Humongous Ice-Age Floods in the Pacific Northwest

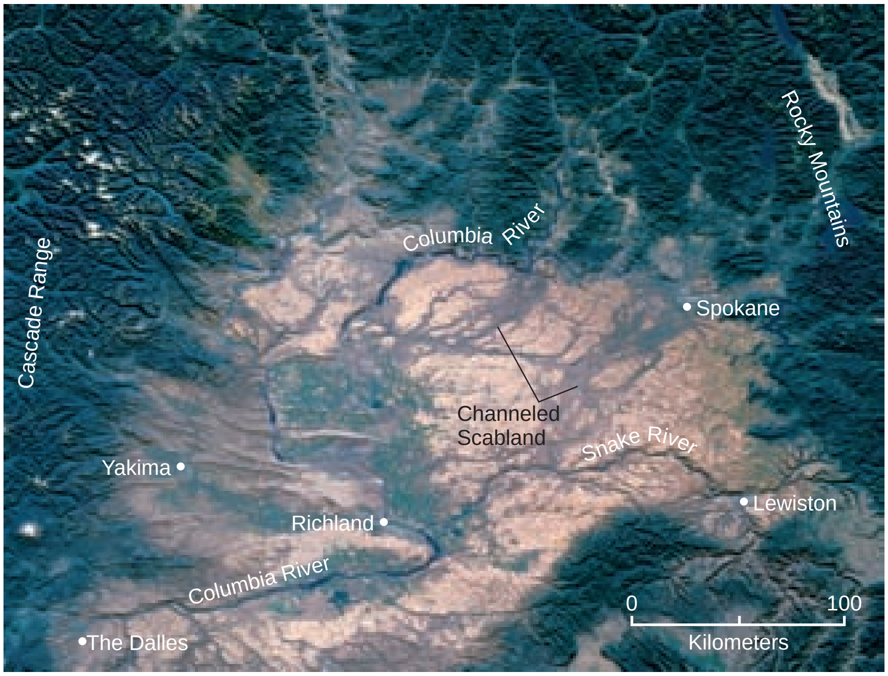
This module describes the unusual landscape features produced by dozens of humongous-discharge floods that crossed the Pacific Northwest of the United States at the same time that ice sheets retreated during the last ice age.

A. Introduction

Geologic interpretations of landscapes typically follow from studies of active processes, such as mass movements on hillslopes, changes along flowing streams, and landforms in modern glacial environments. Some landscapes are more puzzling because they include features that geologists do not observe forming today or that imply processes operating on a scale that is much grander than what has been observed. These features remind us that scientific observations cover a puny fraction of Earth history and geologists have not experienced relatively rare events of the sort that have not occurred during the time of recorded history.

Figure EM18.1-1 shows the view from space of the landscape of southeastern Washington. The image is notable for showing a complex network of dark ribbons that resemble wide river channels. The channels appear dark because they are eroded into black basalt lava flows that spread across more than 100,000 square kilometers of this region about 15 million years ago. Over most of this region a thick cover of light-colored windblown loess mantles the basalt. In the "Channeled Scabland," however, the loess has been eroded away, and the basalt has been scoured into a highly irregular topography of bare rock. The form of the channels and the evidence of erosion suggest the action of rivers, except for the facts that most of the channels are dry and they are wider than any active river channels on Earth.

It took geologists more than half a century to unlock the clues to the origin of the Channeled Scabland. This module briefly summarizes the results of those studies, which conclude that dozens of humongous floods rushed across the region as the last ice-age glaciers were retreating northward into Canada. The floodwater originated from a lake that formed when a large river was dammed by a tongue of glacial ice. The largest of the floods, resulting from the hypothesized collapse of the ice dam, had a discharge 20 times greater than today's total global discharge of river water to the oceans! **Figure EM18.1-2** includes a map that outlines the area affected by these floods; several photographs illustrate some of the evidence for their occurrence.

