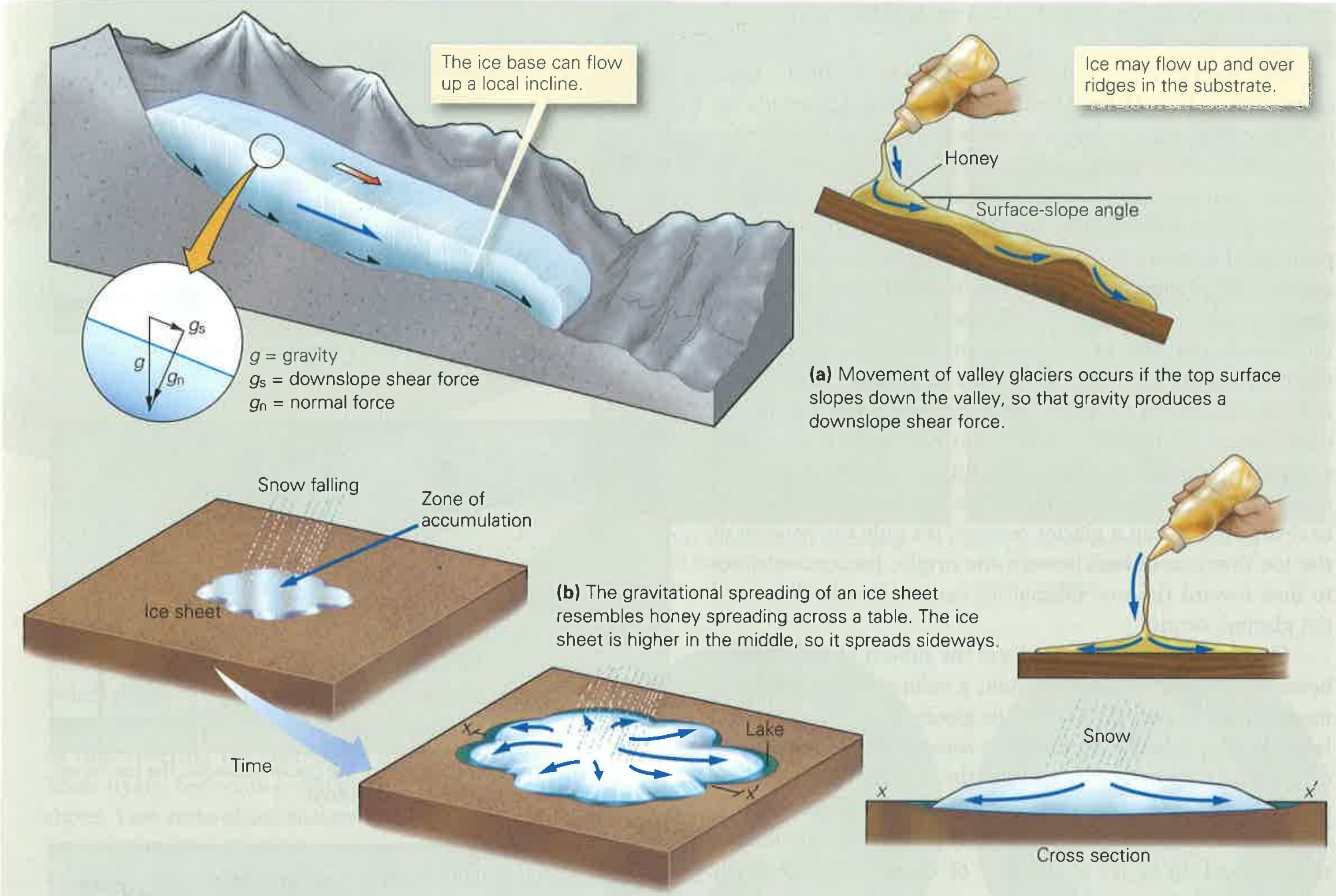


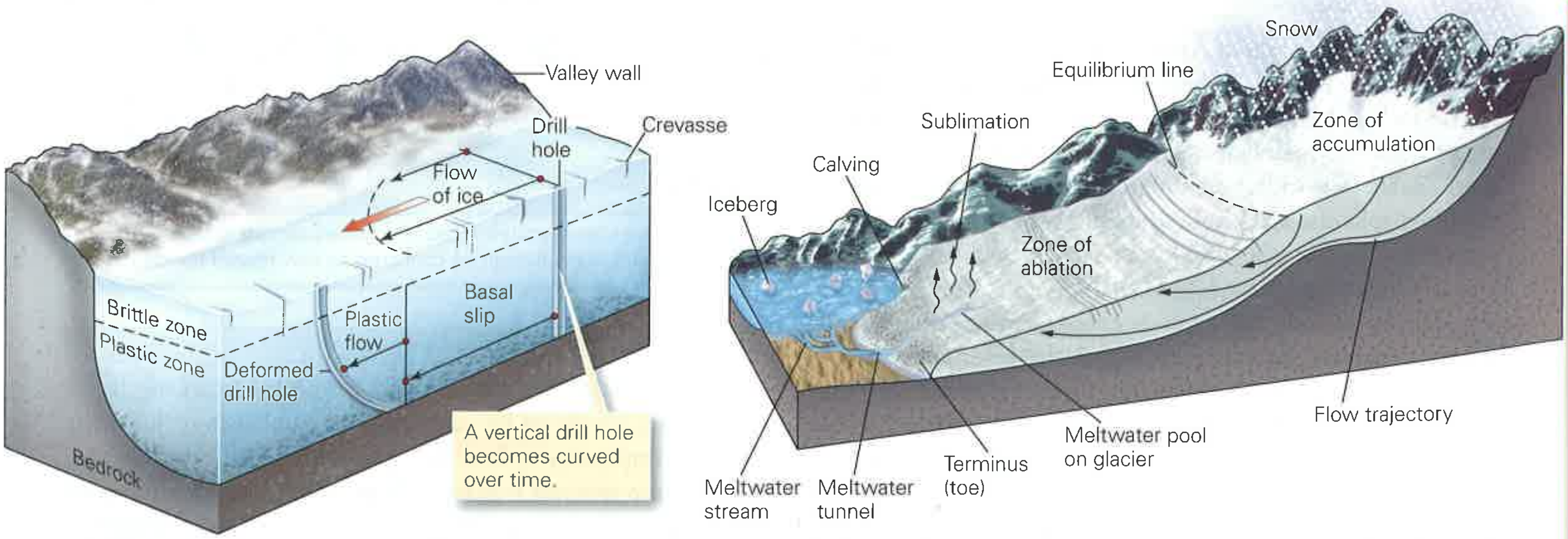
FIGURE 18.6 Forces that drive the movement of glaciers.



(a) Movement of valley glaciers occurs if the top surface slopes down the valley, so that gravity produces a downslope shear force.

(b) The gravitational spreading of an ice sheet resembles honey spreading across a table. The ice sheet is higher in the middle, so it spreads sideways.

FIGURE 18.7 Flow velocities vary with location in a glacier. Overall, ice flows from the zone of accumulation to the toe.



(a) Different parts of a glacier flow at different velocities, due to friction with the substrate. The top and center regions flow fastest.

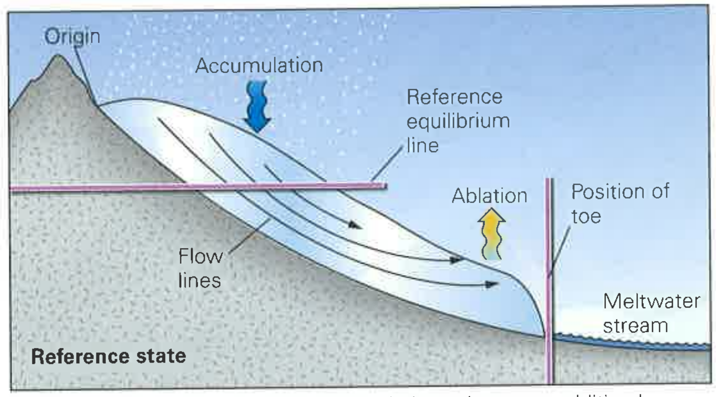
(b) The equilibrium line separates the zone of accumulation from the zone of ablation. As indicated by arrows, ice flows down in the zone of accumulation and up in the zone of ablation.

the **zone of accumulation**, whereas ablation subtracts in the **zone of ablation**; the boundary between these two zones is the **equilibrium line**.

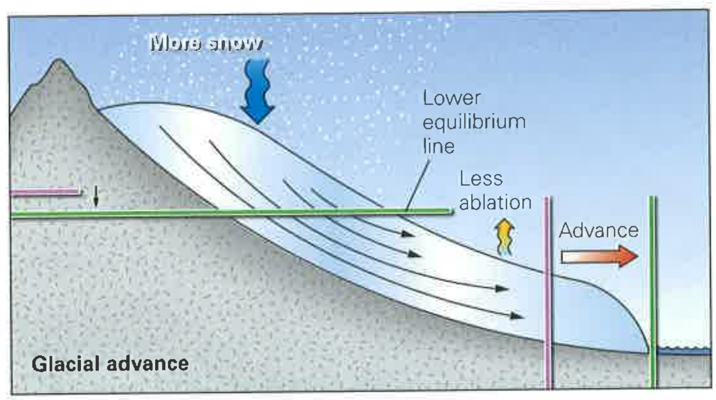
The leading edge or margin of a glacier is called its *toe*, or terminus (**Fig. 18.8a**). If the rate at which ice builds up in the zone of accumulation exceeds the rate at which ablation occurs below the equilibrium line, then the toe moves forward into previously unglaciated regions. Such a change is called a *glacial advance* (**Fig. 18.8b**). In mountain glaciers, the position of a toe moves downslope during an advance, and in continental glaciers, the toe moves outward, away from the glacier's origin. If the rate of ablation below the equilibrium line equals the rate of accumulation, then the position of the toe remains fixed. But if the rate of ablation exceeds the rate of accumulation, then the position of the toe moves back toward the origin of the glacier; such a change is called a *glacial retreat* (**Fig. 18.8c**). During a mountain glacier's retreat, the position of the toe moves upslope. It's important to realize that when a glacier retreats, it's only the *position* of the toe that moves back toward the origin, for ice continues to flow toward the toe. Glacial ice cannot flow back toward the glacier's origin.

One final point before we leave the subject of glacial flow: beneath the zone of accumulation, a volume of ice gradually moves down toward the base of the glacier as new ice accumulates above it, whereas beneath the zone of ablation, a volume of ice gradually moves up toward the surface of the glacier, as overlying ice ablates. Thus, as a glacier flows, ice volumes follow curved trajectories (see Fig. 18.8a–c). For this reason, rocks picked up by ice at the base of the glacier may slowly move to the surface.

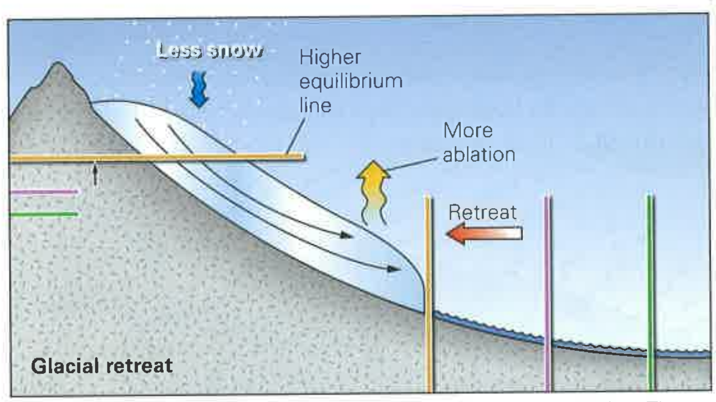
FIGURE 18.8 Glacial advance and retreat.



(a) The position of the toe represents a balance between addition by accumulation and loss by ablation.



(b) If accumulation exceeds ablation, the glacier advances, the toe moves farther from the origin, and the ice thickens.



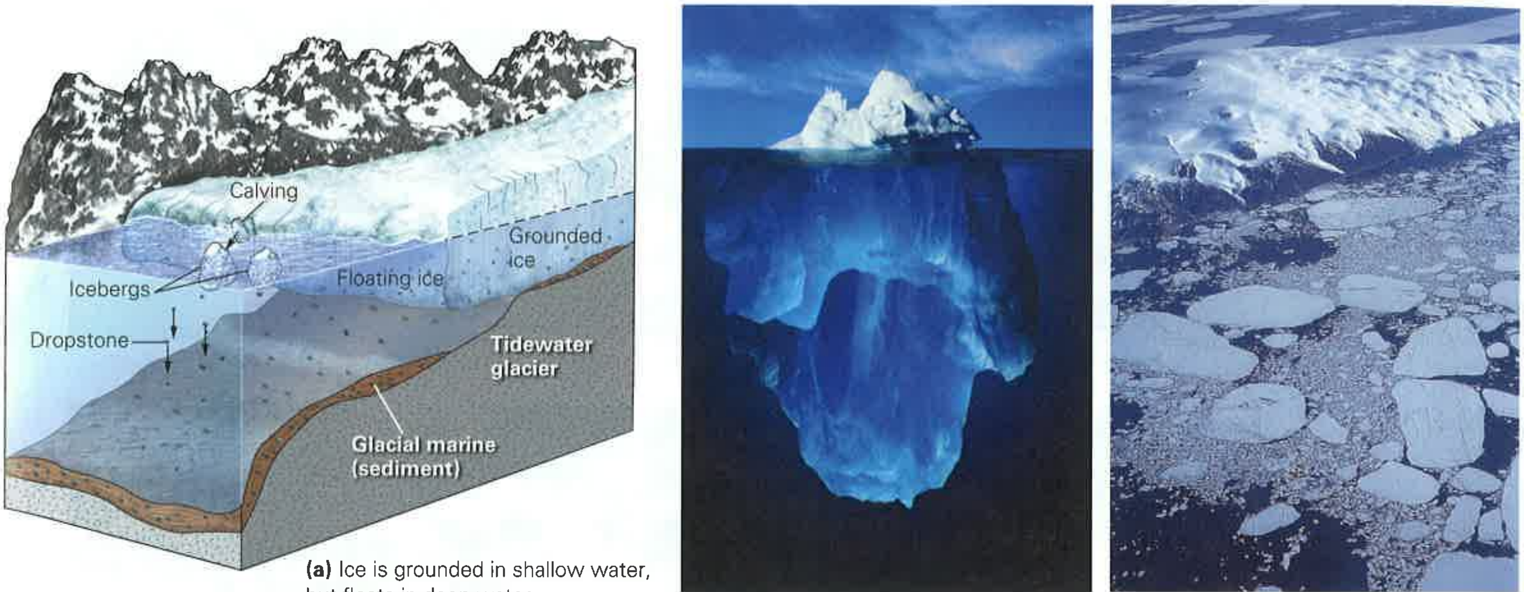
(c) If ablation exceeds accumulation, the glacier retreats and thins. The toe moves back, even though ice continues to flow toward the toe.

