THE MISSOULA FLOOD

Dry Falls in Grand Coulee, Washington, is the largest waterfall in the world, but it is currently inactive because it is on an intermittent stream that is not expected to flow again until the next Missoula Flood. Height of falls is 385 ft [117 m]. Flood waters were about 260 ft deep [80 m] *above* the top of the falls, so a more appropriate name might be Dry Cataract.

OVERVIEW

In latest Pleistocene time, about 14 000 years ago, glaciers from the Cordilleran ice sheet in Canada advanced southward and dammed andor diverted two rivers, the Columbia River and one of its major tributaries, the Clark Fork River [Fig. 1].

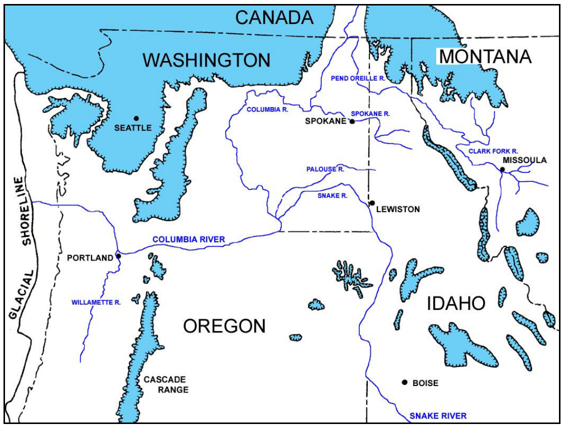


Figure 1—Columbia River drainage as the Cordilleran ice sheet advanced southward.

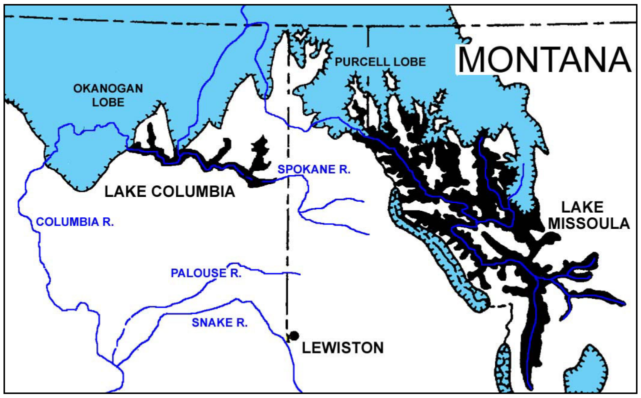


Figure 2—Lakes Columbia and Missoula created by ice dams.

The Okanogan lobe of the Cordilleran ice sheet advanced into the Columbia River valley, creating Lake Columbia and diverting the Columbia River into the Grand Coulee. Another lobe of the ice sheet advanced southward down the Purcell Trench to the present Lake Pend Oreille in Idaho and dammed the Clark Fork River. This created an enormous Lake Missoula, about 4½ times the size of Lake Erie [530 mi^3 or 2200 km^3], that had no outlet [Fig. 2].

When the dammed water got deep enough, it started *floating* the glacier, and the tremendous surge of water under the ice immediately broke up the ice dam, leading to the cataclysmic dumping of Lake Missoula. A wall of water close to 2000 ft [700 m] high surged through the breached dam and poured across eastern Washington at speeds of up to 100 mph [45 m/s]. Discharge was about 17 million cubic m^3/s, about 20 times the size of the Bonneville Flood and a rate that would drain Lake Erie dry in about 8 hours. This was, perhaps, the largest flood discharge known [see The Altai Flood].

Floodwaters poured into Lake Columbia and surged right on over the south bank into three major spillways [Fig. 3]. In each of these flood spillways, water scoured the land down to bare bedrock to create the *scablands* of eastern Washington.