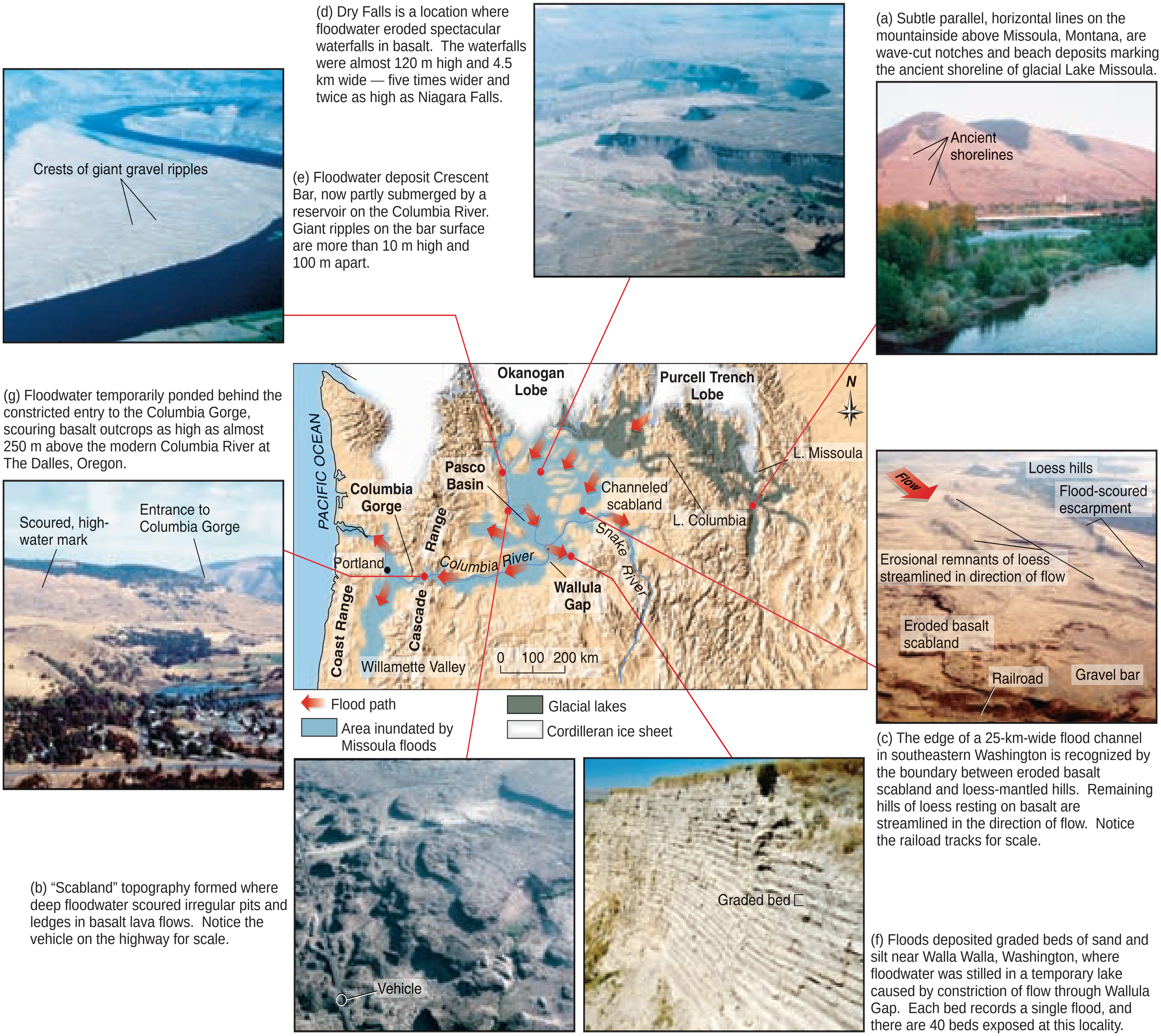


▲ **Figure EM18.1-1 Giant channels visible from space.** The Channeled Scabland of eastern Washington is seen here as a network of now dry channels that were scoured by humongous floods from a glacial lake in western Montana during the waning phase of the last ice age.

(*Source*: Image courtesy of NASA)

B. Dynamics of Glacial Lakes

The floods that scoured eastern Washington originated two states away in western Montana. During the last ice age, the Purcell Trench lobe of the vast Cordilleran ice sheet flowed southward through a long valley in the Rocky Mountains and completely blocked the Clark Fork River, which drains a large region of western Montana. The evidence for glacial Lake Missoula includes tens of meters of lake-clay layers and shoreline traces along mountainsides, as illustrated in Figure EM18.1-2a. The multiple levels of shoreline marks indicate that the lake changed in size over time. The highest wave-cut notches and old beaches indicate that the lake was more than 600 meters deep at its deepest point (which is more than 100 meters deeper than any



(a) Subtle parallel, horizontal lines on the mountainside above Missoula, Montana, are wave-cut notches and beach deposits marking the ancient shoreline of glacial Lake Missoula.

