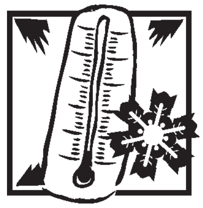

Chapter 6: Glaciers in the Northwest Central US

Glaciers have had a profound impact on the Northwest Central's scenery, geology, and water resources. Today, small **cirque** glaciers and larger valley glaciers are found largely in the mountains of Wyoming and Montana, while a few small glaciers and **perennial** snowfields can be seen in Idaho. Ongoing research into how these glaciers have changed since the last major **ice age** is proving invaluable to our understanding of **climate change**.

What is a glacier?

A **glacier** is a large mass of ice (usually covered by snow) that is heavy enough to flow like a very thick fluid. Glaciers form in areas where more snow accumulates than is lost each year. As new snow accumulates, it buries and **compresses** old snow, transforming it from a fluffy mass of snowflakes into ice crystals with the appearance of wet sugar, known as **firn**. As this firn is buried yet deeper, it coalesces into a mass of hard, dense ice that is riddled with air bubbles. Much of this transformation takes place in the high part of a glacier where annual snow accumulation outpaces snow loss—a place called the **accumulation zone**. At a depth greater than about 50 meters (165 feet), the pressure is high enough for plastic flow to occur. Ice flow is driven by gravity, and it causes movement downhill and out from the center (*Figure 6.1*). Once the ice becomes thick enough, it flows outward to the **ablation zone**, where the ice is lost due to melting and **calving** (*Figure 6.2*). The boundary between these two zones, the equilibrium line, is where annual ice accumulation equals annual ice loss. Because the altitude of this line is dependent on local temperature and precipitation, glaciologists frequently use it to assess the impact of climate change on glaciers.

Most broadly, there are two types of glaciers: smaller alpine glaciers and larger continental glaciers. Found in mountainous areas, alpine glaciers have a shape and motion that is largely controlled by **topography**, and they naturally flow from higher to lower altitudes. Glaciers confined to valleys are called valley glaciers, while bowl-shaped depressions called cirques are located in mountainous areas. Continental glaciers are much larger, and they are less controlled by the landscape, tending to flow outward from their center of accumulation. **Ice sheets** are large masses of ice that cover continents (such as those found in Greenland) or smaller masses that cover large parts of mountain ranges (**ice fields**). Because ice fields often appear to be crowning a mountain range, they are sometimes called **ice caps** as well. Mountains fringing the ice sheets cause the descending ice to break up into outlet glaciers (streams of ice resembling alpine glaciers) or broad tongues of ice called piedmont glaciers.

cirque *• a large bowl-shaped depression carved by glacial erosion and located in mountainous regions.*

perennial *• continuous; year-round or occurring on a yearly basis.*

ice age *• a period of global cooling of the Earth's surface and atmosphere, resulting in the presence or expansion of ice sheets and glaciers.*

climate change *• See global warming: the current increase in the average temperature worldwide, caused by the buildup of greenhouse gases in the atmosphere.*

compression *• flattening or squeezing as a result of forces acting on an object from all or most directions.*

calving *• the process by which ice breaks off from the end of a glacier.*

CHAPTER AUTHOR

Libby Prueher

6 Glaciers

Review

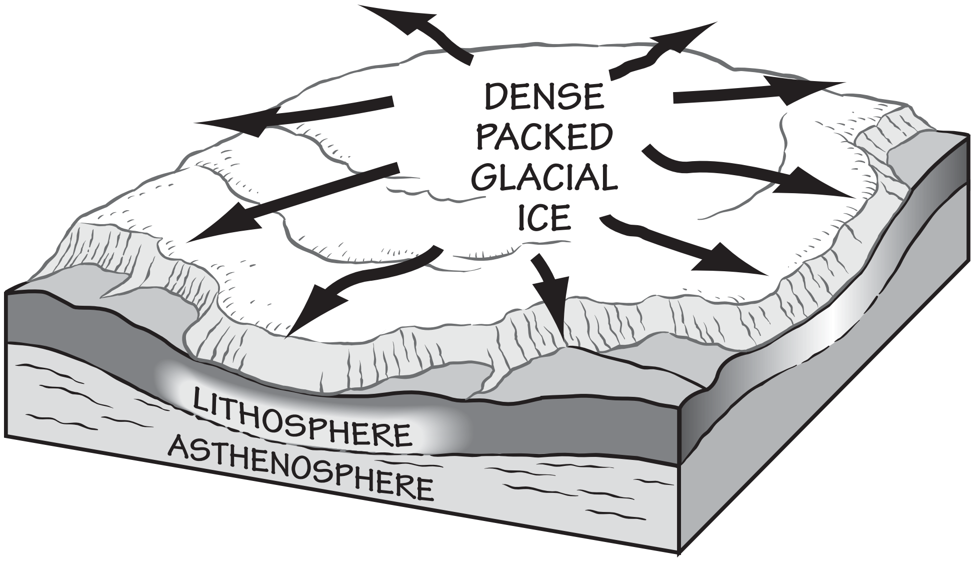

Figure 6.1: As dense glacial ice piles up, a glacier is formed. The ice begins to move under its own weight and pressure.

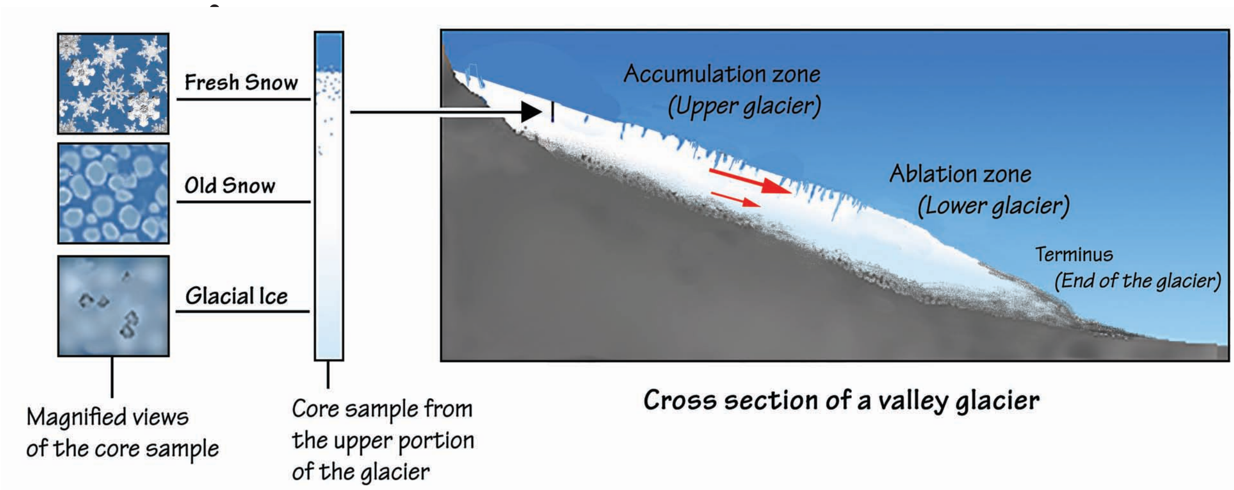

Figure 6.2: Cross-section of an alpine (valley) glacier, showing snow being converted into glacial ice and the two major zones of a glacier's surface. The red arrows show the direction and relative speed of different parts of the glacier. The longer the arrow, the faster the ice is moving.

While only the two broadest categories of glaciers are discussed here, glaciers exist in a variety of forms. Even these broadest of distinctions are not quite so clear-cut (e.g., continental glaciers often have tongues that feed into valleys, which may become alpine glaciers).