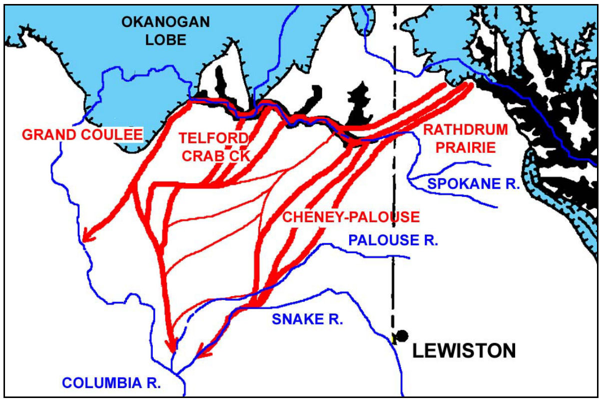


Figure 3—Lake Missoula floodwaters swept across Idaho and eastern Washington.

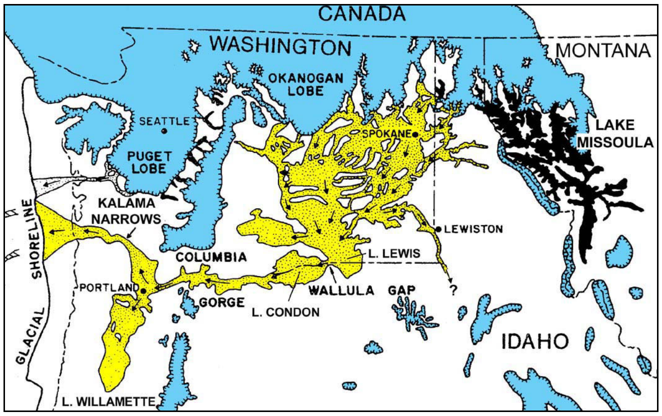


Figure 4—Flood discharge across Washington and Oregon.

As floodwaters rushed to the Pacific Ocean, discharge was so great that existing valleys couldn't carry the floodwaters. Mile-wide valley constrictions simply could not conduct that much water, causing temporary ponding by hydraulic damming that created ephemeral lakes [Fig. 4]. The floodwaters scoured scablands and coulees, ripped out kolk lakes, and dumped enormous loads of gravel in bars, often with giant current ripples. Huge chunks of glacier rafted 100-ton rocks to the Pacific Ocean.

There was at least one such catastrophic flood, probably about 40, perhaps as many as 89.

LAKE MISSOULA

Lake Missoula was created when the Purcell lobe crossed the Clark Fork River valley and wedged against the north end of the Bitterroot Range. River water backed up and the lake grew for 50 or 60 years, during which varves were deposited. Lake Missoula backed up to about Deer Lodge on the Clark Fork, past Darby in the Bitterroot Valley, and up against the Flathead glacier lobe at Flathead Lake [Fig. 5]. Lake Missoula eventually reached an areal extent of 2900 mi^2 [7,500 km^2].

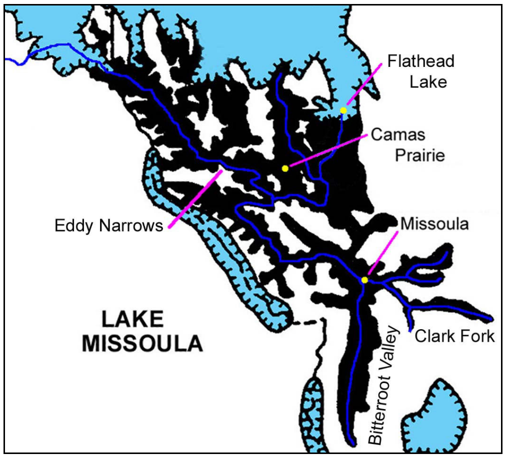


Figure 5—Lake Missoula at its maximum extent.

Figure 6—Lake Missoula strandlines above University of Montana campus at Missoula.

Shorelines around the perimeter show the lake reached an elevation of 4250 ft [1295 m], which made the water at Missoula about 950 ft [290 m] deep [Fig. 6], and an astounding 2000 ft [700 m] deep at the ice dam! Lake volume at highstand was about 530 mi^3 [2,200 km^3], or slightly more than Lakes Erie and Ontario combined [509 mi^3].