(b) “Scabland” topography formed where deep floodwater scoured irregular pits and ledges in basalt lava flows. Notice the vehicle on the highway for scale.

(c) The edge of a 25-km-wide flood channel in southeastern Washington is recognized by the boundary between eroded basalt scabland and loess-mantled hills. Remaining hills of loess resting on basalt are streamlined in the direction of flow. Notice the railroad tracks for scale.

(d) Dry Falls is a location where floodwater eroded spectacular waterfalls in basalt. The waterfalls were almost 120 m high and 4.5 km wide — five times wider and twice as high as Niagara Falls.

(e) Floodwater deposit Crescent Bar, now partly submerged by a reservoir on the Columbia River. Giant ripples on the bar surface are more than 10 m high and 100 m apart.

(f) Floods deposited graded beds of sand and silt near Walla Walla, Washington, where floodwater was stilled in a temporary lake caused by constriction of flow through Wallula Gap. Each bed records a single flood, and there are 40 beds exposed at this locality.

(g) Floodwater temporarily ponded behind the constricted entry to the Columbia Gorge, scouring basalt outcrops as high as almost 250 m above the modern Columbia River at The Dalles, Oregon.

▲ **Figure EM18.1-2 Visualizing the evidence for the humongous Missoula floods.**

(*Source*: Gary A. Smith)

of the modern Great Lakes). Tracing the old shoreline features shows that the lake covered as much as 7500 square kilometers and held nearly 2200 cubic kilometers of water, which is roughly half the volume of Lake Michigan.

Ice-dam lakes have peculiar dynamics. Studies of modern glacial lakes in Alaska and Iceland, although all much smaller than glacial Lake Missoula, provide useful insights. The plastic nature of glacial ice means that it seals closely against valley walls when it flows across a valley, so the ice seemingly makes an effective dam. It is important to remember, however, that ice is less dense than water. When the water depth adjacent to the ice dam is about nine-tenths the thickness of the ice, then the pressure at the bottom of the lake is greater than the weight of the ice. When these conditions exist, the water pressure raises the buoyant ice and water flows out beneath the glacier.

The sudden outburst of water from beneath the glacier causes a flood downstream. The size of the flood depends on how much water is in the lake and how the glacier responds to the subglacial discharge. As water rushes out beneath the glacier, the friction of the flowing water carves out tunnels through the ice that increase the floodwater discharge. In many cases, the flood ends before all of the glacial lake drains because the ice dam settles back down onto the valley bottom as the lake depth diminishes during the flood. In some cases, however, the eroded ice tunnels weaken the structural integrity of the ice dam and the dam collapses, which rapidly unleashes the entire lake. Floods from glacial Lake Missoula likely included both partial and complete emptyings on different occasions.

A glance at Figure EM18.1-2 reveals a complication that is key to interpreting the consequences of floods from glacial Lake Missoula. Missoula floods flowed westward toward the Columbia River in northern Washington. The Columbia River was impounded behind the Okanogan lobe of glacial ice, so glacial Lake Missoula floodwater flowed into glacial Lake Columbia. The level of Lake Columbia quickly rose until it overflowed several almost equally low spots along the southwestern margin of the lake. Glacial Lake Columbia, therefore, essentially deflected floods from Lake Missoula into the loess-covered landscape of eastern Washington to cause erosion of the Channeled Scabland.

C. Flood Evidence in the Landscape

Photographs in Figure EM18.1-2 illustrate just a few of the remarkable landforms and sedimentary deposits that provide evidence for humongous floods from glacial Lake Missoula. The floodwater encountered rather uniform geologic conditions across most of southeastern and south-central Washington. More than 100,000 square kilometers of central Washington and adjacent parts of Oregon and Idaho were buried beneath an average thickness of one kilometer of basalt lava about 15 million years ago. In most places, the basalt is covered by more than ten meters of windblown silty loess that forms rich, moisture-retentive soils throughout the region.