In summary, glaciers grow when it is cool enough for an ice sheet to accumulate snow more quickly than it melts. As they grow, ice sheets become so massive that they flow outwards, covering an increasing area until melting at the margins catches up to the pace of accumulation. Glaciers that reached the Northwest Central States flowed from centers of accumulation far to the north (in what is now Canada), and glacial growth southward through the Midwest was more a result of this lateral flow than of direct precipitation from falling snow. By 18,000 years ago, the ice was in retreat due to a slight warming of the **climate**—it was not actually flowing backward, but melting faster than it was accumulating and advancing.

Glacial Landscapes

The interaction of glaciers with the landscape is a complex process. Glaciers alter landscapes by **eroding**, transporting, and depositing rock and sediment. **Scouring** abrades bedrock and removes sediment, while melting causes the ice to deposit sediment.

See Chapter 4: Topography to learn more about the marks left by glaciers on the Northwest Central's landscape.

Continental glaciers also affect the landscape by depressing the Earth's **crust** with their enormous mass, just as a person standing on a trampoline will cause the center to bulge downwards. The effect is quite substantial, with surfaces being lowered by hundreds of meters. Of course, this means that when the glacier retreats and the mass is removed, the crust will rise to its former height in a process known as **isostasy** (*Figure 6.3*). Dramatic results include marine **reefs** lifted high above sea level and marine sediments composing coastal bluffs.

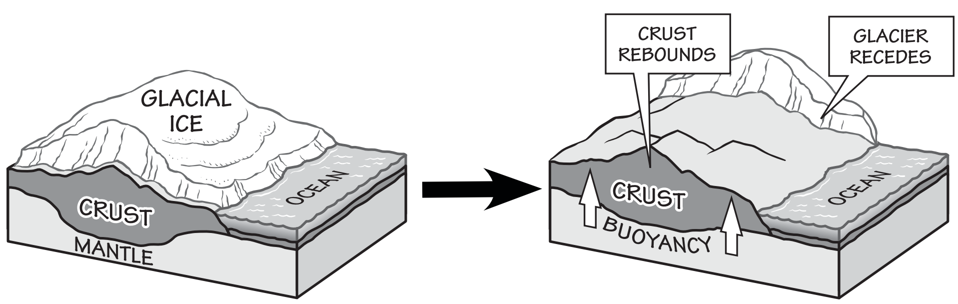

Figure 6.3: Isostatic rebound resulting from glacial retreat.

Glacial erosion can produce rugged mountainous areas with knife-edge ridges (**arêtes**), pointed rocky peaks (**horns**), and bowl-shaped depressions (cirques). These landscape features are most visible in areas where glaciers have retreated (*Figure 6.4*).

climate • *a description of the average temperature, range of temperature, humidity, precipitation, and other atmospheric/hydrospheric conditions a region experiences over a period of many years (usually more than 30).*

erosion • *the transport of weathered materials.*

scouring • *erosion resulting from glacial abrasion on the landscape.*

crust • *the uppermost, rigid outer layer of the Earth, composed of tectonic plates.*

isostasy • *an equilibrium between the weight of the crust and the buoyancy of the mantle.*

reef • *a feature lying beneath the surface of the water, which is a buildup of sediment or other material built by organisms, and which has positive relief from the sea floor.*

arête • *a thin ridge of rock with an almost knife-like edge, formed when two glaciers erode parallel valleys.*

Glaciers

Landscapes

plucking • *process in which a glacier "plucks" sediments and larger chunks of rock from the bedrock.*

frost wedging • *weathering that occurs when water freezes and expands in cracks.*

sand • *rock material in the form of loose, rounded, or angular grains, and formed as a result of the weathering and decomposition of rocks.*

clay • *the common name for a number of very fine-grained, earthy materials that become plastic (flow or change shape) when wet.*

rock flour • *very fine sediments and clay resulting from the grinding action of glaciers.*

igneous rocks • *rocks derived from the cooling of magma underground or molten lava on the Earth's surface.*

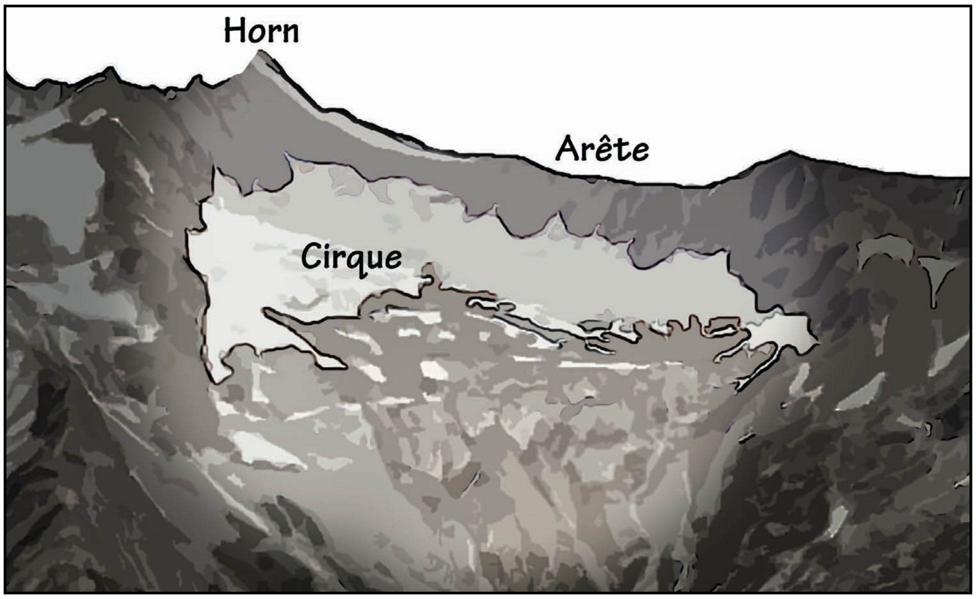

Figure 6.4: Common alpine glacial landscape features.

Erosion

Thousands of years of scraping by ice can have dramatic, and sometimes dramatically varied, effects on a landscape. Glaciers erode the land they flow over via abrasion and **plucking**. Harder bedrock will be scratched and polished by sediment stuck in the ice, while **frost wedging**, when water freezes and expands in cracks, can eventually break chunks of rock away. Softer bedrock is much more easily carved and crushed. Abrasion, or scouring, occurs when rock fragments in the ice erode bedrock as the glacier moves over it. Plucking involves glaciers literally pulling rock from underlying bedrock. The flowing ice cracks and breaks rock as it passes over, pieces of which become incorporated in the sheet or bulldozed forward, in front of the glacier's margin. The less resistant rock over which glaciers move is often eroded and ground-up into very fine **sand** and **clay** (called **rock flour**). Once eroded, this material is carried away by the ice and deposited wherever it melts out (*Figure 6.5*).

More resistant **igneous** and **metamorphic rock** is often polished and scratched by the grinding action of sediments trapped in the glacial ice. Streams of meltwater from the glacier, frequently gushing and full of sediment, cause significant amounts of scour as well. The abrasive sediments in the flowing water create **potholes** in the bedrock and **plunge pools** at the base of waterfalls. At the edge of the sheet, where the ice at last succumbs to melting, the rock is finally deposited. Piles of this rock form some of the distinctive landforms found in the Dakotas and Montana today.