Ice in the Sea

On the moonless night of April 14, 1912, the great ocean liner *Titanic* struck a large iceberg in the frigid North Atlantic. Lookouts had seen the ghostly mass of frozen water only minutes earlier and had alerted the ship's pilot, but the ship had been unable to turn fast enough to avoid disaster. The force of the blow split the steel hull, allowing water to gush in. Less than 3 hours later, the ship disappeared beneath the surface, and 1,500 people perished.

Where do icebergs, such as the one responsible for the *Titanic*'s demise, originate? In high latitudes, mountain glaciers and continental ice sheets flow down to the sea, and they either stop at the shore or flow into the sea. Glaciers whose terminus lies in the water are called **tidewater glaciers**. Valley glaciers may protrude farther into the ocean to become ice tongues. Continental glaciers entering the sea become broad, flat sheets known as **ice shelves**. In shallow water, glacial ice remains grounded (**Fig. 18.9a**). But where the water becomes deep enough, the ice floats with four-fifths of the ice below the water's surface. At the boundary between glacier and ocean, blocks of ice calve off and tumble into the water with an impressive splash. If a free-floating chunk rises 6 m above the water and is at least 15 m long, it is formally called an **iceberg**. Since four-fifths of the ice lies below the surface of the sea, the base of a large iceberg may actually be a few hundred meters below the surface (**Fig. 18.9 b, c**).

FIGURE 18.9 Ice shelves, tidewater glaciers, and sea ice—the nature of coastal areas in glacial regions.

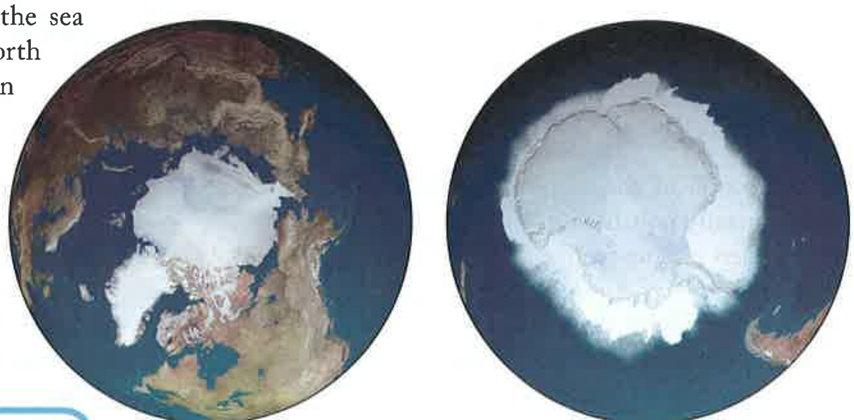


(a) Ice is grounded in shallow water, but floats in deep water.

(b) This artist's rendition of an iceberg emphasizes that most of the ice is underwater.

(c) In summer, some of the sea ice of Antarctica breaks up to form tabular icebergs.

Not all ice floating in the sea originates as glaciers on land. In polar climates, the surface of the sea itself freezes, forming **sea ice** (Fig. 18.9d). The north polar ice cap of the Earth consists of sea ice, formed on the surface of the Arctic Ocean. Some sea ice, such as that covering the interior of the Arctic Ocean, floats freely; but some protrudes outward from the shore. Vast areas of ice shelves and of sea ice have been disintegrating in recent years. For example, ice-free openings develop in the Arctic Ocean sea ice during the summers, and the area of the ice shelf in Antarctica has been decreasing rapidly.



(d) Sea ice covers most of the Arctic ocean (left) and surrounds Antarctica (right).

Take-Home Message

Glaciers form when buried snow lasts all year and turns to ice. Mountain glaciers form at high elevation and flow downslope. Ice sheets form in high latitudes and spread over continents. The balance of accumulation to ablation controls glacial advance or retreat. In polar regions, sea ice covers large areas.

18.3 Carving and Carrying by Ice

Glacial Erosion and Its Products

During the last ice age, valley glaciers cut deep, steep-sided valleys into the Sierra Nevada mountains of California. In the process, some granite domes were cut in half, leaving a rounded surface on one side and a steep cliff on the other. Half Dome, in Yosemite National Park, formed in this way (Fig. 18.10a); its steep cliff has challenged many rock climbers. Such glacial erosion also produces the knife-edge ridges and pointed spires of high mountains (Fig. 18.10b) and broad expanses where rock outcrops have been stripped of overlying sediment and polished smooth (Fig. 18.10c). In many localities, the rock surface visible today is the same rock surface once in contact with ice. In some places, subsequent rockfalls and river erosion have substantially modified the surface.

As glaciers flow, clasts embedded in the ice act like the teeth of a giant rasp and grind away the substrate. This process, glacial abrasion, produces long gouges, grooves, or scratches called **glacial striations** (Fig. 18.10d). Striations range from 1 cm to 1 m across and may be tens of centimeters to tens of meters long. As you might expect, striations run parallel to the

FIGURE 18.10 Products of glacial erosion. Ice is a very aggressive agent of erosion.

(a) Half Dome, in Yosemite National Park, California.

(b) The sharp peaks of the Alps were carved, in part, by the action of ice.

(c) Glacially polished outcrop in Central Park, New York City.

(d) Glacial striations in Victoria, British Columbia.

flow direction of the ice. Rasping by embedded sand yields shiny **glacially polished surfaces**.

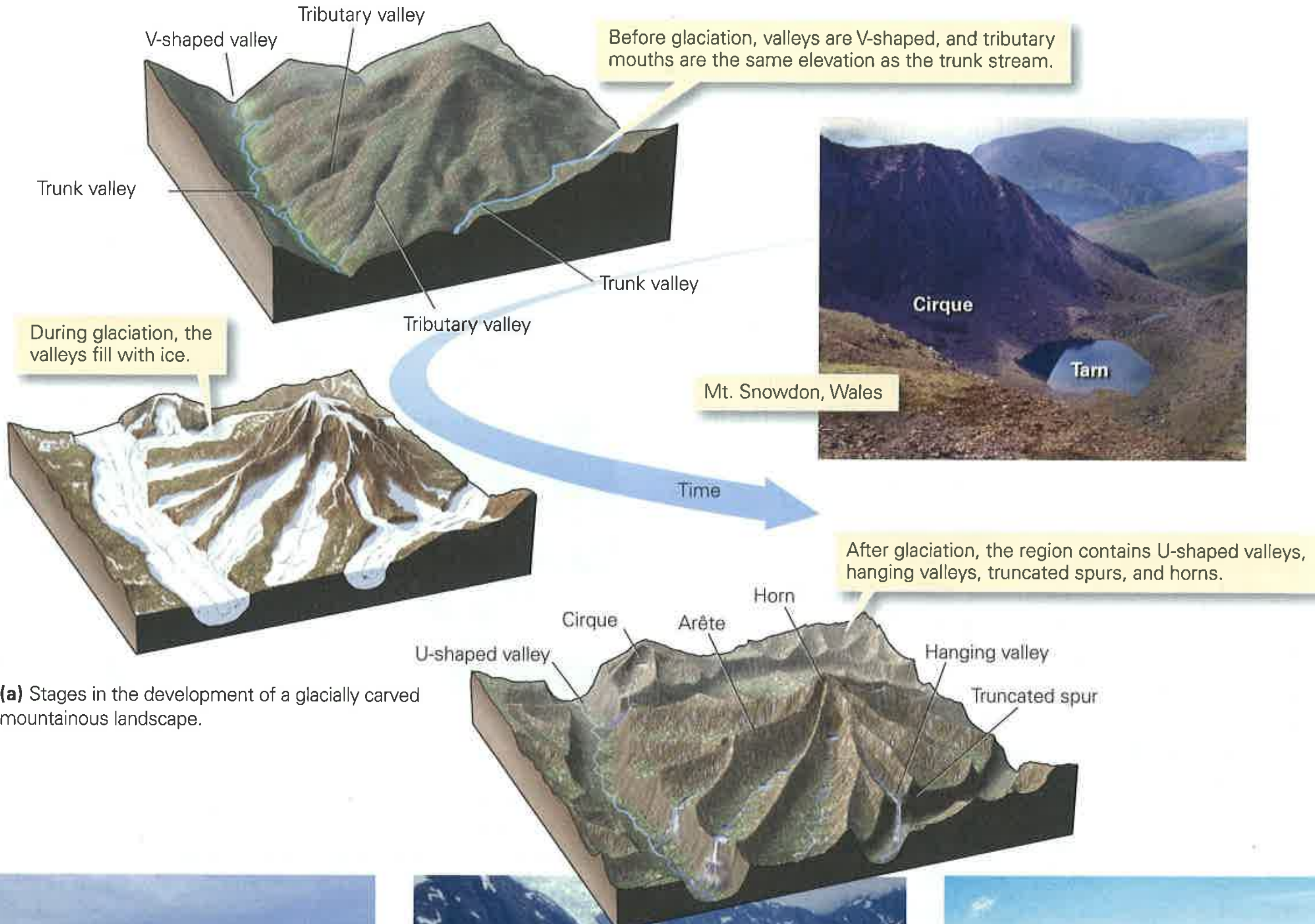
Glaciers pick up fragments of their substrate in several ways. During *glacial incorporation*, ice surrounds debris so the debris starts to move with the ice. During *glacial plucking* (or glacial quarrying), a glacier breaks off fragments of bedrock. Plucking occurs when ice freezes around rock that has just started to separate from its substrate, so that movement of the ice can lift off pieces of the rock. At the toe of a glacier, ice may actually bulldoze sediment and trees slightly before flowing over them.

Let's now look more closely at the erosional features associated with a mountain glacier (**Fig. 18.11a**). Freezing and thawing during the fall and spring help fracture the rock bordering the head of the glacier (the ice edge high in the mountains). This rock falls on the ice or gets picked up at the base of the ice, and moves downslope with the glacier. As a consequence, a bowl-shaped depression, or **cirque**, develops on the side of the mountain. If the ice later melts, a lake called a **tarn** may form at the base of the cirque. The shape of a cirque may be maintained or even amplified by rockfalls after the glacier is gone. An **arête** (French for ridge), a residual knife-edge ridge of rock, separates two adjacent cirques. A pointed mountain peak surrounded by at least three cirques is called a **horn**. The Matterhorn, a peak in Switzerland, is a particularly beautiful example of a horn; each of its four faces is a cirque (**Fig. 18.11b**).

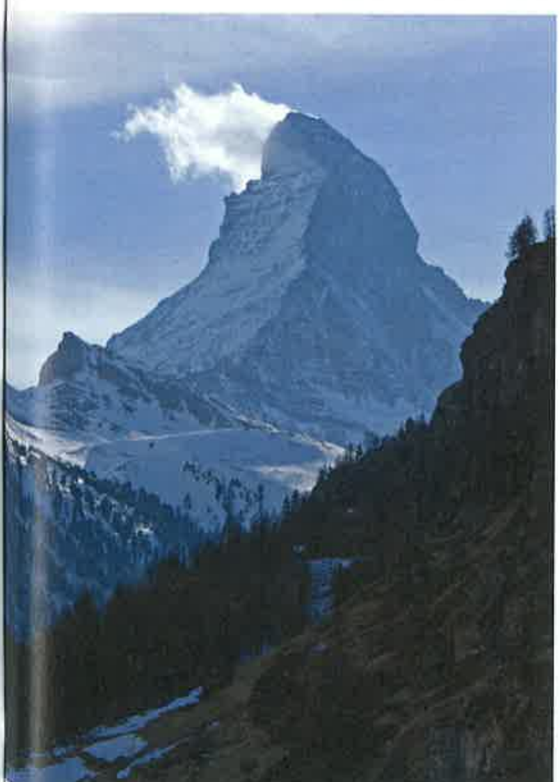
Glacial erosion severely modifies the shape of a valley. To see how, compare a river-eroded valley with a glacially eroded valley. If you look along the length of a river in unglaciated mountains, you'll see that it typically flows down a V-shaped valley, with the river channel forming the point of the V. The V develops because river erosion occurs only in the channel, and mass wasting causes the valley slopes to approach the angle of repose. But if you look down the length of a glacially eroded valley, you'll see that it resembles a U, with steep walls. A **U-shaped valley** (**Fig. 18.11c**) forms because the combined processes of glacial abrasion and plucking not only lower the floor of the valley but also bevel its sides.

Glacial erosion in mountains also modifies the intersections between tributaries and the trunk valley. In a river system, the trunk stream serves as the local base level for tributaries (see Chapter 14), so the mouths of the tributary valleys lie at the *same* elevation as the trunk valley. The ridges (spurs) between valleys taper to a point when they join the trunk valley floor. During glaciation, tributary glaciers flow down side valleys into a trunk glacier. But the trunk glacier cuts the floor of its valley down to a depth that far exceeds the depth cut by the tributary glaciers. Thus, when the glaciers melt away, the mouths of the tributary valleys perch at a higher elevation than the floor of the trunk valley. Such side valleys are called **hanging valleys**. The water in a post-glacial stream that flows down a hanging valley cascades over a spectacular waterfall to reach the post-glacial trunk stream

FIGURE 18.11 Landscape features formed by the glacial erosion of a mountainous landscape.



(a) Stages in the development of a glacially carved mountainous landscape.



(b) The Matterhorn in Switzerland. The first ascent was in 1865.

(c) A U-shaped glacial valley in the Tongass National Forest, Alaska.

(d) A waterfall spilling out of a U-shaped hanging valley in the Sierra Nevada.

(**Fig. 18.11d**). As they erode, trunk glaciers also chop off the ends of spurs (ridges) between valleys, to produce truncated spurs.

Now let's look at the erosional features produced by continental ice sheets. To a large extent, these depend on the nature of the pre-glacial landscape. Where an ice sheet spreads over a region of low relief, such as the Canadian Shield, glacial erosion creates a vast region of polished, flat, striated surfaces. Where an ice sheet spreads over a hilly area, it deepens valleys and smooths hills. Glacially eroded hills may end up being elongate in the direction of flow and may be asymmetric, for glacial rasping smoothes and bevels the upstream part of the hill, creating a gentle slope, whereas glacial plucking eats away at the downstream part, making a steep slope. Ultimately, the hill's profile may resemble that of a sheep lying in a meadow—such a hill is called a **roche moutonnée**, from the French for sheep rock (**Fig. 18.12a, b**).

Fjords: Submerged Glacial Valleys

As noted earlier, where a valley glacier meets the sea, the glacier's base remains in contact with the ground until the water depth exceeds about four-fifths of the glacier's thickness, at which point the glacier floats. Thus, glaciers can carve U-shaped valleys even below sea level. In addition, during an ice age, water extracted from the sea becomes locked in the ice sheets on land, so sea level drops significantly. Therefore, the floors of valleys cut by coastal glaciers during the Pleistocene Ice Age were cut much deeper than present sea level. Today, the sea has flooded these deep valleys, producing **fjords** (see Chapter 15). In the spectacular fjord-land regions along the coasts of Norway, New Zealand, Chile, and Alaska, the walls of submerged U-shaped valleys rise straight from the sea as vertical cliffs up to 1,000 m high (**Fig. 18.13**). Fjords also develop where an inland glacial valley fills to become a lake.