The rushing floodwater easily stripped away the fine-grained loess particles and aggressively plucked the fractured basalt bedrock. The distinctive scabland topography, illustrated in Figure EM18.1-2b, resulted from complete removal of the loess and differential erosion of the basalt. The distinction of the smooth, loess-covered landscapes and the rough flood-scoured basalt landscapes is visible in Figure EM18.1-2c at a location where floodwater was more than 100 meters deep in a scabland channel more than 25 kilometers wide. In some places, remnant hills of loess still rise above the scabland floor and have flood-sculptured whaleback shapes elongated parallel to the direction of flood flow.

Figure EM18.1-2d shows the location where a huge waterfall formed that was primarily active during passage of floodwater from glacial Lake Missoula. During one or more Missoula floods, Dry Falls dwarfed the well-known Niagara Falls. Water poured over a flood-eroded escarpment that is twice as high as and five times wider than Niagara Falls.

Floodwater following multiple courses through the Channeled Scabland cascaded into canyons of the Columbia and Snake Rivers along the scabland margins. The floods left their mark in these big river canyons, too. The Snake River was so overwhelmed with water spilling in from the Channeled Scabland that the floods flowed *upstream* more than 200 kilometers into Idaho (see the map in Figure 18.1-2). The floods carried large volumes of eroded basalt fragments in flows more than 100 meters deep down the Columbia River valley. Figure EM18.1-2e shows a giant gravel point bar, the size of a small city, along an inside bend in the Columbia River. Giant "ripples," roughly 10 meters high and spaced about 100 meters apart, cover the surface of this and many other gravel bars in the region affected by the Missoula floods. Ripples are common structures in current-transported sediment, but the huge scale of the ripples shown in Figure EM18.1-2e indicates a flow that is much deeper and stronger than any measured flood.

All of the floodwater in the Channeled Scabland and flowing down the Columbia and Snake Rivers converged on the Pasco basin, a vast desert valley in south-central Washington. The Columbia River exits the Pasco basin through a narrow gorge, called Wallula Gap, eroded through a high anticline ridge of folded basalt. Floodwater entered the basin much faster than it could discharge through Wallula Gap. The evidence for the resulting temporary lakes consists of erosional scour marks hundreds of meters above the valley floor, fine-grained silt and sand that settled out of the stilled floodwater (see Figure EM18.1-2f), and scattered piles of nonbasalt boulders and finer gravel that form a discontinuous "bathtub" ring along the hillsides that surround the Pasco basin. The rock types in these gravel piles match with the geology near the Montana ice dam. Geologists interpret these piles as rocks that were frozen into the glacier and then transported in the flood as iceberg fragments of the failed ice dam. The icebergs grounded around the edge of the temporary lake upstream of Wallula Gap and left behind their frozen sediment accumulations when they later melted. The elevations of the iceberg-rafted gravel indicate that at least one Missoula flood filled the Pasco basin with 250 meters of water to form a temporary lake with a volume of 1200 cubic kilometers, or roughly half the size of glacial Lake Missoula. The lake covered more than 5000 square kilometers, completely filling the area of the Pasco basin and backing up into river valleys adjacent to the basin for more than 100 kilometers.

The full discharge of each Missoula flood flowed along the Columbia River valley downstream of Wallula Gap. Constrictions in the width of the valley where it crossed the Cascade Range and the Coast Range caused the water to back up into temporary lakes smaller than those formed in the Pasco basin. Figure EM18.1-2g shows the scoured high-water mark of the temporarily impounded floodwater on the upstream side of the Columbia Gorge through the Cascade Range. When water backed up in the Columbia valley downstream of Portland, Oregon, the water swamped the Willamette River Valley for about 200 kilometers upstream; at the confluence of the Willamette and the Columbia the water was 100 meters deep, as indicated by iceberg-rafted debris piles of rock carried all the way from western Montana.

Floodwater was as deep as 100 meters when it passed the position of the present coastline and headed toward the shore, which was about 60 kilometers farther west because sea level was lower during the ice age. The story does not end at the coastline, however. Studies of deep-sea sediment penetrated in scientific boreholes west of Oregon show that the sediment-laden floodwater formed turbidity currents that continued west and then south for more than 1100 kilometers (see Section 5.7 in your text for more information about turbidity currents).