The nature of the glacier causing the erosion is also crucial. Because continental glaciers spread from a central accumulation zone, they cannot go around peaks in their path, so they instead slowly crush and scrape them away. For the most part, this results in flatter landscapes. Conversely, alpine glaciers tend to follow

Landscapes

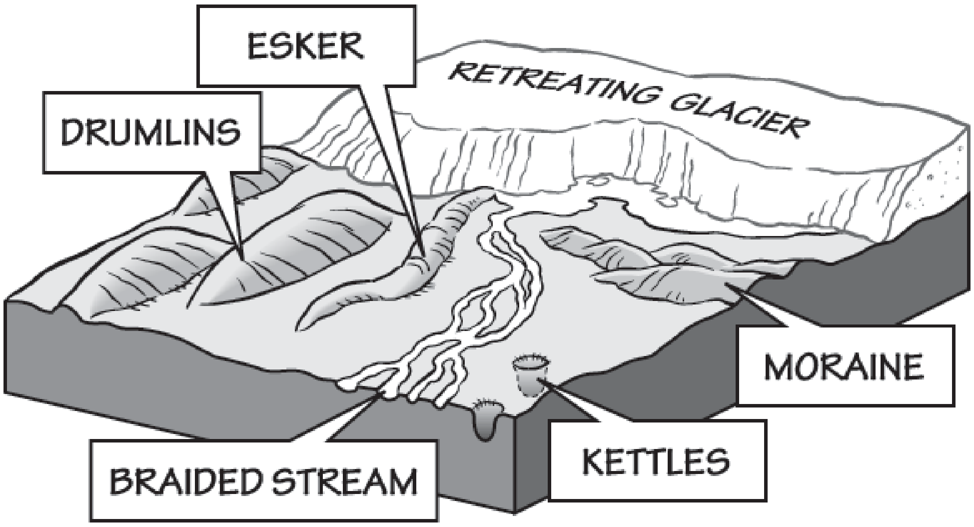

Figure 6.5: Common erosional glacial landscape features.

the existing topography, flowing downhill. This frequently causes them to scour existing low points, making them lower still. While this gouging increases the overall **relief** of an area, anything directly in the path of the ice is flattened. For example, a glacier might deepen a valley while surrounding peaks remain high, yet the valley itself, initially cut by a narrow stream into a sharp V-shape, is smoothed into a distinctive U-shape by the wider glacier (*Figure 6.6*).

Figure 6.6: A glacially carved valley in Glacier National Park, Montana.

metamorphic rocks • *rocks formed by the recrystallization and realignment of minerals in pre-existing sedimentary, igneous, and metamorphic rocks when exposed to high enough temperature and/or pressure.*

pothole • *a shallow, rounded depression eroded in bedrock by a glacier.*

plunge pool • *a stream pool, lake, or pond that is small in diameter, but deep.*

relief • *the change in elevation over a distance.*

6 Glaciers

Landscapes

gravel *• unconsolidated, semi-rounded rock fragments larger than 2 millimeters (0.08 inches) and smaller than 75 millimeters (3 inches).*

silt *• fine granular sediment most commonly composed of quartz and feldspar crystals.*

till *• unconsolidated sediment that is eroded from the bedrock, then carried and eventually deposited by glaciers as they recede.*

moraine *• an accumulation of unconsolidated glacial debris (soil and rock) that can occur in currently glaciated and formerly glaciated regions.*

drift *• unconsolidated debris transported and deposited by a glacier.*

outwash plain *• large sandy flats created by sediment-laden water deposited when a glacier melts.*

Deposition

As glaciers scrape over the earth, sediment is incorporated into or shoved ahead of the advancing ice. The unsorted mixture of boulders, **gravel**, sand, **silt**, and clay that is picked up and later deposited by glaciers is called **till**. It is important to note that whether a glacier is advancing, in equilibrium, or retreating, its ice is still flowing forward, like a conveyor belt that is constantly depositing till at its margin. In places where a glacier stopped its advance and then melted back, a ridge of till that had been pushed in front of it is left behind, marking the farthest extent of the glacier's margin, or terminus. A ridge of till formed this way is called a terminal **moraine**, and it may range in length from hundreds to thousands of meters. Moraines can also form when till is pushed to the sides of an advancing glacier (*Figure 6.7*).

Figure 6.7: The snakelike ridge in the foreground is a now-forested lateral moraine deposited by a valley glacier. Today, it curves along the left side of Mission Reservoir, located about 48 kilometers (30 miles) north of Missoula, Montana.

Drift-covered plains with lakes and low ridges and hills appear near the terminus of a glacier as dwindling ice leaves behind glacial till. Beyond the terminus, meltwater streams leave more orderly deposits of sediment, creating an **outwash plain** where the finest sediments are farthest from the terminus, while cobbles and boulders are found much closer. Spoon- or teardrop-shaped hills called **drumlins** (*Figure 6.8*) are composed largely of till that was trapped beneath a glacier and streamlined in the direction of the flow of ice moving over it. The elongation of a drumlin provides an excellent clue to the direction of flow during an ice sheet's most recent advance and reflects the final flow direction before the glacier receded.

Meltwater flowing off a glacier also leaves behind deposits. Unlike till deposits, meltwater deposits are well sorted: large rocks can only be moved by high-energy water, while finer sand and mud are washed downstream until enough energy is lost so that even they are dropped. In other words, the faster the water is moving, the coarser the sediment deposited (*Figure 6.9*). As a glacier melts, streams of sediment-laden meltwater often create networks of **braided streams** in front of the glacier. Streams of meltwater flowing under a glacier can deposit sand and gravel, and when an ice sheet retreats, these snaking ridges of stream deposits, known as **eskers**, are left behind (*Figure 6.10*).

Other glacial features include **kettles**, **kames**, and **erratics**. Kettles are depressions left behind by the melting glacier. Blocks of ice may be broken off from the glacier and buried or surrounded by meltwater sediments (*Figure 6.11*). When the ice eventually melts, the overlying sediments have no support, so they frequently collapse and form a depression that often fills with water to become a lake. Kames are formed in nearly the opposite way: layers of sediment fill in depressions in the ice, leaving mound-like deposits of sorted sediment after the glacier retreats (*Figure 6.12*). Often, kettles and kames occur near one another.

braided stream • *a stream consisting of multiple, small, shallow channels that divide and recombine numerous times, forming a pattern resembling strands of braided hair.*

sedimentary rock • *rock formed through the accumulation and consolidation of grains of broken rock, crystals, skeletal fragments, and organic matter.*

Figure 6.8: The Eureka Drumlin Field, near Eureka, Montana. These drumlins are arranged in a north-south orientation, indicating the direction of ice flow.

Erratics are rocks that the ice sheet picked up and transported farther south, sometimes hundreds of kilometers (miles) from their origin. They are often distinctive because they are a different type of rock than that making up the bedrock in the area to which they have been transported. For example, boulders and pebbles of igneous and metamorphic rocks are often found in areas where the bedrock is **sedimentary**. It is sometimes possible to locate the origin of an erratic if its composition and textures are highly distinctive. The pink-colored

quartzite • *a hard metamorphic rock that was originally sandstone.*

Proterozoic • *a geologic time interval that extends from 2.5 billion to 541 million years ago.*

Quaternary • *a geologic time period that extends from 2.6 million years ago to the present.*

aeolian • *pertaining to, caused by, or carried by the wind.*

wind • *the movement of air from areas of high pressure to areas of low pressure.*

permafrost • *a layer of soil below the surface that remains frozen all year round. Its thickness can range from tens of centimeters to a few meters.*