Take-Home Message

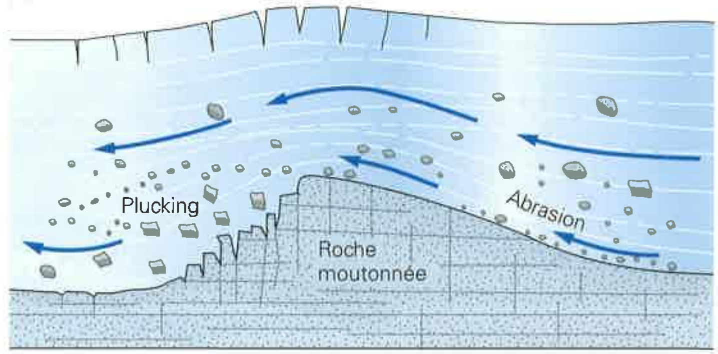
A glacier scrapes up and plucks rock from its substrate, and carries debris that falls on its surface. Glacial erosion polishes and scratches rock and carves distinctive landforms, such as U-shaped valleys and cirques. Since ice is solid, moving ice does not sort sediment.

18.4 Deposition Associated with Glaciation

The Glacial Conveyor

Glaciers can carry sediment of any size and, like a conveyor belt, transport it in the direction of flow (that is, toward the toe; **Fig. 18.14a**). The sediment load either falls onto the surface of the glacier from bordering cliffs or gets plucked and lifted from

FIGURE 18.12 A roche moutonnée is an asymmetric bedrock hill shaped by the flow of glacial ice.



(a) Abrasion rasps the upstream side, and plucking carries away fracture-bounded blocks on the downstream side.

(b) An example of a roche moutonnée in the Sierra Nevada. The glacier flowed from right to left.

FIGURE 18.13 One of the many spectacular fjords of Norway. The water is an arm of the sea that fills a glacially carved valley. Tourists are standing on Pulpit Rock (Prekestolen).

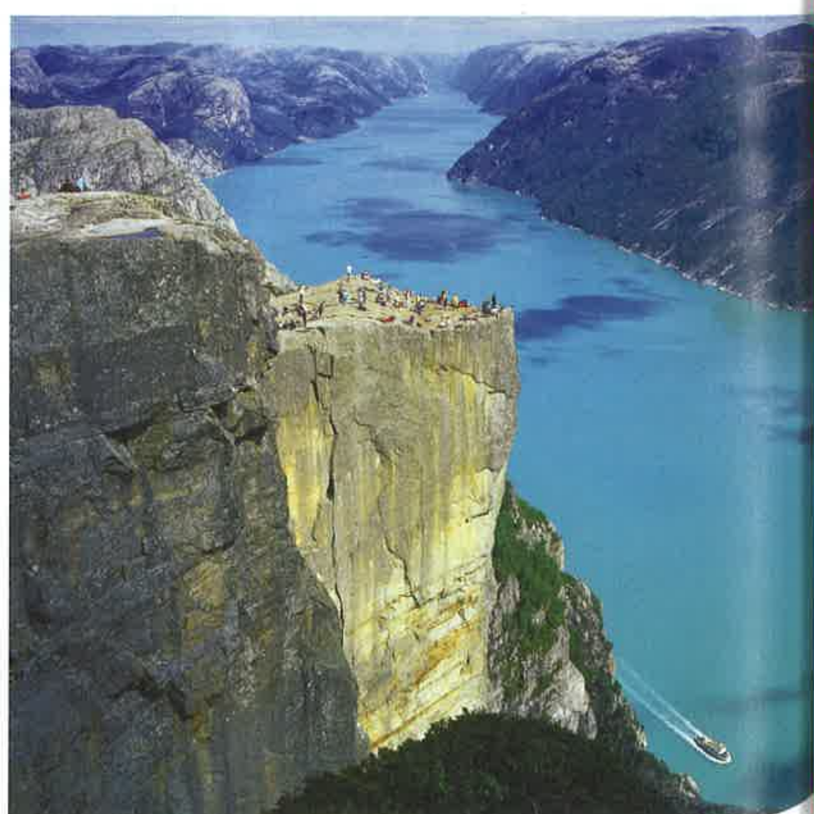
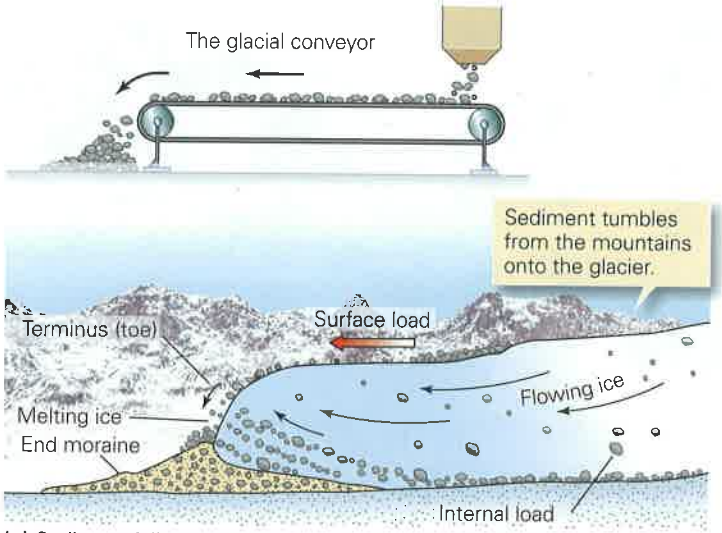
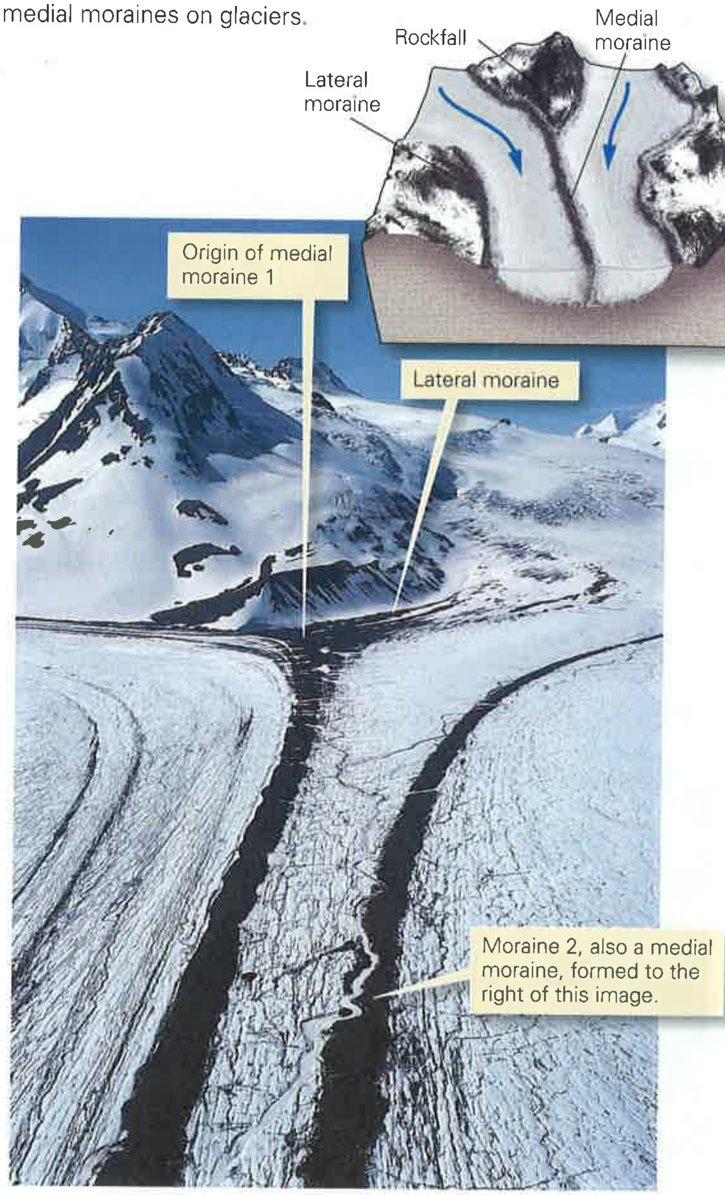


FIGURE 18.14 The glacial conveyor and the formation of lateral and medial moraines on glaciers.



(a) Sediment falls on a glacier from bordering mountains and gets plucked up from below. Glaciers are like conveyor belts, moving sediment toward the toe of the glacier.



(b) A medial moraine forms where lateral moraines of two valley glaciers merge.

the substrate and incorporated into the moving ice. Geologists refer to a pile of debris carried by or left by glaciers as a **moraine**. Sediment dropped on the glacier's surface moves with the ice and becomes a stripe of debris. Stripes formed along the side edges of the glacier are *lateral moraines*. When a glacier melts, lateral moraines lie stranded along the side of the glacially carved valley, like bathtub rings. Where two valley glaciers merge, the debris constituting two lateral moraines merges to become a *medial moraine*, running as a stripe down the interior of the composite glacier (**Fig. 18.14b**). Trunk glaciers created by the merging of many tributary glaciers contain several medial moraines. Sediment transported to a glacier's toe by the glacial conveyor accumulates in a pile at the toe and builds up to form an *end moraine*.

Types of Glacial Sedimentary Deposits

Several different types of sediment can be deposited in glacial environments; all of these types together constitute **glacial drift**. The term dates from pre-Agassiz studies of glacial deposits, when geologists thought that the sediment had "drifted" into place during an immense flood. Specifically, glacial drift includes the following:

- *Till*: Sediment transported by ice and deposited beneath, at the side, or at the toe of a glacier is called **glacial till**. Glacial till is unsorted because the solid ice of glaciers can carry clasts of all sizes (**Fig. 18.15a**).
- *Erratics*: Glacial erratics (**Fig. 18.15b**) are cobbles and boulders that have been dropped by a glacier. Some lie within or on till piles, and others rest on glacially polished surfaces.
- *Glacial marine*: Where a sediment-laden glacier flows into the sea, icebergs calve off the toe and raft clasts out to sea. As the icebergs melt, they drop the clasts. Sediment consisting of ice-rafted clasts mixed with marine sediment makes up glacial marine.
- *Glacial outwash*: Till deposited by a glacier at its toe may be picked up and transported by meltwater streams that sort the sediment. The clasts are deposited by a braided stream network to form a broad area of gravel and sandbars called an outwash plain. This sediment is known as **glacial outwash** (**Fig. 18.15c**).
- *Loess*: When the warmer air above ice-free land beyond the toe of a glacier rises, the cold, denser air from above the glacier rushes in to take its place. A strong wind, called katabatic wind, therefore blows at the margin of a glacier. This wind picks up fine clay and silt and transports it away from the glacier's toe. Where the winds die down, the sediment settles and forms a thick layer. This sediment, called **loess**, sticks together because of the electrical charges on clay flakes. Thus, steep escarpments can develop by erosion of loess deposits (**Fig. 18.15d**).

FIGURE 18.15 Sedimentation processes and products associated with glaciation. Glacial sediment is distinctive.

(a) This glacial till in Ireland is unsorted, because ice can carry sediment of all sizes.

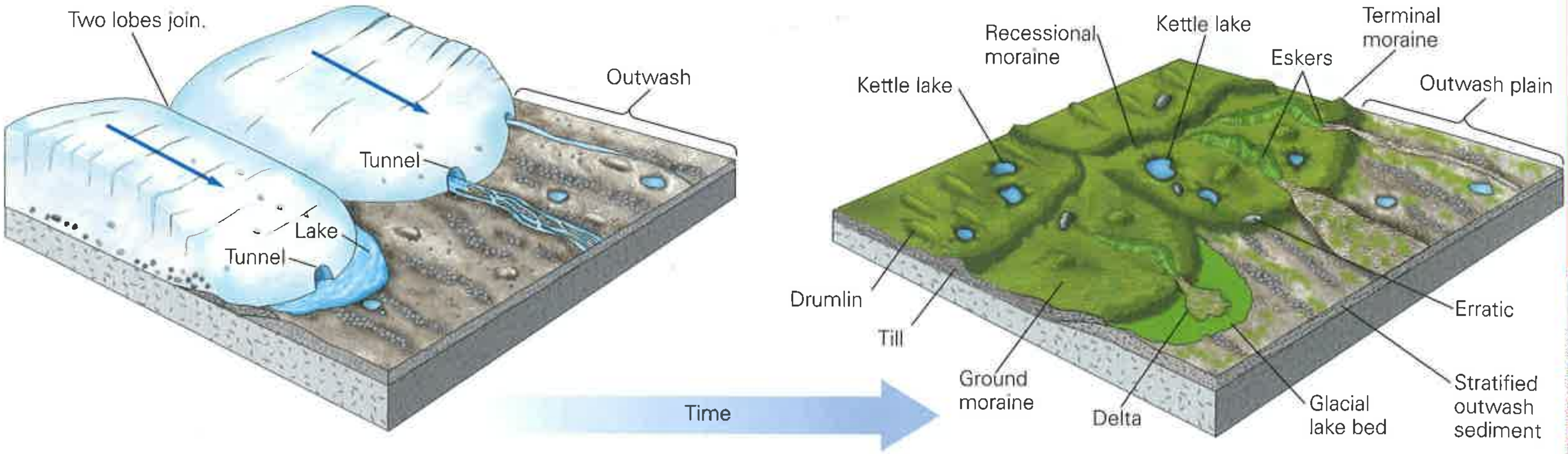
(b) Glacial erratics resting on a glacially polished surface in Wyoming.

(c) Braided streams choked with glacial outwash in Alaska. The streams carry away finer sediment and leave the gravel behind.

(d) Thick loess deposits underlie parts of the prairie in Illinois.

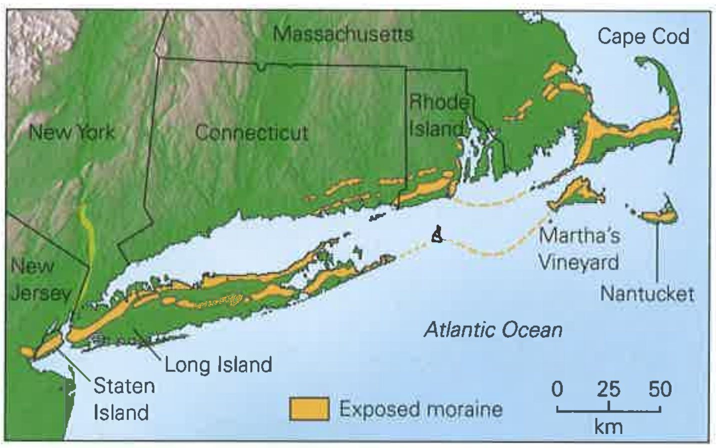
(e) In the quiet water of an Alaskan glacial lake, fine-grained sediments accumulate. Alternating layers in the sediment (varves), now exposed in an outcrop near Puget Sound, Washington, reflect seasonal changes.