D. Number, Size, and Age of Floods

Geologists established compelling evidence that glacial Lake Missoula dumped floods into eastern Washington on several dozen occasions. The outcrop of flood sediment illustrated in Figure EM18.1-2f provides one piece of evidence for many floods. Each graded bed of sand and silt is capped by windblown loess with traces of plant roots and small-animal burrows that record the existence of normal, dry hillsides between the floods that deposited the graded beds. There are more than 40 beds exposed along this steep ditch bank, which implies that more than 40 Missoula floods backed up behind Wallula Gap. In northern Washington, clay layers deposited on the floor of glacial Lake Columbia are interrupted by more than 80 coarse-sediment layers that geologists interpret as resulting from strong, sediment-laden flood currents entering the lake from glacial Lake Missoula.

Geologists have used volcanic-ash layers and scattered pieces of charcoal to determine when the Missoula floods happened. In many places, such as the locality shown in Figure EM18.1-2f, volcanic ash layers are present in the thin loess accumulations between beds of flood-deposited sediment. The volcanic-ash composition provides a chemical fingerprint to correlate the ash to well-dated volcanic eruptions in the Cascade Range about 13,000 years ago. The rare charcoal fragments found in some layers provide ^{14}C radioactive-isotope ages between about 15,500 and 13,000 years ago. The features illustrated in Figure EM18.1-2 appear, therefore, to have formed between about 15,500 and 13,000 years ago as the Cordilleran ice sheet was starting to shrink back from its maximum ice-age extent.

There is, however, also evidence of older floods. At a few scattered locations throughout the Channeled Scabland, Pasco basin, and back-flooded river valleys adjacent to the main flood routes, there are flood deposits buried beneath windblown silt and well-developed soils. These field relationships suggest that there were multiple episodes of humongous floods from glacial Lake Missoula. Geologists hypothesize that each episode occurred during and shortly after the peak of each ice age over at least the past one million years. During each episode, glaciers dammed the Clark Fork River to produce a self-dumping lake, which frequently lifted or broke apart to send large discharges across Washington and Oregon to the Pacific Ocean. The total number of floods will likely never be known but likely numbered in the hundreds.

Geologists have also attempted to quantify the size of the largest Missoula flood. There were many floods, and it is likely that they ranged considerably in the amount of water released from the glacial lake. The volume and rate of release of floodwater would depend on whether the ice dam remained intact, raising and lowering during a flood, or whether it completely failed so that the entire lake was released. In addition, the amount of water in the lake at the time of a flood determines how big the flood could be. Elevations of erosional trim lines, high-water marks of iceberg-rafted gravel, and flood-deposited sediment provide insights to flood magnitude. Geologists assume that the highest-elevation features all correspond to the largest flood that moved through the region. They then use the area submerged along each channel cross section of the flood below these high elevations to calculate the discharge required to form a flow with this depth.

The resulting calculations provide mind-boggling numbers. Near the point of flood release at the ice dam, the calculated discharge is roughly 17 million cubic meters per second. Calculations for the floodwater cross section at Wallula Gap indicate a discharge of about 10 million cubic meters per second. To put these numbers in perspective, the modern-day discharge of all the world's rivers to the oceans is about 700,000 cubic meters per second. Although the peak discharge of this largest Missoula flood may only have persisted for a few hours, it still is incredible to think of a flow that was more than 20 times larger than all of the modern world rivers, combined. The calculations show that such a large flood requires a complete and abrupt failure of the ice dam when glacial Lake Missoula was filled to the elevation of its highest shoreline notch. The calculations of flood discharge suggest that it took about 70 hours to empty the lake, although the total length of a flood was certainly longer because of the spreading of water over such a large area and the temporary impoundments behind Wallula Gap and other constrictions along the Columbia River. The temporary lake in the Pasco basin, for example, probably filled over a period of about two days and then drained over about three days during the largest flood.

Putting It Together

- The landscape of eastern Washington and adjacent areas bears the erosional and depositional evidence of dozens of floods, most or all of which dwarf any historically documented river flood.
- The floods originated at glacial Lake Missoula, in western Montana, which frequently emptied, partly or completely, because of the unstable dynamics of the series of buoyant ice dams that impounded the lake.
- The largest flood had a peak discharge more than 20 times greater than all of the modern world rivers, combined.