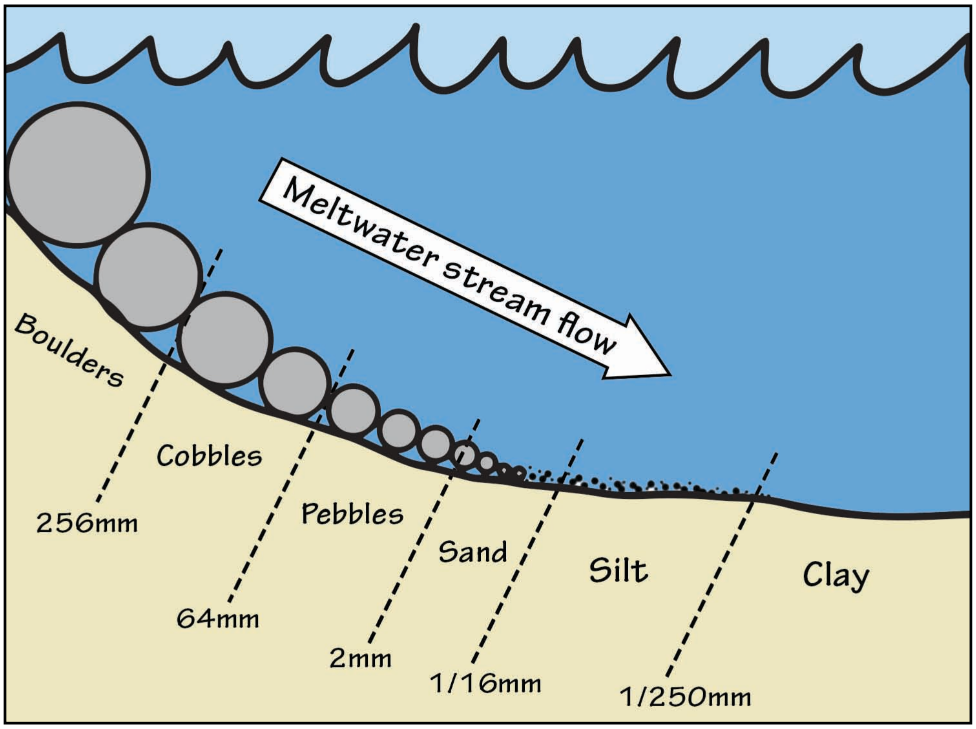

Figure 6.9: Moving water deposits sediment in what is known as a horizontally sorted pattern. As water slows (i.e., loses energy) with decreased gradient, it deposits the large particles first. The sizes in the figure represent the boundaries between categories of sediment type.

Sioux **quartzite**, which originates in southeastern South Dakota as well as northeastern Nebraska and several of the Midwestern states, is one such example. Erratics from this **Proterozoic** outcrop are found across much of northwestern Kansas and north-central Iowa, carried there by ice during the **Quaternary**.

See Chapter 2: Rocks to learn more about the Sioux Quartzite.

Periglacial Environments

Though a large portion of the Northwest Central was covered by ice, even unglaciated areas felt its effects. The land covered by the ice sheet was scoured and covered with glacial deposits, while the area south of the ice sheet developed its own distinctive landscape and features due to its proximity to the ice margin. This unglaciated but still affected area is called a **periglacial zone**.

There are a variety of features associated with a periglacial zone that also provide clues to the extent of the most recent ice sheet. In the tundra-like environment of a periglacial zone, **aeolian**, or windblown deposits, are common. Sand dunes and **wind**-transported sediments, such as those found in the Sandhills of Nebraska and Wyoming's Red Desert, are found in former periglacial areas of the Northwest Central. The **permafrost** associated with

Figure 6.10: Eskers are sinuous deposits composed of sand and gravel deposited by streams that once flowed under the ice.

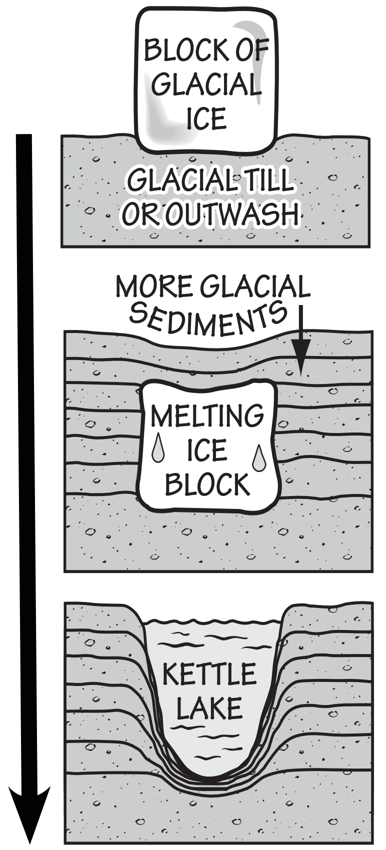

Figure 6.11: Kettle lakes form where large, isolated blocks of ice become separated from the retreating ice sheet. The weight of the ice leaves a shallow depression in the landscape that persists as a small lake.

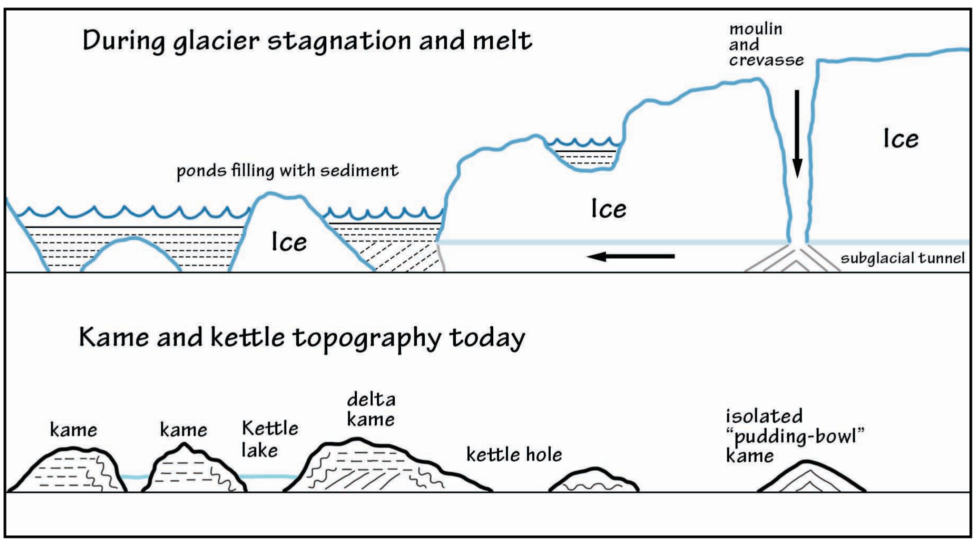

Figure 6.12: Glacial sediment deposits and the resulting hills called kames.

soil • the collection of natural materials that collect on Earth's surface, above the bedrock.

solifluction • a type of mass wasting where waterlogged sediment moves slowly downslope, over impermeable material.

weathering • the breakdown of rocks by physical or chemical means.

fracture • a physical property of minerals, formed when a mineral crystal breaks.

joint • a surface or plane of fracture within a rock.

talus • debris fields found on the sides of steep slopes, common in periglacial environments.

Laurentide Ice Sheet • an ice sheet that covered most of Canada during the last major glaciation.

the periglacial area, in which the ground is frozen much of the year, can cause mass movement of sediment. When the surface layer of the permafrost ground thaws, it is full of moisture. This water-heavy layer of **soil** may move rapidly downhill in a process called **solifluction**.