FIGURE 18.16 The formation of depositional landforms associated with continental glaciation.



(a) The ice in continental glaciers flows toward the toe; sediment accumulates at the base and at the toe of the ice sheet.

(b) Several distinct depositional landforms form during glaciation; some developed under the ice and some at the toe.



(c) Cape Cod, Long Island, and other landforms in the northeastern United States formed at the end of the continental ice sheet.

- *Glacial lake-bed sediment*: Streams transport fine clasts, including rock flour, away from the glacial front. This sediment eventually settles in meltwater lakes, forming a layer of glacial lake-bed sediment that commonly contains varves. A *varve* is a pair of thin layers deposited during a single year. One layer consists of silt brought in during spring floods and the other of clay deposited in winter when the lake's surface freezes over and the water is still (**Fig. 18.15e**).

Depositional Landforms of Glacial Environments

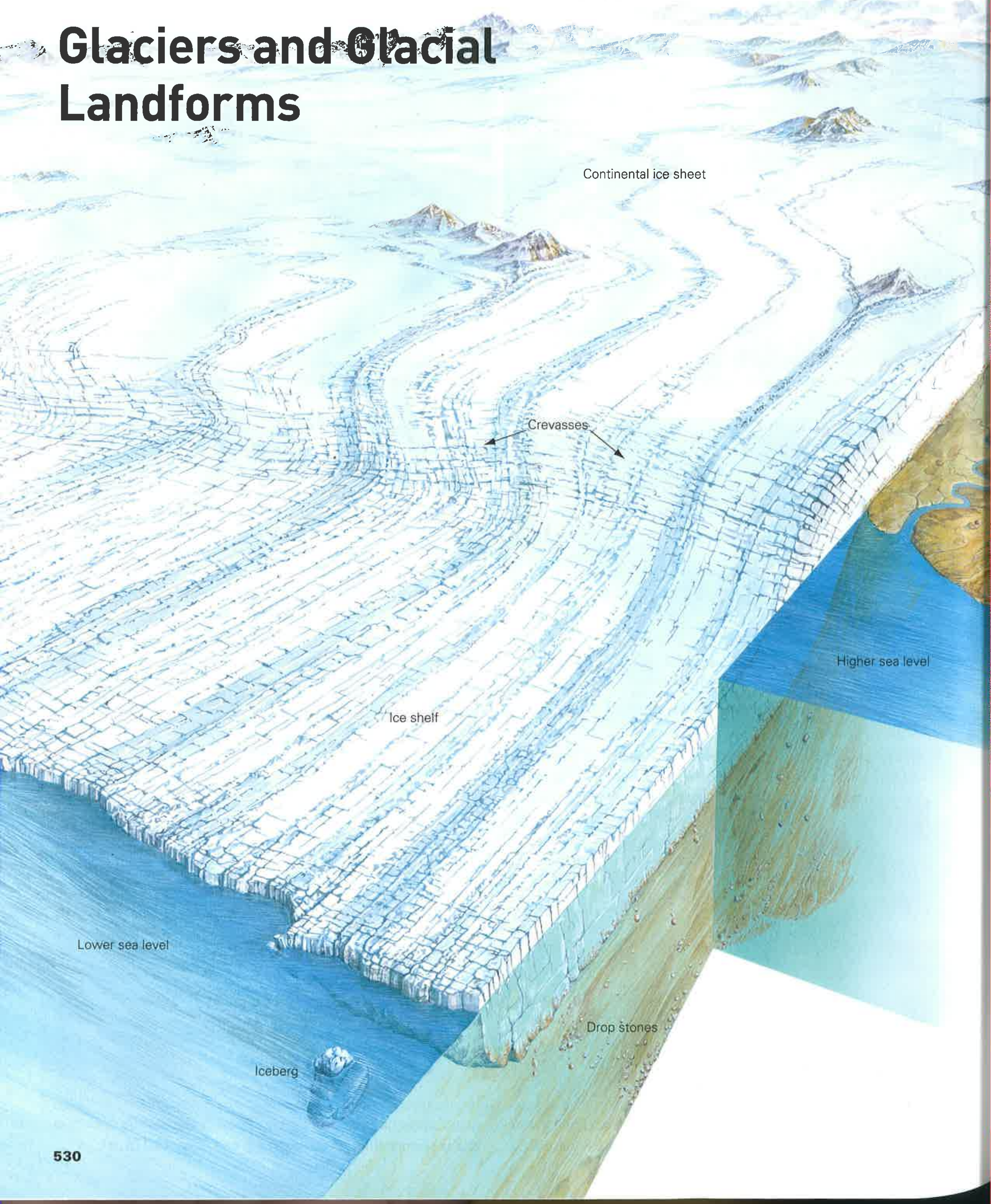
Picture a group of hunters, dressed in reindeer skin, gazing southward from the crest of an ice cliff at the toe of a continental glacier in what is now southern Canada. It's about 12,000 years ago, and the glacier has been receding for at least a millennium. The hunters would have been able to see a variety of landscape features, some formed by glacial erosion and some by deposition, due to moving ice and meltwater (**Geology at a Glance,** pp. 530–531). We've already described erosional features, so now let's focus on the depositional features of the landscape (**Fig. 18.16a, b**).

From their vantage point, the hunters would probably have seen a few curving, hummocky ridges of sediment in the region between the glacier's toe and the horizon. Each of these ridges is an *end moraine*, formed when the position of the glacier's toe remained in the same location for a while. Ice keeps flowing to the toe, and like a giant conveyor belt, transports sediment to the toe. As the ice melts, this sediment accumulates to form a pile of till, and this pile comprises the end moraine. Geologists refer to the end moraine at the farthest limit of glaciation as the *terminal moraine*. In the northeastern United States, a large terminal moraine built up during the Pleistocene Ice Age—this ridge of sediment now underlies Long Island, New York, and Cape Cod, Massachusetts (**Fig. 18.16c**). When a glacier starts receding, it may stall several times—the end moraines that form when a glacier stalls while receding are known as *recessional moraines*. The hummocky layer of till between end moraines is known as lodgment till or *ground moraine*. Since this till was deposited by moving ice, clasts within it may be aligned and scratched.

The hummocky surface of a moraine reflects both variations in the amount of sediment supplied by the ice and the development of kettle holes. A **kettle hole** is a roughly circular depression made when a block of ice that calved off the toe of a glacier became buried by till. When the block eventually melts, it leaves behind a depression (**Fig. 18.17a, b**). Geologists refer to a land surface spotted with many kettle holes separated by rounded hills or ridges of sediment as "knob-and-kettle topography" (**Fig. 18.17c**).

In some locations, glacial ice flow molds underlying till into an elongate hill known as a **drumlin** (from the Gaelic word for small hill or ridge). Drumlins commonly occur in swarms, and tend to be about 50 m high. Their long axis trends parallel to the flow direction of the glacier. Notably, drumlins taper in the direction of flow—a drumlin's upstream end is steeper than its downstream end (**Fig. 18.17d, e**).

Glaciers and Glacial Landforms



Glaciers are rivers or sheets of ice that stay frozen all year and slowly flow. Continental glaciers, vast sheets of ice up to a few kilometers thick, covered extensive areas of land during times when Earth had a colder climate. Continental glaciers form when snow accumulates at high latitudes, then, when buried deeply enough, packs together and recrystallizes to make glacial ice. Ice, though solid, is weak, and thus ice sheets spread over the landscape like syrup over a pancake. At the peak of the last ice age, ice sheets covered almost all of Canada, much of the United States, northern Europe, and parts of Russia.

The upper part of a sheet is brittle and may crack to form crevasses. Because ice sheets store so much of the Earth's water, sea level becomes lower during an ice age. When a glacier reaches the sea, it becomes an ice shelf. Rock that the glacier has plucked up along the way is carried out to sea with the ice; when the ice melts, the rocks fall to the sea floor as dropstones. At the edge of the shelf, icebergs calve off and float away.

A second class of glaciers, called mountain or alpine glaciers, exist in mountainous areas because snow can last all year at high elevations. During an ice age, mountain glaciers grow and flow out onto the land surface beyond the mountain front. The glacier at the right has started to recede after formerly advancing and covering more of the land. Glacial recession may happen when the climate warms, so ice melts away faster at the toe (terminus) of the glacier than it can be added at the source. In front of the glacier, you can find consequences of glacial erosion such as striations on bedrock and roches moutonnées.

When the glacier pauses, till (unsorted glacial sediment) accumulates to form an end moraine. Meltwater lakes gather at the toe, and streams carry sediment and deposit it as glacial outwash. Sediment that accumulates in ice tunnels, exposed when the glacier melts, make up sinuous ridges called eskers. Even when the toe remains fixed in position for a while, the ice continues to flow, and thus molds underlying sediment into drumlins. Ice blocks buried in till melt to form kettle holes. (Though the examples shown here were left after the melting away of a piedmont glacier, most actually form during continental glaciation.)

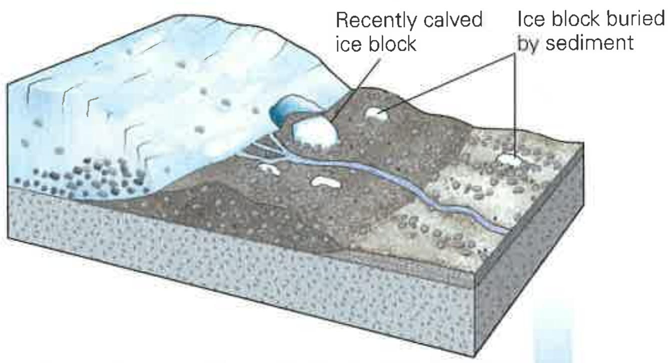
In the mountains, glaciers fill valleys or form ice caps. Sediment falling from the mountains creates lateral and medial moraines. Glaciers carve distinct landforms in the mountains, such as cirques, arêtes, horns, and U-shaped valleys.

As we've noted, not all of the sediment—or "drift"—associated with glacial landscapes was deposited directly by ice, for meltwater also carries and deposits sediment. Water-transported sediment, in contrast to till, tends to be sorted and stratified. Sediment deposited in meltwater tunnels beneath a glacier itself may remain as a sinuous ridge, known as an **esker**, when the glacier melts away (**Fig. 18.18a, b**). Braided meltwater streams that flow beyond the end of a glacier deposit layers of sand and gravel that underlie *glacial outwash plains*. Meltwater may collect in a lake adjacent to the glacier's toe, to form an *ice-margin lake*. Additional lakes and swamps may form in low areas on the ground moraine. Sediments deposited in eskers and glacial outwash plains serve as important sources of sand and gravel for construction, and the fine sediment of former glacial lake beds evolves into fertile soil for agriculture.

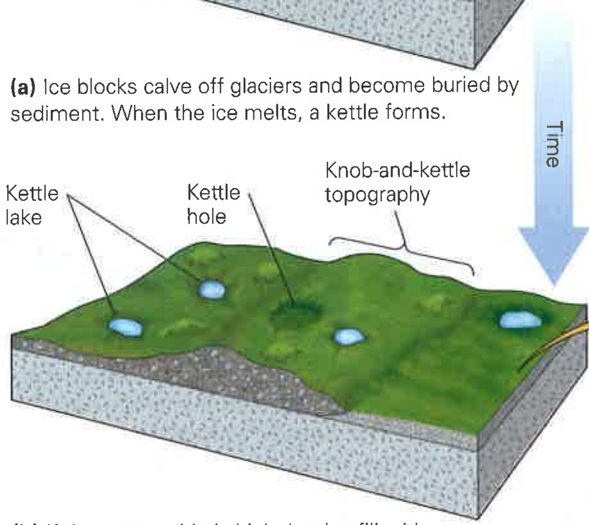
Take-Home Message

When ice melts, it deposits unsorted till. Meltwater streams and wind transport sort the sediment to form outwash-plain gravels and loess deposits, respectively. Deposition by glaciers produces distinctive landforms, such as moraines, eskers, and kettle holes.

FIGURE 18.17 Knob-and-kettle topography and drumlins characterize some areas that were once glaciated.

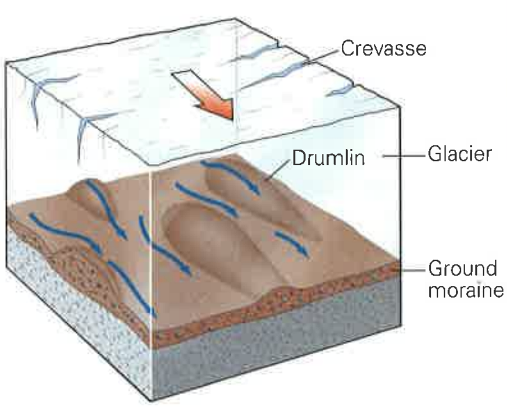


(a) Ice blocks calve off glaciers and become buried by sediment. When the ice melts, a kettle forms.

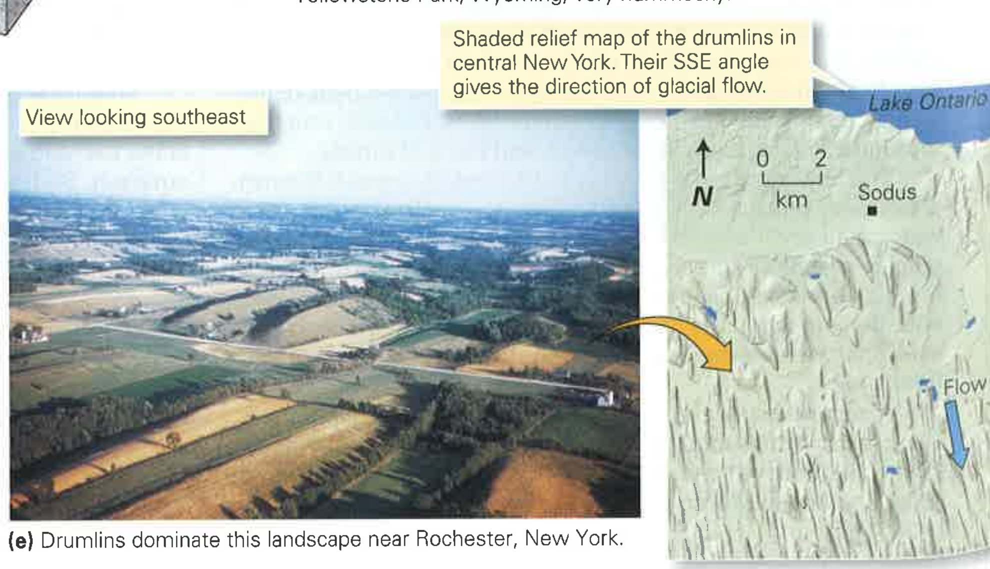


(b) If the water table is high, kettles fill with water and turn into roughly circular lakes.

(c) Knob-and-kettle topography make the surface of this moraine in Yellowstone Park, Wyoming, very hummocky.



(d) The formation of a drumlin beneath a glacier.