Physical **weathering** of the bedrock is magnified in the periglacial environment because of the freeze-thaw cycles associated with permafrost. When water enters cracks and fissures in the ground and subsequently freezes, the ice wedges the cracks farther and farther apart (*Figure 6.13*). Freeze-thaw is important in any climate that cycles above and below the freezing point of water. Because ice takes up more space than water, the pre-existing cracks and **fractures** are widened when the water freezes. Along ridges, rocks are eventually broken off as ice wedges continue to expand in **joints** and fractures. The boulders and blocks of bedrock roll downhill and are deposited along the slope or as **talus**. Frost action also brings cobbles and pebbles to the surface to form nets, circles, polygons, and garlands of rocks. These unusual patterns of sorted rock are known as **patterned ground**. Solifluction and ice wedging are found exclusively where the ground remains perennially frozen yet is not insulated by an ice sheet. Such conditions only occur in areas adjacent to ice sheets, and evidence for them can be seen all along the glacial margin of the **Laurentide Ice Sheet**, from Nebraska to Idaho.

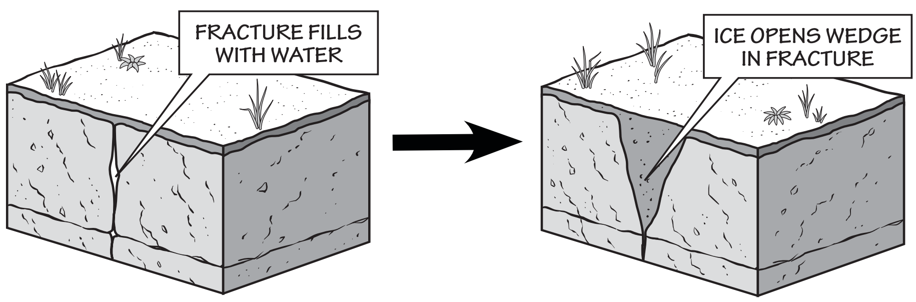

Figure 6.13: Physical weathering from a freeze-thaw cycle.

Glaciers and Climate

Glaciers are sometimes called the "canary in the coal mine" when it comes to climate change. This is because alpine glaciers are highly sensitive to changes in climate. For instance, a glacier grows (advances) when it accumulates more ice than it loses from melting or calving. Advances tend to happen when cold, wet years dominate the local climate. On the other hand, a glacier will shrink (retreat) during warm, dry periods as it loses more ice than it gains each year.

As discussed in the chapter on climate, for much of Earth's history there have not been persistent ice sheets in high latitudes. Any time that the world is cool enough to allow them to form is called an "ice age." Based on this definition, we are living in an ice age right now! The current ice age began about 34 million years ago when ice sheets first began forming on Antarctica, followed by their appearance on Greenland at least 18 million years ago, and finally on North America, which defined the beginning of the Quaternary period (about 2.6 million years ago). When most people use the phrase “the ice age,” however, they are referring to the **last glacial maximum** during which much of North America and Europe covered in ice thousands of meters (feet) thick and many kinds of large, wooly mammals roamed the unfrozen portions of those continents.

The Quaternary period is divided into two epochs. The earlier **Pleistocene** encompasses the time from 2.6 million to 11,700 years ago, including all of the Quaternary up until the most recent episode of glacial retreat—the beginning of the **Holocene**. During the Pleistocene, there were several dozen intervals of glaciation separated by warmer **interglacial** intervals characterized by glacial retreat. In North America, these cycles are known as the **pre-Illinoian** (1.8 million to 302,000 years ago), **Illinoian** (191,000–131,000 years ago), Sangamonian (131,000–85,000 years ago), and **Wisconsinan** (85,000–11,000 years ago). The Illinoian and Wisconsinian were cooler periods that saw glaciers advance, while the Sangamonian was a warm interglacial period.

Age of the Quaternary

In 2009, scientists at the International Commission on Stratigraphy voted to move the beginning of the Quaternary period to 2.6 million years ago, shifting it 0.8 million years earlier than the previous date of 1.8 million years ago—a date set in 1985. They argued that the previous start date was based on data that reflected climatic cooling that was only local to the region in Italy where it was first observed. In contrast, the 2.6-million-year mark shows a global drop in temperature, and it includes the entirety of North American and Eurasian glaciation, rather than having it divided between the Quaternary and the earlier *Neogene* period.

The pre-Illinoian glaciation included many glacial and interglacial periods that were once subdivided into the Nebraskan, Aftonian, Kansan, and Yarmouthian ages. New data and numerical age dates suggest that the deposits are considerably more complicated; they are now lumped together into a single period. Most of the glacial features in the Northwest Central were created in the Pleistocene, during the Wisconsinian glaciation.

last glacial maximum • *the most recent time the ice sheets reached their largest size and extended farthest towards the equator, about 26,000 to 19,000 years ago.*

Holocene • *the most recent portion of the Quaternary, beginning about 11,700 years ago and continuing to the present.*

interglacial • *a period of geologic time between two successive glacial stages.*

pre-Illinoian glaciation • *a grouping of the Midwestern glacial periods that occurred before the Wisconsinian and Illinoian glaciations.*

Neogene • *the geologic time period extending from 23 to 2.6 million years ago.*

Milankovitch cycle • *cyclical changes in the amount of heat received from the Sun, associated with how the Earth's orbit, tilt, and wobble alter its position with respect to the Sun.*

plates • *large, rigid pieces of the Earth's crust and upper mantle, which move and interact with one another at their boundaries.*

atmosphere • *a layer of gases surrounding a planet.*

Ice on a Schedule

The enormous continental glaciers that define an ice age are so large that their extent is most directly affected by global trends, while mountain glaciers are much more susceptible to local and short-term changes in climate. Continental ice sheets advance and retreat in cycles that last tens of thousands of years and are controlled to a large extent by astronomic cycles.

Astronomic Cycles and Ice Sheets

The cyclical movements of ice sheets seem primarily to be caused by specific astronomic cycles called *Milankovitch cycles*, which change the amount of light the Earth receives, particularly when comparing the summer to the winter. The cycles, predicted through principles of physics a century ago, are related to the degree of tilt of the Earth, the Earth's distance to the Sun, and the point in the Earth's revolution around the Sun during which the Northern Hemisphere experiences summer. When the cycles interact such that there is milder seasonality (cooler summers and warmer winters) at high latitudes in the Northern Hemisphere, less snow melts in summer, which allows glaciers to grow. The cyclicity of glacial-interglacial advances was about 40,000 years from before the start of the Quaternary until about a million years ago. For reasons that aren't clear, however, the cycles changed to about 100,000 years. If not for human-induced climate change, we might expect glaciers to approach Kansas and Missouri again in about 80,000 years!

Scientists continue to debate the particular causes of the onset of glaciation in North America over two million years ago. Movement of the Earth's tectonic **plates** may have been a direct or indirect cause of the glaciation. As plates shifted, continents moved together and apart, changing the size and shape of the ocean basins. This, in turn, altered oceanic currents. Mountain building, which occurred when continents collided, erected obstacles to prevailing winds and changed moisture conditions. The freshly exposed rock from the rising of the Himalayas also combined with **atmospheric** carbon dioxide through chemical weathering; this consequent decrease in levels of atmospheric carbon dioxide was at least partially responsible for global cooling. Finally, the presence of continental landmasses over one pole and near the other was also a major factor enabling the development of continental glaciers.

Seeking Detailed Records of Glacial-Interglacial Cycles

While glaciers have advanced over central North America and retreated again dozens of times during the Quaternary, each advance scrapes away and reworks much of what was previously left behind, making it difficult to reconstruct the precise course of events. Therefore, to investigate the details of any associated climate change we must seek environments that record climate change and are preserved in the geologic record. Since the 1970s, the (international) Deep Sea Drilling Project has provided a treasure trove of data on coincident changes in the ocean, preserved in sediments at the ocean bottom (*Figure 6.14*). In the 1980s, coring of ice sheets in Greenland and Antarctica provided similar high-resolution data on atmospheric composition and temperature back nearly one million years (*Figure 6.15*). The data from these programs have revealed that the Earth experienced dozens of warming and cooling cycles over the course of the Quaternary period. Traces of the earlier and less extensive Pleistocene glacial advances that must have occurred have been completely erased on land, so these advances were unknown before records from deep-sea cores and ice cores revealed them.

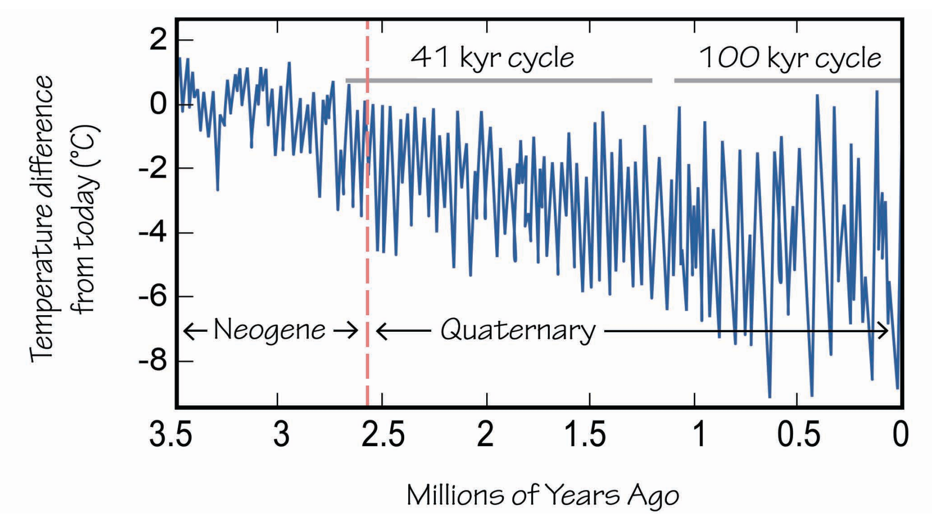

Figure 6.14: Ocean bottom temperatures from 3.6 million years ago to present, based on chemical analyses of foraminifera shells. Notice how the amplitude of glacial-interglacial variations increases through time, and how the length of cycles changes.

A large proportion of glacier and climate research involves making regular inventories of existing glaciers and their characteristics to determine how they are impacted by global, regional, and local climate changes. Equally important is determining the impact of changing glaciers on seasonal streamflow. Glaciers act as water reservoirs where winter snowfall is released as meltwater during summer, when precipitation is low. This characteristic is particularly important to farms and fisheries in areas downslope from glaciated mountains like the Northern Rockies.

Glaciers

Climate

tree • *any woody perennial plant with a central trunk.*

system • *a set of connected things or parts forming a complex whole.*

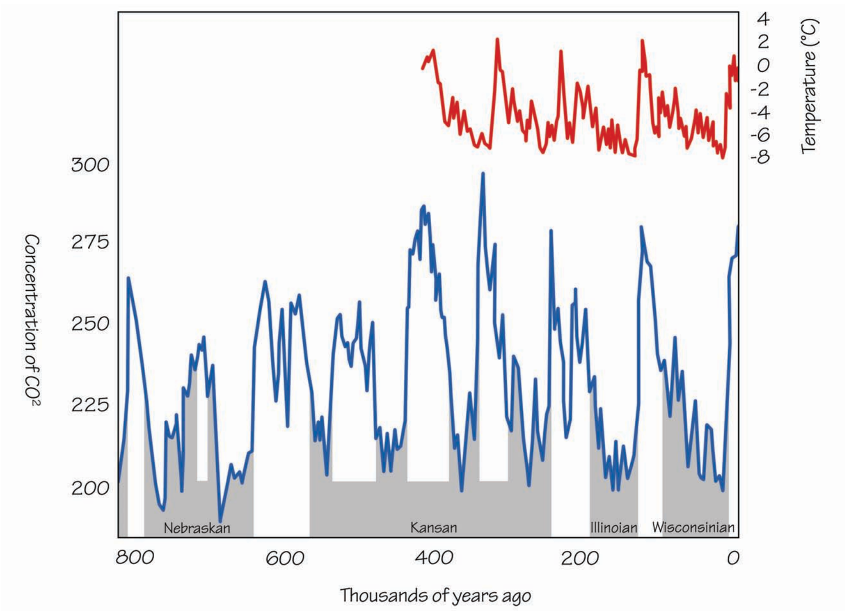

Figure 6.15: Ice core atmospheric temperature and carbon dioxide concentrations from an ice core taken in Vostok in Antarctica along with CO_2 data from several cores in Greenland give a record of glacial advances over the past 800,000 years. Note that Kansan and Nebraskan deposits represent more than one glacial advance.

In addition to investigating present-day glacier behavior, researchers use clues from the landscape to reconstruct ancient glaciers. This information, along with climate evidence from **tree** rings and lake sediments, provides a long view of climate change that has done much to improve our understanding of how climate **systems** work, and what the future might have in store for us.

As the last Pleistocene ice age came to a close, the Laurentide Ice Sheet and alpine ice caps throughout the Rockies retreated, leaving behind rugged mountain ranges, deep glacial valleys, and plains covered with thick deposits of

Figure 6.16: An example of glacial recession in Glacier National Park: Grinnell Glacier, as seen in 1940 and 2006.

glacial sediment. The time from the end of the Pleistocene to now is regarded as an interglacial period (a warm spell with diminished glaciers), but it has not been without its minor ice ages. The most recent of these, the Little Ice Age, began somewhere between 1300 and 1500 CE and ended by the late 19th century. Presently, the continental ice sheets and ice caps of the Pleistocene are gone, but some 150,000 alpine glaciers remain worldwide, and the impact of the ancient ice sheets and caps can be seen in nearly every region of the Northwest Central States.

Today's warming climate is having a profound impact on the glaciers that still exist in the Northwest Central. For example, Glacier National Park in Montana contained 150 named glaciers in 1850, but thanks to the effects of climate change, today only 26 of these glaciers remain. Scientists estimate that all of the park's glaciers will have vanished by 2030 (*Figure 6.16*).

loess • *very fine grained, wind-blown sediment, usually rock flour left behind by the grinding action of flowing glaciers.*

The Impact of Glaciation in the Northwest Central

During the Pleistocene, continental glaciers covered much of Canada, Alaska, and the northern edge of the continental United States (*Figure 6.17*). Continental ice sheets blanketed the Central Lowland and the northern Great Plains, scraping away rock and overlying sediment. When the glaciers retreated, glacial drift and till were deposited. Today, large swaths of the Dakotas and Nebraska are covered in glacial debris. Besides carving vast sections of the northern landscape and depositing huge quantities of sediment in low-lying areas, the glaciers' impact was felt throughout the landscape as glacial outburst floods carved into Idaho and winds laden with glacial **loess** reached deep into Nebraska and Wyoming.

Glacial Erosion and Deposition in the Northwest Central

The Drift Prairie, a relatively flat area consisting of glacial drift, is located in North and South Dakota. In some areas, there are small hills or ridges underlain by glacial debris. The Glaciated Missouri Plateau, also called the Missouri Coteau, is another hilly area underlain by glacial moraines and containing many small, closed kettle lakes. The eastern edge of the plateau, extending north and south across both Dakotas, is marked by a gentle slope that exhibits topographical relief from moraines and pre-existing river valleys. It marks the western extent of glacial ice coverage in the Dakotas during the Wisconsinian glaciation, and is also the boundary between the Central Lowland to the east and the Great Basin to the west.