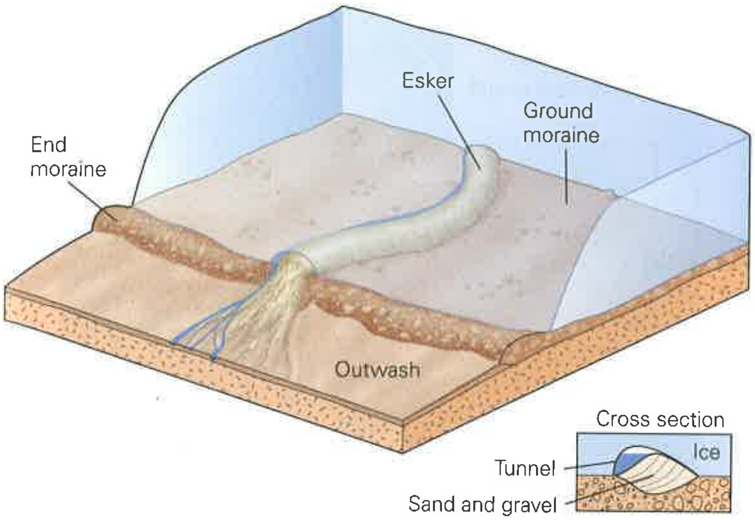
(e) Drumlins dominate this landscape near Rochester, New York.

18.5 Other Consequences of Continental Glaciation

Ice Loading and Glacial Rebound

When a large ice sheet (more than 50 km in diameter) grows on a continent, its weight causes the surface of the lithosphere to sink. In other words, ice loading causes **glacial subsidence.**

FIGURE 18.18 Eskers are snake-like ridges of sand and gravel that form when sediment fills meltwater tunnels at the base of a glacier.



(a) At the time of formation, an esker develops beneath an ice sheet. In cross section (inset), wedges of sand accumulate in the tunnel.

(b) An example of an esker in an area once glaciated, but now farmed.

Lithosphere, the relatively rigid outer shell of the Earth, can sink because the underlying asthenosphere is soft enough to flow slowly out of the way (**Fig. 18.19**). Because of ice loading, much of Antarctica and Greenland now lie below sea level (see Fig. 18.4), so if their ice were *instantly* to melt away, these continents would be flooded by a shallow sea.

What happens when continental ice sheets do melt away? Gradually, the surface of the underlying continent rises back up, by a process called **glacial rebound**, and the asthenosphere flows back underneath to fill the space. This process doesn't take place instantly, the asthenosphere flows so slowly (at rates of a few millimeters per year) that it takes thousands of years for ice-depressed continents to rebound. Thus, glacial rebound is still taking place in some regions that were covered by ice during the Pleistocene Ice Age.

Sea-Level Changes: The Glacial Reservoir

More of the Earth's surface and near-surface freshwater resides in glacial ice than in any other reservoir. During the Pleistocene Ice Age, glaciers covered almost three times as much land area so they held significantly more water than they do today. In effect, water from the ocean reservoir transferred to the glacial reservoir and remained trapped on land. As a consequence, sea level dropped by as much as 100 m, and extensive areas of continental shelves became exposed as the coastline migrated seaward (**Fig. 18.20a–c**). People and animals populated the exposed coastal plains. The drop in sea level also created land bridges across the Bering Strait between North America and northeastern Asia, providing convenient migration routes for prehistoric humans.

Ice Dams, Drainage Reversals, and Lakes

When ice freezes over a sewer opening in a street, neither meltwater nor rain can enter the drain, and the street floods. Ice sheets play a similar role in glaciated regions. The ice may block the course of a river, leading to the formation of a lake. In addition, the weight of a glacier changes the tilt of the land surface and therefore the gradients of streams, and glacial sediment may fill preexisting valleys. In sum, continental glaciation modifies or destroys preexisting drainage networks. While the glacier exists, streams find different routes and carve out new valleys; by the time the glacier melts away, these new streams have become so well established that old river courses may remain abandoned.

Meltwater Floods

Subsidence of the land surface at the toe of a glacier locally led to the growth of large ice-margin lakes. Inevitably, the ice dams that held back these lakes melted and broke. In a matter of hours to days, the contents of the lakes drained, creating immense floodwaters that stripped the land of soil and left behind huge ripple marks. For example, glacial Lake Missoula, in Montana, filled when glaciers advanced and blocked the outlet of a large valley. When the glaciers retreated, the ice dam broke, releasing immense torrents—the Great Missoula Flood—that scoured eastern Washington, creating a barren, soil-free landscape called the channeled scablands.

FIGURE 18.19 The concept of subsidence and rebound, due to continental glaciation and deglaciation. (Not to scale.)

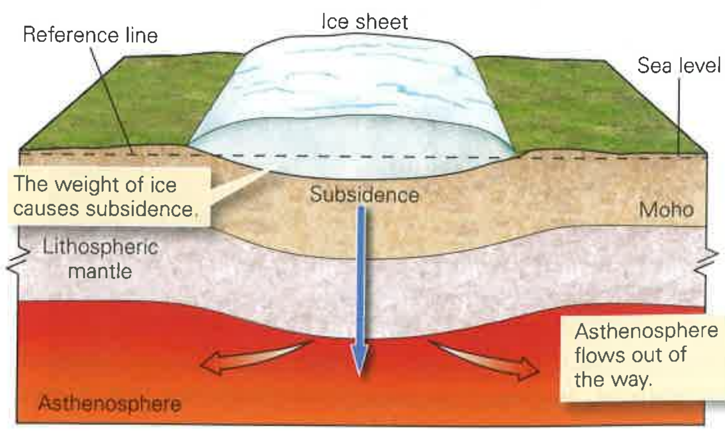
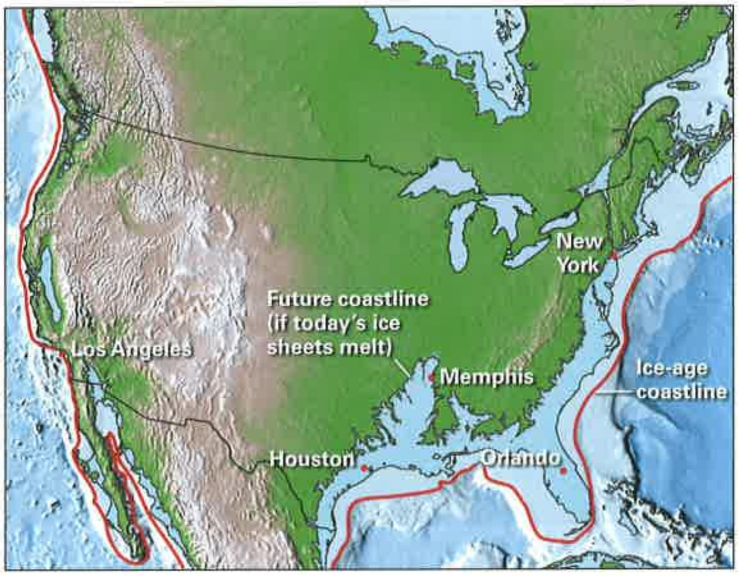
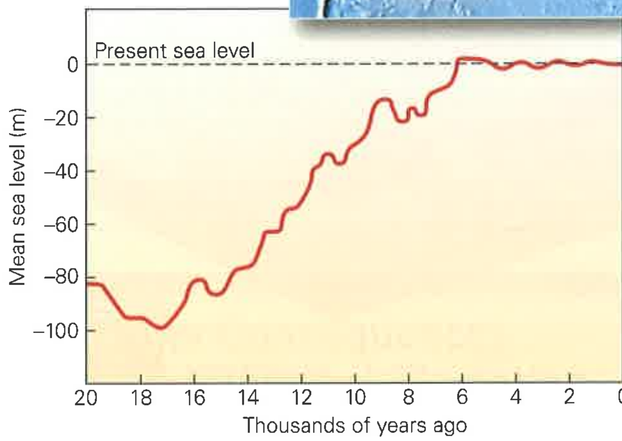


FIGURE 18.20 The link between sea level and global glaciation: glaciers store water so when glaciers grow, sea level falls, and when glaciers melt, sea level rises.



(a) The red line shows the coastline during the last ice age; much of the continental shelf was dry. If present-day ice sheets melt, coastal lands will flood.

(b) Prehistoric people migrated across the Bering Strait land bridge.



(c) Sea-level rise between 17,000 and 7,000 B.C.E. was due to the melting of ice-age glaciers.

The largest known ice-margin lake covered portions of Manitoba and Ontario, in south-central Canada, and North Dakota and Minnesota in the United States (**Fig. 18.21a**). This body of water, Glacial Lake Agassiz, existed between 11,700 and 9,000 years ago, a time during which the most recent phase of the last ice age came to a close and the continental glacier retreated north. At its largest, the lake covered over 250,000 square km (100,000 square miles), an area greater than that of all the present Great Lakes combined. The sudden release of water from Lake Agassiz may have led to a sea-level rise of 1 to 3 m during a single year.

Pluvial Features

During the Pleistocene Ice Age, the climate in regions to the south of continental glaciers was wetter than it is today. Fed by enhanced rainfall, lakes accumulated in low-lying land at a great distance from the ice front. Many such **pluvial lakes** (from the Latin *pluvia*, rain) flooded interior basins of the Basin and Range Province in Utah and Nevada (**Fig. 18.21b**). The largest pluvial lake, Lake Bonneville, covered almost a third of western Utah. When this lake suddenly drained after a natural dam holding it back broke, it left a bathtub ring of shoreline rimming the mountains near Salt Lake City. Today's Great Salt Lake is but a small remnant of Lake Bonneville.

Periglacial Environments

In polar latitudes today, and in regions adjacent to the fronts of continental glaciers during the last ice age, the mean annual temperature stays low enough (below −5°C) that soil moisture and groundwater freeze and, except in the upper few meters, stay solid all year. Such permanently frozen ground is called **permafrost**. Regions with widespread permafrost that do not have a cover of snow or ice are called *periglacial environments* (the Greek *peri* means around, or encircling; periglacial environments appear around the edges of glacial environments; **Fig. 18.22a**).

The upper few meters of permafrost may melt during the summer months, only to refreeze again when winter comes. As a consequence of the freeze-thaw process, the ground of some permafrost areas splits into pentagonal or hexagonal shapes, creating a landscape called **patterned ground** (**Fig. 18.22b**).

Permafrost presents a unique challenge to people who live in polar regions or who work to extract resources from these regions. For example, heat from a building may warm and melt underlying permafrost, creating a mire into which the building settles. For this reason, buildings in permafrost regions must be placed on stilts, so that cold air can circulate beneath them to keep the ground frozen.

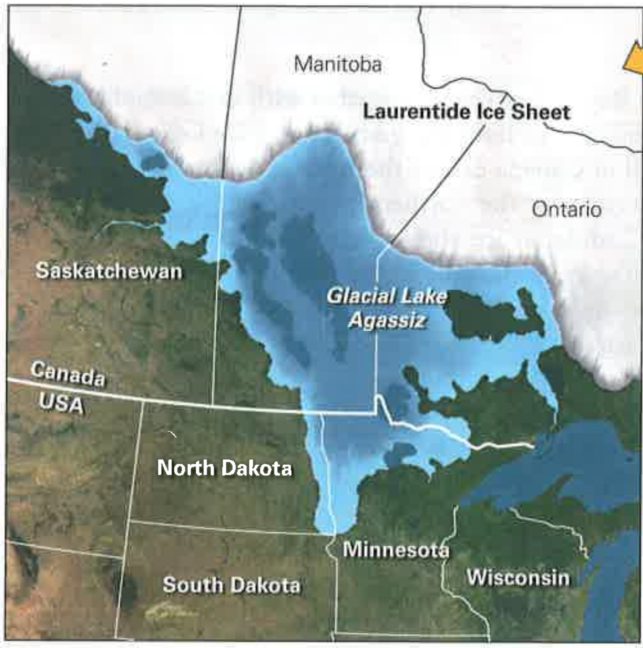
> **Take-Home Message**
>
> **The weight of a continental ice sheet can cause the ground surface to subside, and melting leads to rebound. Continental ice sheets store water, so glacial growth or melting affects sea level. The land beyond an ice sheet may be covered with permafrost or pluvial lakes.**

18.6 The Pleistocene Ice Age

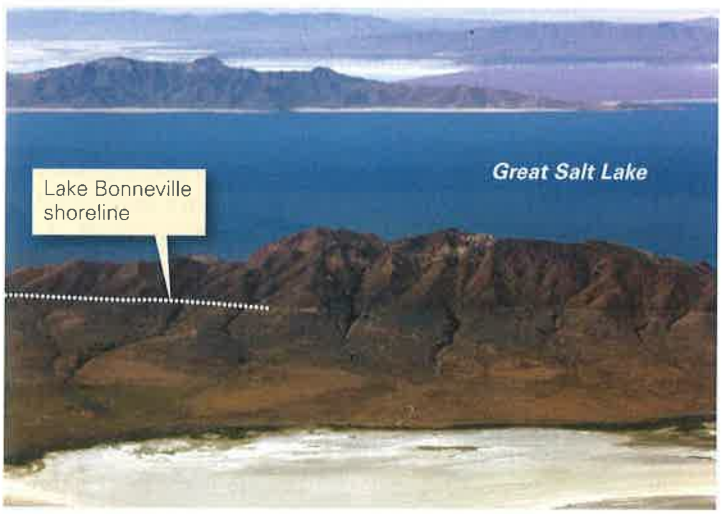
The Pleistocene Glaciers

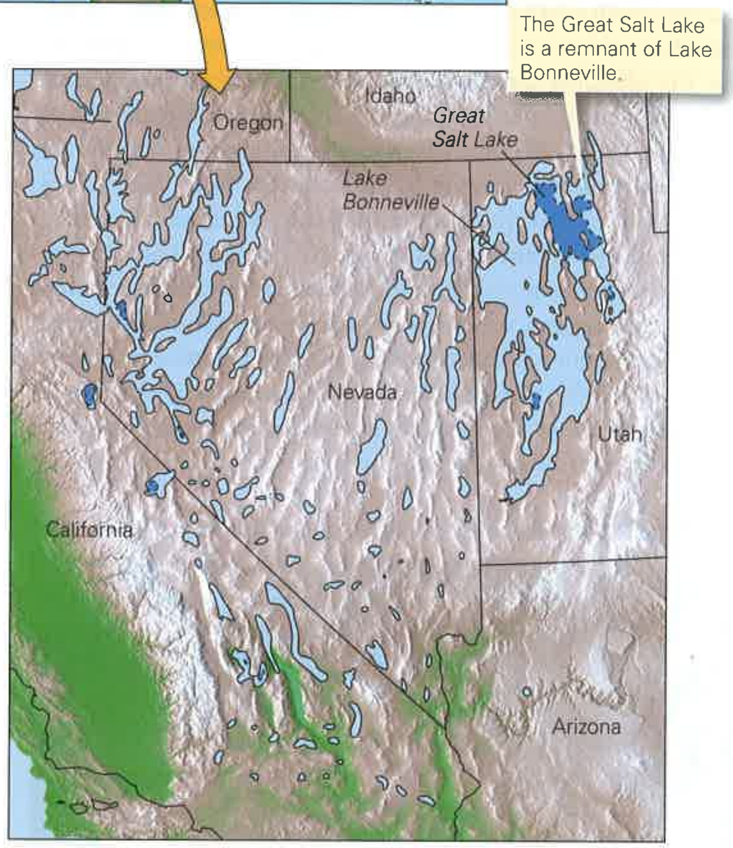
Today, most of the land surface in New York City lies hidden beneath concrete and steel, but in Central Park it's still possible to see land in a seminatural state. If you stroll through the park,

FIGURE 18.21 Ice-age lakes in North America.



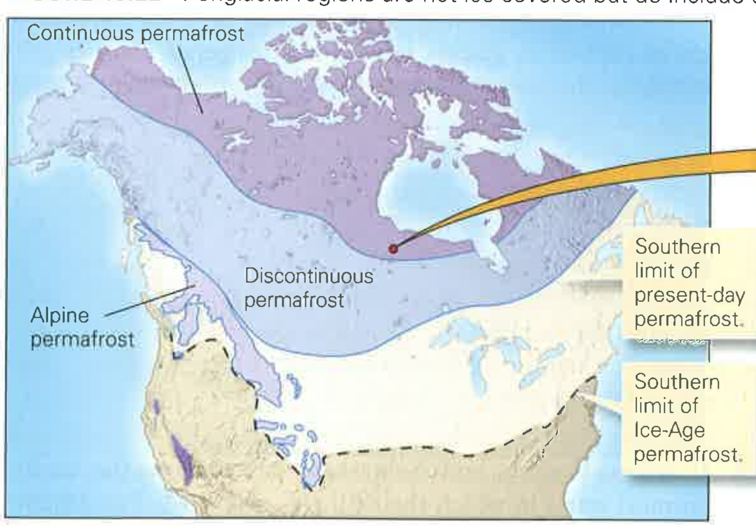
(a) Glacial Lake Agassiz was an ice-margin lake that formed near the end of the last ice age.





(b) Pluvial lakes occurred throughout the Basin and Range Province during the last ice age, due to the wetter climate. The largest of these was Lake Bonneville. Subtle horizontal terraces define the remnants of beaches, now over 100 m above the present level of the Great Salt Lake.

FIGURE 18.22 Periglacial regions are not ice covered but do include substantial areas of permafrost.



(a) The distribution of periglacial environments in North America.

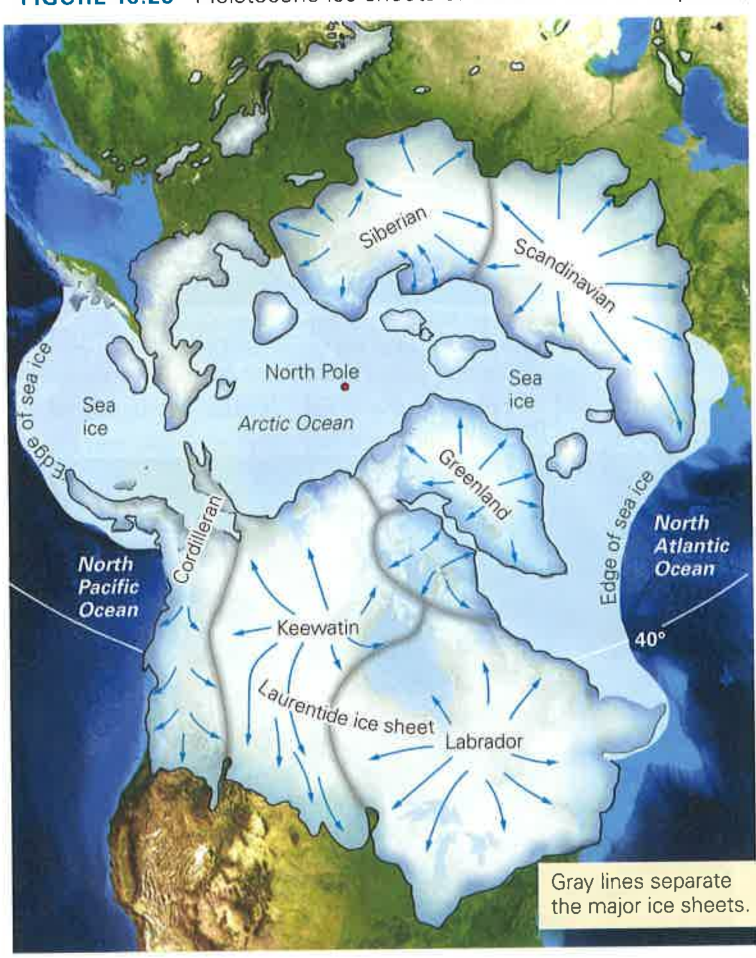
(b) An example of patterned ground near a pond in Manitoba, Canada.

you'll find that the top surfaces of outcrops are smooth and polished, and in places have been grooved and scratched. Here and there, glacial erratics rest on the bedrock. You are seeing evidence that an ice sheet once scraped along this now-urban ground. Geologists estimate that the ice sheet that overrode the New York City area may have been 250 m thick, enough to bury a 75-story building.

The fact that glaciated landscapes still decorate the surface of the Earth means that the last ice age occurred fairly recently during Earth's history. Otherwise, the landscape features would have been either eroded away or buried. The ice age responsible for the glaciated landscapes of North America, Europe, and Asia happened mostly during the Pleistocene Epoch, which began about 2.6 Ma (see Chapter 11), so as we've noted earlier, it is commonly known as the Pleistocene Ice Age.

Based on studying patterns of glacial striations and of the sources of erratics, geologists have developed an approximate idea of where the great Pleistocene ice sheets originated, and the directions in which the ice sheets flowed. In North America, major ice sheets appear to have initiated in at least three locations (**Fig. 18.23**). The Labrador ice sheet formed over northeastern Canada, the Keewatin ice sheet originated in northwestern Canada, and the Baffin ice sheet formed over Baffin Bay. These sheets, together with one or more smaller ones, merged to form the giant *Laurentide ice sheet* that covered all of Canada east of the Rocky Mountains, and spread southward over the northern portion of the United States. The Cordilleran ice sheet, which originated in the mountains of western Canada, spread westward to the Pacific coast and eastward until it merged with the Laurentide ice sheet. Other ice sheets formed in Greenland, Scandinavia, northern Russia, and Siberia.

FIGURE 18.23 Pleistocene ice sheets of the northern hemisphere.



In addition to continental ice sheets, sea ice in the northern hemisphere expanded to cover all of the Arctic Ocean and parts of the North Atlantic during the Pleistocene. Sea ice surrounded Iceland and approached Scotland and also fringed most of western Canada and southeastern Alaska.

Life and Climate in the Pleistocene World

During the Pleistocene Ice Age, all climatic belts shifted southward (**Fig. 18.24a, b**). Geologists can document this shift by examining fossil pollen, which can survive for thousands of years if preserved in the sediment of bogs.

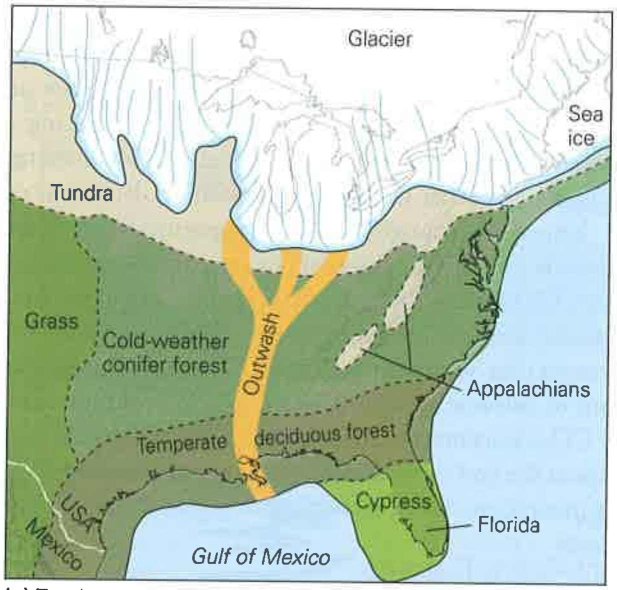
Fossils also tell us that numerous species of now-extinct large mammals inhabited the Pleistocene world (**Fig. 18.24c**). Giant mammoths and mastodons, relatives of the elephant, along with woolly rhinos, musk oxen, reindeer, giant ground sloths, bison, lions, saber-toothed cats, giant cave bears, and hyenas wandered forests and tundra in North America. Early human-like species were already foraging in the woods by the beginning of the Pleistocene Epoch, and by the end modern *Homo sapiens* lived on every continent except Antarctica, and had discovered fire and invented tools.

Timing of the Pleistocene Ice Age

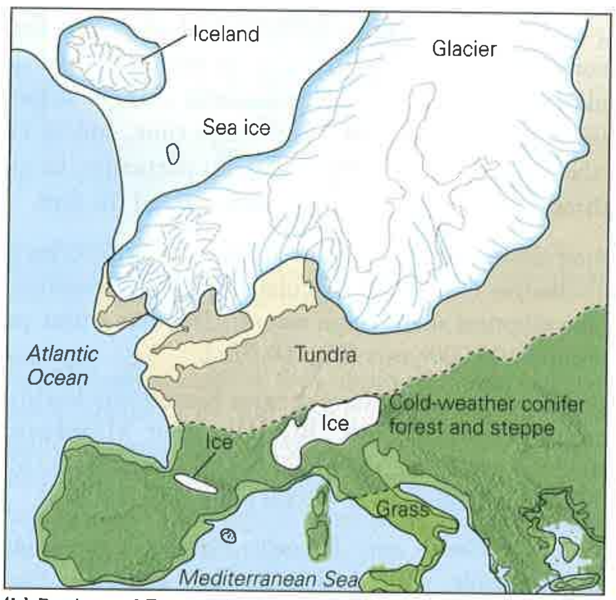
Louis Agassiz assumed that only one ice age had affected the planet. But close examination of the stratigraphy of glacial deposits on land revealed that paleosols (ancient soil preserved in the stratigraphic record), as well as beds containing fossils of warmer-weather animals and plants, lay between distinct layers of glacial sediment. This observation suggested that between episodes of glacial deposition, glaciers receded and temperate climates prevailed. In the second half of the 20th century, when modern methods for dating geological materials became available, the difference in ages between the different layers of glacial sediment could be confirmed. Clearly, glaciers advanced and then retreated more than once during the Pleistocene. Times during which the glaciers grew and covered substantial areas of the continents are called glacial periods, or glaciations, and times between glacial periods are called interglacial periods, or **interglacials**.

Using the on-land sedimentary record, geologists recognized five Pleistocene glaciations in Europe and, traditionally, four in the midwestern United States (Wisconsinan, Illinoian, Kansan, and Nebraskan, named after the southernmost states in which their till was deposited; **Fig. 18.25**).

FIGURE 18.24 Climate belts during the Pleistocene.



(a) Tundra covered parts of the United States, and southern states had forests like those of New England's today.



(b) Regions of Europe that support large populations today would have been barren tundra during the Pleistocene.

(c) Cold-adapted, now-extinct, large mammals roamed regions that are now temperate.

Since the mid-1980s, geologists no longer recognize Nebraskan and Kansan; they are lumped together as "pre-Illinoian."

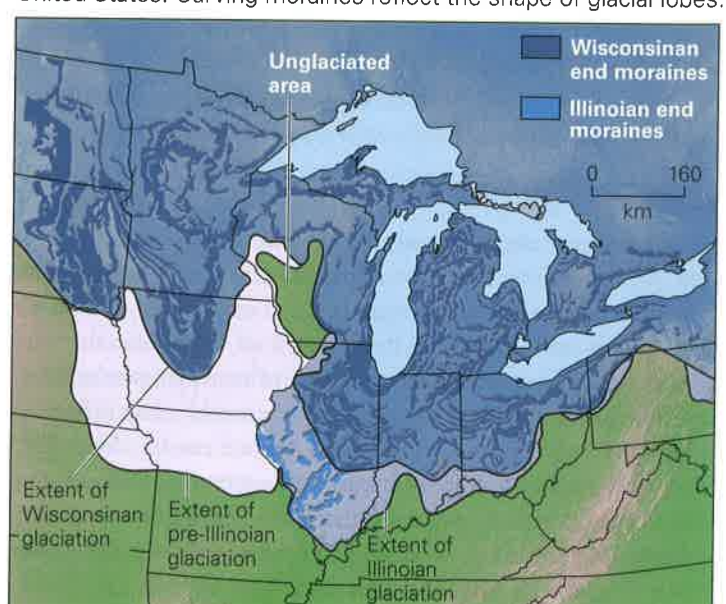
The chronology of glaciations was turned on its head in the 1960s, when geologists began to study submarine sediment. They found that some layers contained glacially transported grains, while others did not. Similarly, they found that at a given location, some layers contained fossils of cold-water plankton and other fossils of warm-water plankton. Researchers found that in sediment of the last 2.6 million years, there is evidence for 20 to 30 glaciations during the Pleistocene Epoch. The traditionally recognized glaciations of Europe and the United States might represent only the largest of these.

Geologists refined their conclusions about the frequency of Pleistocene glaciations by examining the isotopic composition of fossil shells. Shells of many plankton species consist of calcite ($CaCO_3$). The oxygen in the shells includes two isotopes, a heavier one (^{18}O) and a lighter one (^{16}O). The ratio of these isotopes tells us about the water temperature in which the plankton grew; this is because as water gets colder, plankton incorporate a higher proportion of ^{18}O into their shells. The isotope record confirms that 20 to 30 of these events occurred during the last 2.6 million years (**Fig. 18.26a**).

Older Ice Ages during Earth History

So far, we've focused on the Pleistocene Ice Age because of its importance in developing Earth's present landscape. Was this the only ice age during Earth history, or do ice ages happen frequently? To answer such questions, geologists study the stratigraphic record and search for ancient glacial deposits that have hardened into rock. These deposits, called tillites, consist of larger clasts distributed throughout a matrix of sandstone and mudstone. In many cases, tillites are deposited on glacially polished surfaces.

FIGURE 18.25 Pleistocene glacial deposits in the north-central United States. Curving moraines reflect the shape of glacial lobes.



By using the stratigraphic principles described in Chapter 10, geologists have determined that tillites were deposited during the Late Paleozoic; these are the deposits Alfred Wegener studied when he argued in favor of continental drift (**Fig. 18.26b**). Tillites were also deposited between 850 and 630 Ma (at the end of the Proterozoic Eon), about 2.4 to 2.1 Ga (near the beginning of the Proterozoic), and perhaps about 2.9 Ga (in the Archean Eon). Strata deposited at other times in Earth history do not contain tillites. Thus, it appears that glacial advances and retreats have not occurred steadily throughout Earth history, but rather are restricted to specific time intervals, or ice ages, of which there were four or five: Pleistocene, Permian, late Proterozoic, early Proterozoic, and perhaps Archean.