See Chapter 4: Topography for more about the features of the Drift Prairie and other glaciated areas.

Eastern Nebraska is covered by glacial till, indicating that glaciers covered that portion of the state. Deposits of loess—silt-sized windblown material that is

Impact

basalt • *an extrusive igneous rock, and the most common rock type on the surface of the Earth.*

Figure 6.17: Extent of glaciation over North America during the last glacial maximum.

commonly associated with continental ice sheets—are also common throughout Nebraska (*Figure 6.18*). Strong winds blowing off of the ice sheet deposited sand, silt, and other glacial debris over the landscape to create relatively flat areas as well as forming hills and dunes (such as the Sandhills). In northwest Idaho, the Columbia River Basalts are also covered by loess. Because the sediment was not deposited evenly over the **basalts**, the area is characterized by hummocky terrain.

The drainage of rivers and streams was also changed by the Pleistocene glaciation (*Figure 6.19*). Prior to the ice age, North Dakota's water—including the Missouri River—drained to the north, into Hudson Bay. During the ice age, glaciers created dams that diverted rivers to the south and formed lakes such as Glacial Lake Agassiz (*Figure 6.20*). This enormous lake, stretching from Saskatchewan down into Minnesota and eastern North Dakota, was formed by water that accumulated in front of the Laurentide Ice Sheet. Most of the area

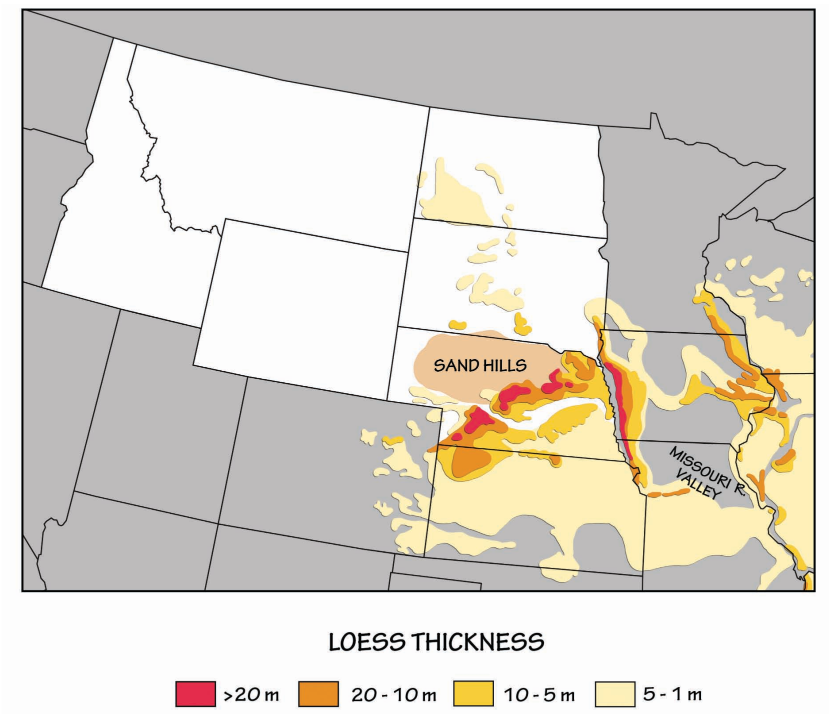

Figure 6.18: Loess deposits in Nebraska and surrounding states. (See TFG website for full-color version.)

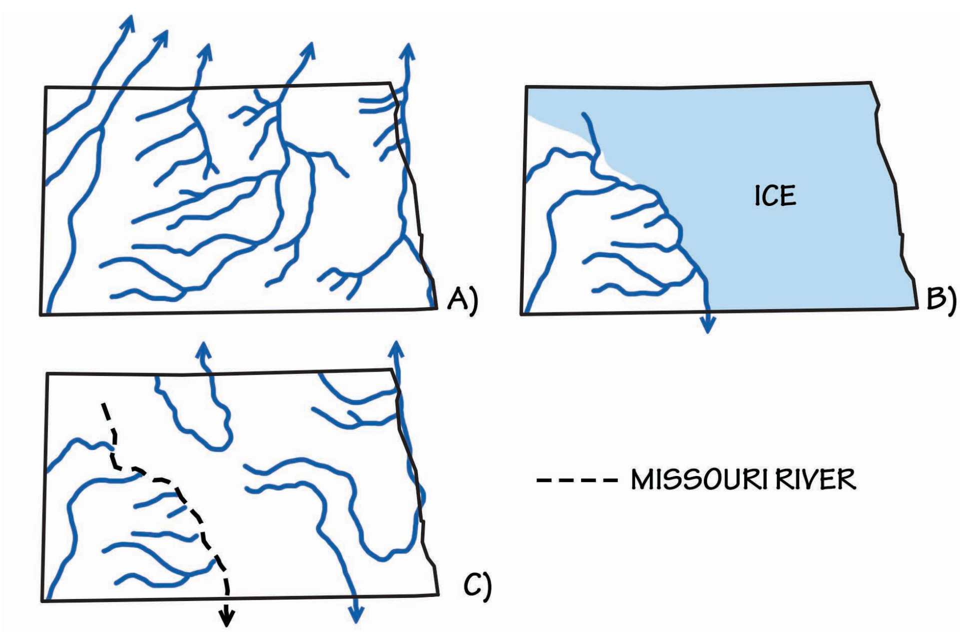

Figure 6.19: Drainage valleys of North Dakota. A) Pre-glacial river valleys drained into the Hudson Bay. B) Ice coverage and drainage during the Pleistocene. Water flowed along the margins of the ice to the south. C) After the Pleistocene, the Missouri river flowed south through the channel created during glaciation. Note that a few of the pre-glacial valleys became river valleys once more, after the glaciers retreated.

Impact

ice lobe *• a broad, rounded section of a continental glacier that flows out near the glacier's terminus.*

Figure 6.20: The maximum extent of Glacial Lake Agassiz.

that is now eastern North Dakota would have been close to the shoreline of Lake Agassiz, and waves along its coastline modified the area. Today, the Red River Valley in North Dakota marks the extent to which Lake Agassiz covered the state. The James River Valley, extending from central North Dakota across South Dakota to the Mississippi River, was also carved by a **lobe** that extended from the ice sheet.

Glacial Lake Missoula, another massive glacial lake located in Montana, was created when the Clark Fork River in Idaho was dammed by ice over 610 meters (2000 feet) high. As the lake grew deeper and higher, waves eroded the ground along the shoreline (*Figure 6.21*), and water pressure against the ice dam increased, eventually causing catastrophic failure of the dam. Water flowed out of the dam at a calculated speed of 105 kilometers (65 miles) per hour, allowing the lake to drain in a few days. Along with water, ice and glacial debris were carried to the west as the lake drained. This event carved the Channeled Scablands, a barren, scoured landscape that extends from Idaho through Washington and Oregon (*Figure 6.22*).

Figure 6.21: Wave-cut terraces along Mt. Jumbo near Missoula, Montana mark the ancient lakeshore of Lake Missoula.