Did you ever wonder . . .
how many ice ages have happened during Earth history?

Of particular note, some tillites of the late Proterozoic event were deposited at equatorial latitudes, suggesting that, for at least a short time, the continents worldwide were largely glaciated, and the sea may have been covered worldwide by ice. Geologists refer to the ice-encrusted planet as **snowball Earth**.

Take-Home Message

During the Pleistocene (2.6 Ma to 11 Ka), ice sheets advanced and retreated many times; the record on land is less complete than that in marine strata. Ice ages also happened earlier in Earth history; in the Proterozoic, ice may have covered all of "snowball Earth."

18.7 The Causes of Ice Ages

Ice ages occur only during restricted intervals of Earth history, hundreds of millions of years apart. But within an ice age, glaciers advance and retreat with a frequency measured in tens of thousands to hundreds of thousands of years. Thus, there must be both long-term and short-term controls on glaciation.

Long-Term Causes

Plate tectonics exercises some long-term control over glaciation for several reasons. First, continental drift due to plate tectonics determines the distribution of continents relative to the equator and, therefore, the amount of solar heat that the land receives. Second, the distribution of continents relative to upwelling and downwelling zones of the mantle may influence overall land elevation. Finally, global climate can be affected by heat redistributed by oceanic currents—growth of island arcs and drift of continents can influence the configuration of currents and determine whether high-latitude regions can become cold enough to host ice-sheet formation.

The concentration of carbon dioxide in the atmosphere also determines whether an ice age can occur. Carbon dioxide is a greenhouse gas—it traps infrared radiation rising from the Earth—so if the concentration of CO_2 increases, the atmosphere becomes warmer. Ice sheets cannot form during periods when the atmosphere has a relatively high concentration of CO_2, even if other factors favor glaciation. But what might cause long-term changes in CO_2 concentration? Possibilities include changes in the number of marine organisms that extract CO_2 to make shells; changes in the amount of chemical weathering on land (determined by the abundance of mountain ranges) for weathering absorbs CO_2; and changes in the amount of volcanic activity. Major stages in evolution may also affect CO_2 concentration. For example, the appearance of coal swamps at the end of the Paleozoic may have removed CO_2, for plants incorporate CO_2, thus triggering glaciations of Pangaea.

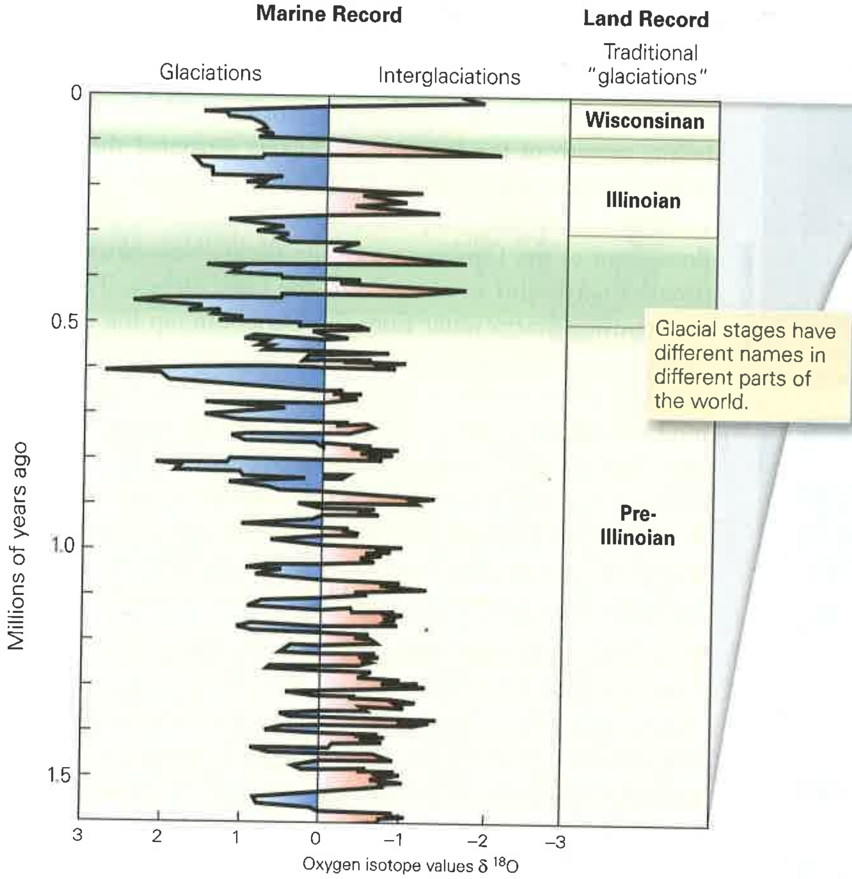
Short-Term Causes

Now we've seen how the stage could be set for an ice age to occur, but why do glaciers advance and retreat periodically *during* an ice age? In 1920, Milutin Milanković, a Serbian astronomer and geophysicist, came up with an explanation. Milanković studied how the Earth's orbit changes shape and how its axis changes orientation through time, and he calculated the frequency of these changes. In particular, he evaluated three aspects of Earth's movement around the Sun.

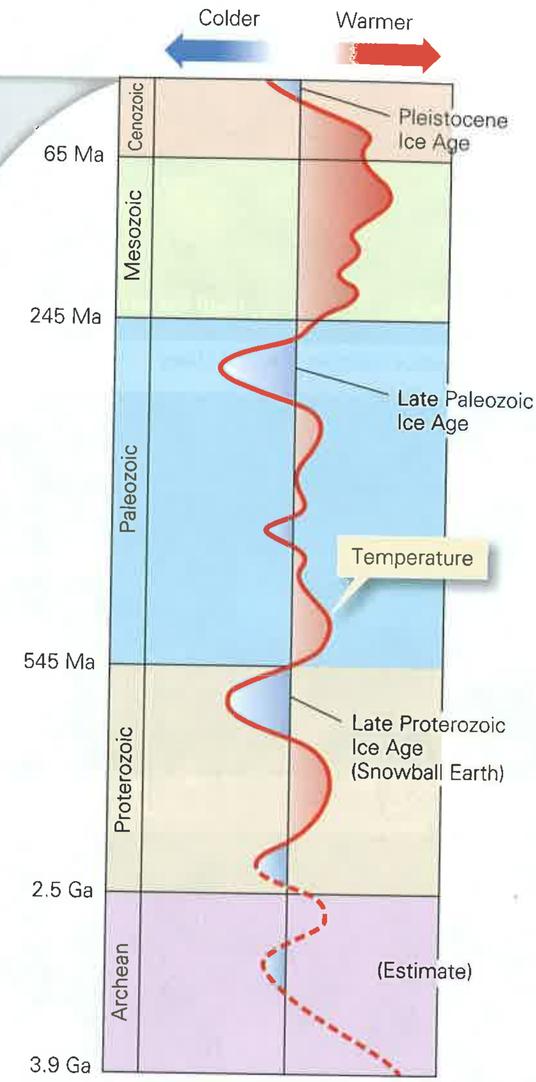
- *Orbital shape*: Milanković showed that the Earth's orbit gradually changes from a more circular shape (low eccentricity) to a more elliptical shape (high eccentricity) over a time period of around 100,000 years (**Fig. 18.27a**).
- *Tilt of Earth's axis*: We have seasons because the Earth's axis is not perpendicular to the plane of its orbit. Milanković calculated that over time, the tilt angle varies between 22.5° and 24.5°, with a frequency of 41,000 years (**Fig. 18.27b**).
- *Precession of Earth's axis*: If you've ever set a top spinning, you've probably noticed that its axis gradually traces a conical path. This motion, or wobble, is called precession (**Fig. 18.27c**). Milanković determined that the Earth's axis wobbles over the course of about 23,000 years. Precession determines the relationship between the timing of the seasons and the position of Earth along its orbit around the Sun.

Milanković showed that precession, along with variations in orbital eccentricity and tilt, combine to affect the total annual amount of insolation (exposure to the Sun's rays) and the seasonal distribution of insolation that the Earth receives at the mid- to high-latitude regions (such as 65°N) by as much as 25%. For example, such regions receive more insolation when the Earth's axis is almost perpendicular to its orbital plane than when its axis is greatly tilted. According to Milanković, glaciers tend to advance during times of cool summers at 65°N, which occur periodically (**Fig. 18.27d**). When geologists began

FIGURE 18.26 The timing of glaciations. Ice ages have occurred at several times in the geologic past.



(a) Oxygen–isotope ratios from marine sediment define 20 to 30 glaciations in the Pleistocene. Tan bands represent traditional glacial stages of the midwestern United States.



(b) The Pleistocene is not the only ice-age time in Earth history. Glacial events happened in colder intervals of earlier eras, too.

to study the climate record, they found climate cycles with the frequency predicted by Milanković. These climate cycles are now called **Milanković cycles.**

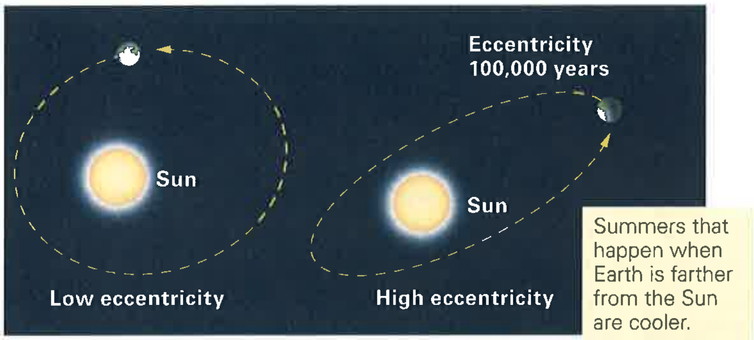
Milanković cycles, however, cannot be the whole story. Geologists suggest that several other factors may come into play in order to trigger a glacial advance.

- *Solar variability*: Changes in the radiation output of the Sun could affect the amount of energy the Earth receives.
- *A changing albedo*: When snow remains on land throughout the year, or clouds form in the sky, the albedo (reflectivity) of the Earth increases, so Earth's surface reflects incoming sunlight and thus becomes even cooler.
- *Interrupting the global heat conveyor*: As the climate cools, evaporation rates from the sea decrease, so seawater does not become as salty. Decreasing salinity might stop the system of thermohaline currents that brings warm water to high latitudes (see Chapter 15). Thus, the high latitudes become even colder than they would otherwise.
- *Biological processes that change CO_2 concentration*: As we have noted, biological processes may have amplified climate changes by altering the concentration of carbon dioxide in the atmosphere.

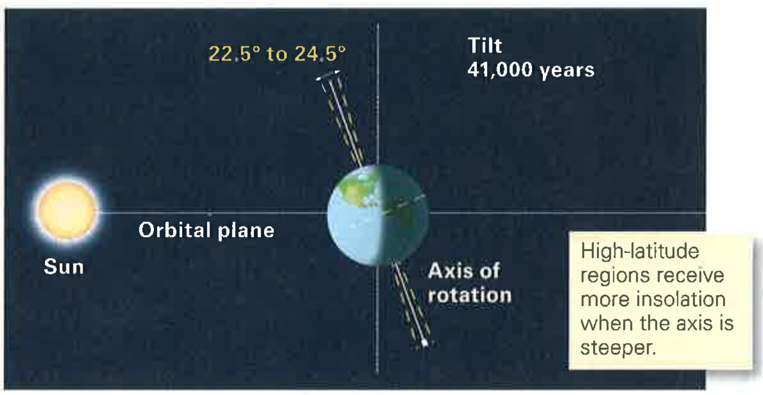
A Model for Pleistocene-Ice-Age History

Long-term cooling in the Cenozoic Era. Taking all of the above causes into account, we can now propose a scenario for the events that led to the Pleistocene glacial advances. Our story begins in the Eocene Epoch, about 55 Ma (**Fig. 18.28**). At that time, climates were warm and balmy not only in the tropics, but even above the Arctic Circle. Near the end of the Middle Eocene about 40 Ma, the climate began to cool. This long-term climate change may have been caused, in part, by change in the pattern of atmospheric circulation that happened when India collided with Asia. Specifically, the uplift of the Himalayas and Tibet diverted winds in a way that cooled the climate. Further, this uplift exposed more rock to chemical weathering, perhaps leading to extraction of CO_2 from the atmosphere. The formation of the circum-Antarctic current and the isolation of Antarctica also happened about this time. Studies show that this event could have cooled the global ocean.

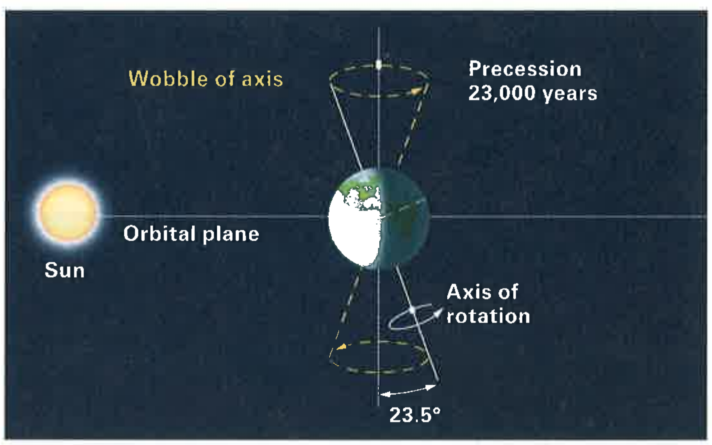
FIGURE 18.27 Milanković cycles influence the amount of insolation received at high latitudes.



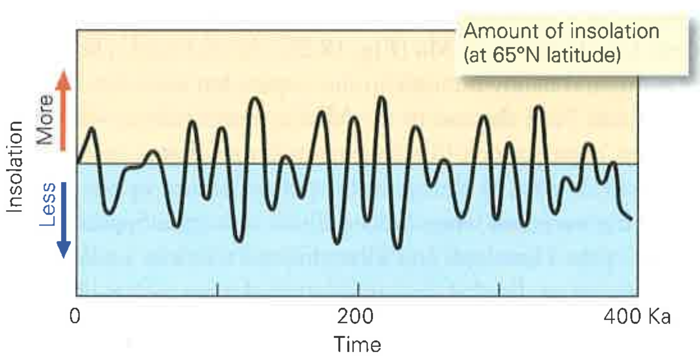
(a) Variations caused by changes in orbital shape.



(b) Variations caused by changes in axis tilt.



(c) Variations caused by the precession of Earth's axis.



(d) Combining the effects of eccentricity, tilt, and precession produces distinct periods of more or less insolation.

So far, we've examined hypotheses that explain long-term cooling since about 40 Ma, but what caused the sudden beginning of the Laurentide ice sheet growth at about 2.6 Ma? This event may coincide with other plate-tectonic events. For example, the closing of the gap between North and South America by the growth of the Isthmus of Panama separated the waters of the Caribbean from those of the tropical Pacific for the first time, and when this happened, warm currents that previously flowed out of the Caribbean into the Pacific were blocked and diverted northward to merge with the Gulf Stream. This current transfers warm water from the Caribbean, up the Atlantic Coast of North America, and ultimately to the British Isles. As the warm water moves up the Atlantic Coast, it generates warm, moisture-laden air that provides a source for the snow that falls over New England, eastern Canada, and Greenland. In other words, the Arctic has long been cold enough for ice caps, but it wasn't until the Gulf Stream was diverted northward by the growth of Panama, that there was sufficient moisture to serve as a source for the abundant snow needed for glacial growth.

Short-term advances and retreats in the Pleistocene Epoch. Once the Earth's climate had cooled overall, short-term climate changes due to Milanković cycles led to periodic advances and retreats of the glaciers. To understand how, let's look at a possible case history of a single advance and retreat of the Laurentide ice sheet. (Note that such models remain the subject of vigorous debate.)

- *Stage 1*: During the overall cooler climates of the late Cenozoic Era, the Earth reaches a point in the Milanković cycle when the average mean temperature in temperate latitudes drops. Not all of winter's snow melts away during the summer in northern Canada. The snow reflects sunlight, so the region grows still colder and even more snow accumulates as evaporation off the Gulf Stream provides moisture. Finally, the snow at the base of the pile turns to ice, and the ice begins to spread outward under its own weight. A new continental glacier has been born.
- *Stage 2*: The ice sheet continues to grow as more snow piles up in the zone of accumulation, and the atmosphere continues

FIGURE 18.28 Until recently, Earth's atmosphere has been gradually cooling, overall, since the Cretaceous.

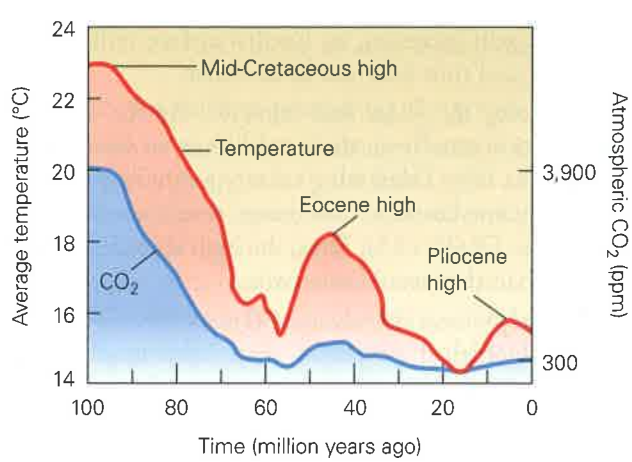
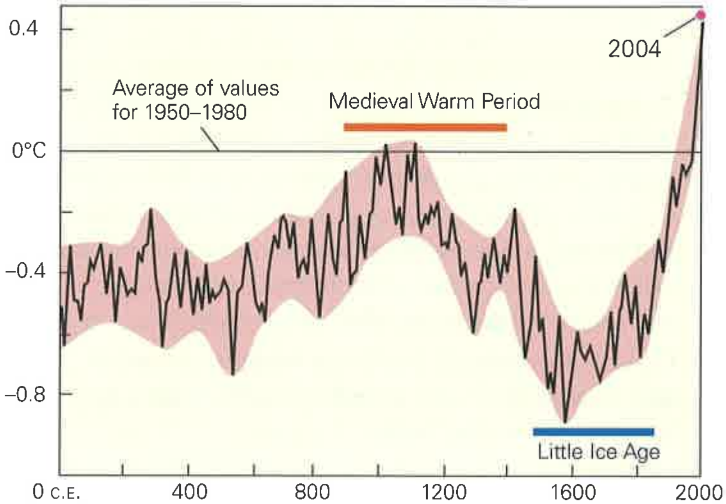
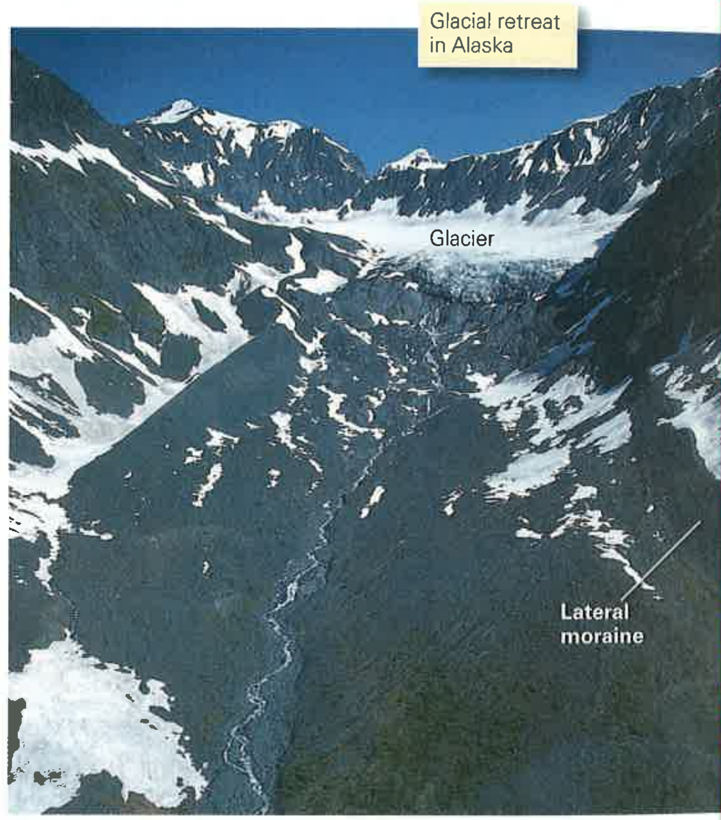


FIGURE 18.29 The Little Ice Age and its demise. Glaciers that advanced between 1550 and 1850 have since retreated.



(a) A model of global temperature for the past 2,000 years. Overall trends display the Medieval Warm Period followed by the Little Ice Age. Since 1850, temperatures have warmed.


(b) Skaters (ca. 1600) on the frozen canals of the Netherlands during the Little Ice Age.



(c) During the Little Ice Age, a glacier filled this valley. In this 2003 photo, most of the glacier has vanished. Most of the retreat has happened in the last century.

to cool because of the albedo effect. But now, the weight of the ice loads the continent and makes it sink, so the elevation of the glacier decreases, and its surface approaches the equilibrium line. Also, the temperature becomes cold enough that in high latitudes the Atlantic Ocean begins to freeze. As the sea ice covers the ocean, the amount of seawater evaporation decreases, so the source of moisture for snow is cut off and the amount of snowfall diminishes. The glacial advance pretty much chokes on its own success.

- *Stage 3*: As the glacier retreats, albedo decreases, temperatures gradually increase, and the sea ice begins to melt. The supply of water to the atmosphere from evaporation increases once again, but with the warmer temperatures and lower elevations, this water precipitates as rain during the summer. The rain drastically accelerates the rate of ice melting, so the retreat can progress quite rapidly.

Will There Be Another Glacial Advance?

What does the future hold? Considering the periodicity of glacial advances and retreats during the Pleistocene Epoch, we may be living in an interglacial period. Pleistocene interglacials lasted about 10,000 years, and since the present interglacial began about 11,000 years ago, the time may be ripe for a new glaciation. If a glacier on the scale of the Laurentide ice sheet were to develop, major cities and agricultural belts would be overrun by ice, and their populations would have to migrate southward. Long before the ice front arrived, though, the climate would become so hostile that the cities would already be abandoned.

The Earth actually had a brush with ice-age-like conditions between the 1300s and the mid-1800s, when average annual temperatures in the northern hemisphere fell sufficiently for mountain glaciers to advance significantly. During this period, now known as the Little Ice Age, sea ice surrounded Iceland and canals froze in the Netherlands, leading to that country's tradition of skating (**Fig. 18.29a, b**).

During the past 150 years, temperatures have warmed, and most mountain glaciers have retreated significantly (**Fig. 18.29c**). Such global warming could conceivably cause a "super-interglacial" period. The next chapter addresses the causes and consequences of such change.

Take-Home Message

Ice ages occur when the distribution of continents, ocean currents, and the concentration of atmospheric CO_2 are appropriate. Advances and retreats during an ice age are controlled by Milanković cycles defining variations in Earth's orbit and rotation axis. We may be living in a super-interglacial period.

CHAPTER 18 REVIEW

Chapter Summary

- Glaciers are streams or sheets of recrystallized ice that survive for the entire year and flow in response to gravity. Mountain glaciers exist in high regions and fill cirques and valleys. Continental glaciers (ice sheets) spread over substantial areas of the continents.
- Glaciers form when snow accumulates over a long period of time. With progressive burial, the snow first turns to firn and then to ice.
- Temperate glaciers melt during part of the year. Polar glaciers do not. Glaciers move by basal sliding over water or wet sediment, and/or by plastic deformation of ice grains. In general, glaciers move tens of meters per year.
- Glaciers move because of gravitational pull; they flow in the direction of their overall surface slope.
- Whether the toe of a glacier stays fixed in position, advances, or retreats depends on the balance between the rate at which snow builds up in the zone of accumulation and the rate at which glaciers melt, calve, or sublimate in the zone of ablation.
- Icebergs break off glaciers that flow into the sea. Continental glaciers that flow into the sea along a coast make ice shelves. Sea ice forms where the ocean's surface freezes.
- As glacial ice flows over sediment, it incorporates clasts. The clasts embedded in glacial ice abrade the substrate.
- Mountain glaciers carve numerous landforms, including cirques, arêtes, horns, U-shaped valleys, hanging valleys, and truncated spurs. Fjords are glacially carved valleys that filled with water when sea level rose after an ice age.
- Glaciers can transport sediment of all sizes. Glacial drift includes till, glacial marine, glacial outwash, lake-bed mud, and loess. Lateral moraines accumulate along the sides of valley glaciers, medial moraines form down the middle, and end moraines accumulate at a glacier's toe.
- Glacial depositional landforms include moraines, knob-and-kettle topography, drumlins, kames, eskers, meltwater lakes, and outwash plains.
- Continental crust subsides as a result of ice loading. When the glacier melts away, the crust rebounds.
- When water is stored in continental glaciers, sea level drops. When glaciers melt, sea level rises.
- During past ice ages, the climate in regions south of the continental glaciers was wetter, and pluvial lakes formed. Permafrost exists in periglacial environments.
- During the Pleistocene Ice Age, large continental glaciers covered much of North America, Europe, and Asia.
- The stratigraphy of Pleistocene glacial deposits indicates that glaciers advanced and retreated many times during the ice age. The record of glaciations is more complete in oceanic sediment.
- Long-term causes of ice ages include plate tectonics and changes in the concentration of CO_2 in the atmosphere. Short-term causes include the Milanković cycles.

Key Terms

ablation (p. 520)
arête (p. 524)
cirque (p. 524)
continental glacier (ice sheet) (p. 518)
crevasse (p. 520)
drumlin (p. 529)
equilibrium line (p. 522)
erratic (p. 515)
esker (p. 532)
fjord (p. 526)
glacial drift (p. 527)
glacially polished surface (p. 524)
glacial outwash (p. 527)
glacial rebound (p. 532)
glacial striation (p. 523)
glacial subsidence (p. 532)
glacial till (p. 527)
glacier (p. 515)
hanging valley (p. 524)
horn (p. 524)
ice age (p. 516)
iceberg (p. 522)
ice shelf (p. 522)
interglacial (p. 536)
kettle hole (p. 529)
loess (p. 527)
Milanković cycle (p. 539)
moraine (p. 527)
mountain (alpine) glacier (p. 518)
patterned ground (p. 534)
permafrost (p. 534)
pluvial lake (p. 534)
polar glacier (p. 519)
roche moutonnée (p. 526)
sea ice (p. 523)
snowball Earth (p. 538)
tarn (p. 524)
temperate glacier (p. 518)
tidewater glacier (p. 522)
U-shaped valley (p. 524)
zone of ablation (p. 522)
zone of accumulation (p. 522)

Review Questions

1. What evidence did Louis Agassiz offer to support the idea of an ice age?
2. How do mountain glaciers and continental glaciers differ?
3. Describe the transformation from snow to glacial ice.
4. Explain how arêtes, cirques, and horns form.

smartwork smartwork.wwnorton.com

Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- Interactive exercises on the process of glacial flow.
- A What a Geologist Sees question on glacial features.
- Problems that help students calculate rates of glacial advance and retreat.

5. Describe the mechanisms that enable glaciers to move, and explain why glaciers move.
6. How fast do glaciers normally move? How fast can they move during a surge?
7. Explain how the balance between ablation and accumulation controls advances and retreats.
8. How can a glacier continue to flow toward its toe even though its toe is retreating?
9. How does a glacier transform a V-shaped valley into a U-shaped valley? Discuss how hanging valleys form.
10. Describe the various kinds of glacial deposits. Be sure to note the materials from which the deposits are made and the landforms that result from deposition.
11. How does the lithosphere respond to the weight of glacial ice?
12. How was the world different during the glacial advances of the Pleistocene Ice Age? Be sure to mention the relation between glaciations and sea level.
13. How was the on-land chronology of glaciations developed? Why was it so incomplete? How was it modified with the study of marine sediment?
14. Were there ice ages before the Pleistocene? If so, when?
15. What are some of the long-term causes that lead to ice ages? What are the short-term causes that trigger glaciations and interglacials?

On Further Thought

16. If you fly over the barren cornfields of central Illinois during the early spring, you will see slight differences in soil color due to variations in moisture content—wetter soil is darker. These variations outline the shapes of polygons that are tens of meters across. What do these patterns represent, and how might they have formed?
17. An unusual late Precambrian rock unit crops out in the Flinders Range, a small mountain belt in South Australia, near Adelaide. Structures in the belt formed at the beginning of the Paleozoic. This unit consists of clasts of granite and gneiss, in a wide range of sizes, suspended through a matrix of slate. The rock unit lies unconformably above a basement of granite and gneiss, and if you dig out the unconformity surface, you will find that it is polished and striated. What is the unusual rock?

SEE FOR YOURSELF R . . . Glacial Landscapes

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet R of our **Geotours Workbook**.

Baffin Island, Canada
Latitude 67°8′27.56″N,
Longitude 64°49′49.31″W

From 40 km, you can see two valley glaciers draining the Baffin Island ice cap. They merge into a trunk glacier that flows NE and then into a fjord, partly filling a U-shaped valley. Note the lateral and medial moraines. In some nearby fjords, meltwater has deposited a delta of outwash at the end of the glacier.

Glaciated Peaks, Montana
Latitude 48°56′33.66″N,
Longitude 113°49′54.59″W

Viewed from 8 km, you can see three cirques bounding a horn in the Rocky Mountains, north of Glacier National Park. Note the knife-edge arêtes between the cirques. The glaciers that carved the cirques have melted away. The thin stripes on the mountain face are traces of bedrock sedimentary beds.