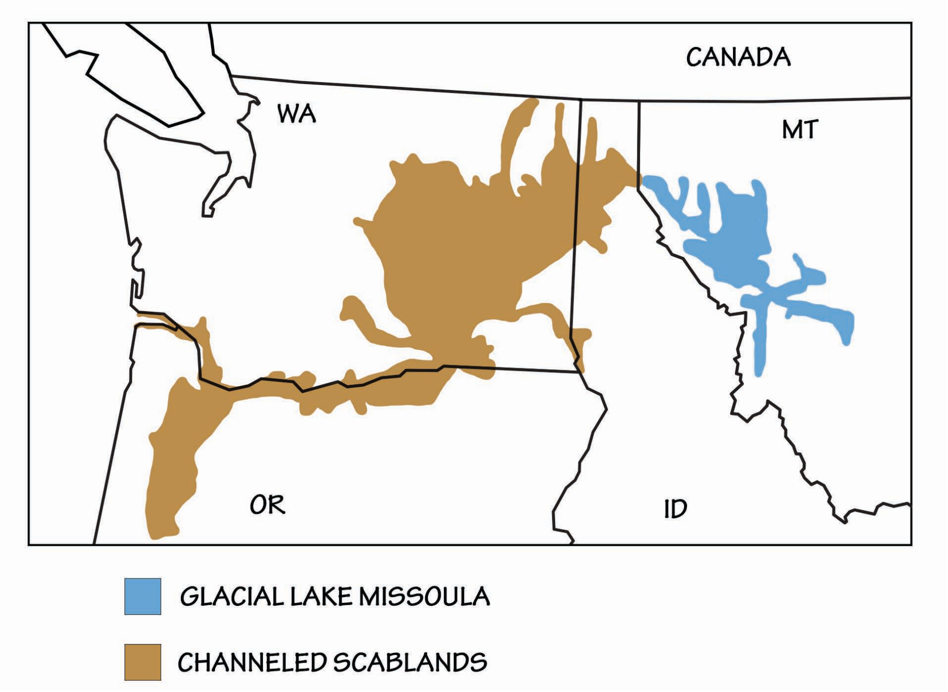

Figure 6.22: Glacial Lake Missoula and the extent of the Channeled Scablands. (See TFG website for full-color version.)

6 Glaciers

Impact

hanging valley *• a tributary valley that drops abruptly into a much larger and deeper valley.*

Alpine Glaciers in the Northwest Central States

One of the hallmarks of alpine glaciers in the Northwest Central States is the rugged mountain terrain they carve. The stunning characteristics of the Rocky Mountains—from jagged peaks and bowls to glacial valleys and high meadows—are largely a result of glacial erosion and deposition during the Pleistocene. In several cases, these glaciers coalesced into ice caps covering entire mountain ranges. In other instances, they merged with advancing continental ice sheets, eventually becoming indistinguishable as separate glaciers, only to regain their distinctiveness as the ice sheets retreated. As these glaciers retreated, they not only exposed characteristic U-shaped valleys, but they also revealed a diverse collection of peaks, bowls, ridges, and lakes scraped into the bedrock (*Figures 6.23, 6.24*).

For instance, in the Wind River Mountains of Wyoming, the Beartooth-Absaroka Range in Montana, and the Sawtooth Mountains of Idaho, glaciers have carved a series of horns, arêtes, and cirques. Below these prominent features, we often find chains of lakes that form when meltwater pools behind lateral and terminal moraines. Likewise, in and around Yellowstone National Park and the Teton Mountains of Wyoming, a network of small Pleistocene glaciers merged like streams flowing into a large river. As the glaciers retreated, they left behind a collection of smaller U-shaped valleys (known as **hanging valleys**) that drop abruptly into a much larger valley. This phenomenon is responsible for the formation of spectacular waterfalls like Tower Fall (*Figure 6.25*)

Figure 6.24: Glacial meltwater lakes near Yellowstone National Park in Wyoming.

Figure 6.23: Glacially sculpted mountain ranges with horns, arêtes, and cirques are common in Glacier National Park, Montana.

Figure 6.25: Tower Fall, Yellowstone National Park.

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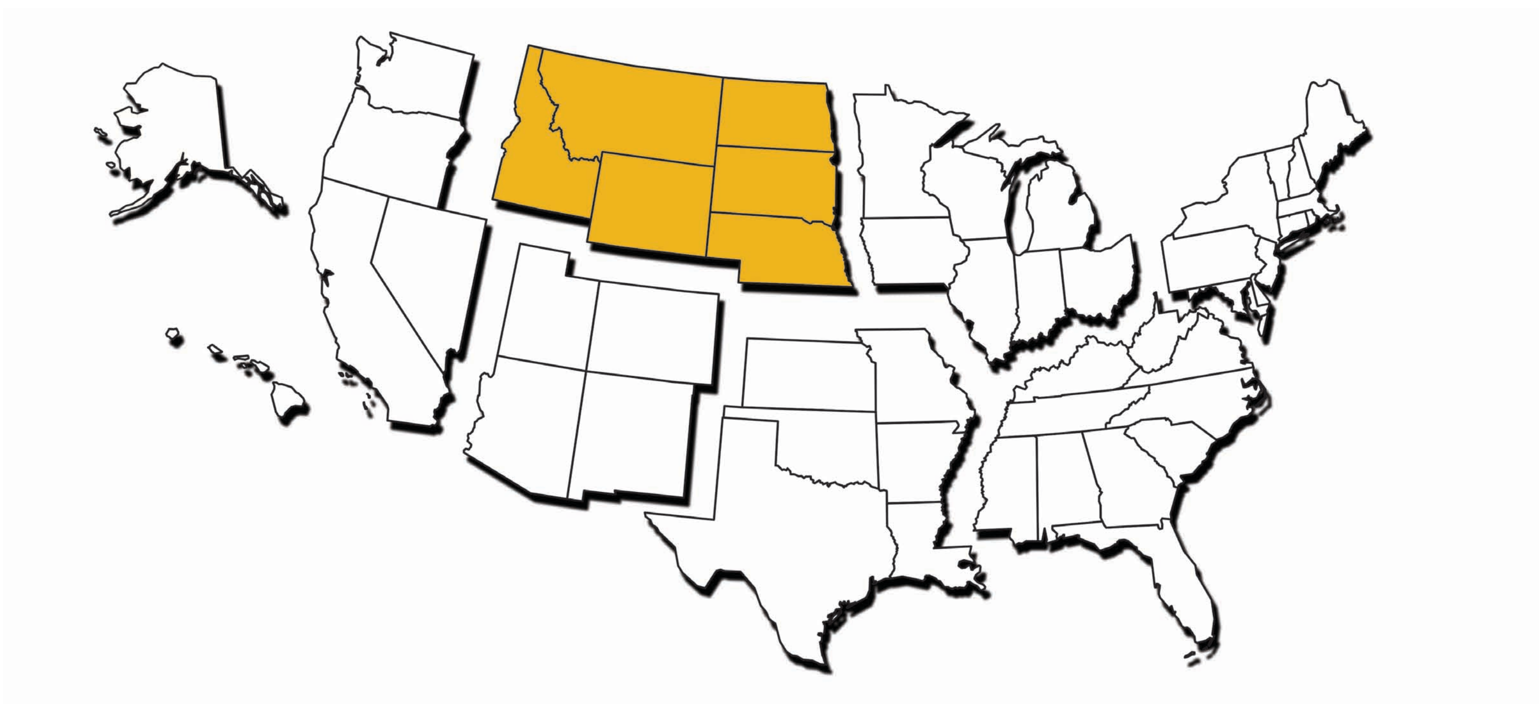

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On the back cover: Blended geologic and digital elevation map of the Northwest Central US. Each color represents the age of the bedrock at the surface. Adapted from Barton, K.E., Howell, D.G., Vigil, J.F., *The North America Tapestry of Time and Terrain*, US Geological Survey Geologic Investigations Series I-2781, http://pubs.usgs.gov/imap/i2781.