The glacier must have been about 2200 ft thick at the dam, and when the water level behind the dam rose to 2000 ft, the ice dam floated off its base, leading to catastrophic failure. Lake Missoula emptied immediately! *Immediately*, of course, took a finite period of time, probably about two days. Water below Eddy Narrows, about a quarter of the total, was unimpeded, but Eddy Narrows and other local constrictions slowed upvalley waters.

Most of the water in the northeast area around Flathead Lake flowed west across the submerged ranges bordering Camas Prairie. Initially these ranges were under about a thousand feet of water, and as the lake level dropped, waters increasingly converged to flow through former passes in these submerged ranges, creating extreme currents through the sublake notches [Fig. 7].

Initial drainage was westward through an outlet in resistant Belt Series metasedimentary rocks about 660 ft deep [200 m]. Rainbow Lake was gouged out by converging currents that initiated kolks in this outlet channel.

> *Kolks* are subvertical vortices that form in very deep, very fast currents, especially in boundary areas of shear. They are similar to the concept of a whirlpool, but a whirlpool is to a kolk as a dust devil is to a tornado. Kolks can be thought of as underwater tornadoes, capable of plucking multi-ton blocks of rock and transporting them in suspension for some thousands of meters. Evidence of kolks consists of plucked-bedrock pits or lakes and downstream deposits of gravel-supported blocks that show percussion but no rounding.

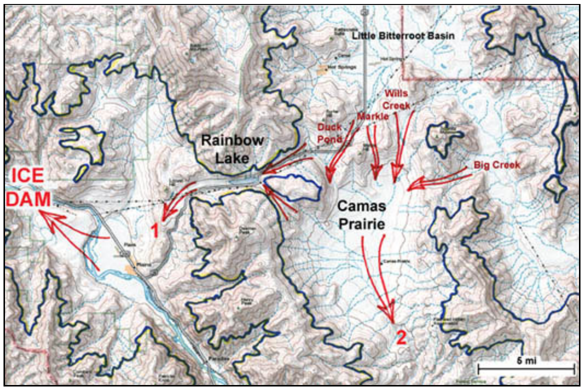


Figure 7—Camas Prairie showing shoreline at highstand. Initially, flood released through Rainbow Lake outlet [1], but when lake dropped below this level, flow turned south across Camas Prairie [2]. Discharge became increasingly concentrated through four sublake notches.

Rainbow Lake is a large kolk lake [Fig. 8], and downstream are enormous gravel bars with floating kolk blocks [Fig. 9]. The gravels formed a large deposit where this drainage emptied into the Clark Fork River at Plains, creating landforms that gave a good name for the place.

Figure 8—Rainbow Lake was created by kolk plucking of metasedimentary rocks.

Figure 9—Gravel bar a few kilometers downcurrent from Rainbow Lake.

When lake level dropped enough to abandon the Rainbow Lake outlet, drainage turned south through the Camas Prairie to join the Flathead River at Perma. There were now four sublake notches into Camas Prairie: Duck Pond Pass to the northwest was the highest, with a depth of about 200 ft when the Rainbow Lake spillway emerged, and Wills Creek Pass was the lowest, under about 470 ft of water [Fig.7].

Below these sublake notches are the testaments to the unusual currents that Pardee [1942] interpreted: trains of giant current ripples stretching for miles to the south across the Camas Prairie [Fig. 10]. One envisions very deep, strong, bottom currents dragging bedloads of gravels through the notches and spreading them out onto the lake floor below. These current ripples are hundreds of feet [tens of meters] to more than a half-mile long [one km] long. In plan view they are convex downcurrent with central axes of ripple fields emanating from the notches, and below individual notches more than one axis is recognized, suggesting more than one flow regime occurred [Fig. 11]. Amplitudes vary from less than 1 ft to 50 ft [15 m], and wavelengths vary from a few feet to 500 ft [150 m; Pardee, 1942], with mean values of about 15 ft [5 m] and 250 ft

[75 m]. The highest ripples below Wills Creek Pass have shorter and steeper upcurrent sides, suggesting antidune formation, with average heights of about 10 ft [3 m].

Figure 10—Giant current ripples at Camas Prairie.

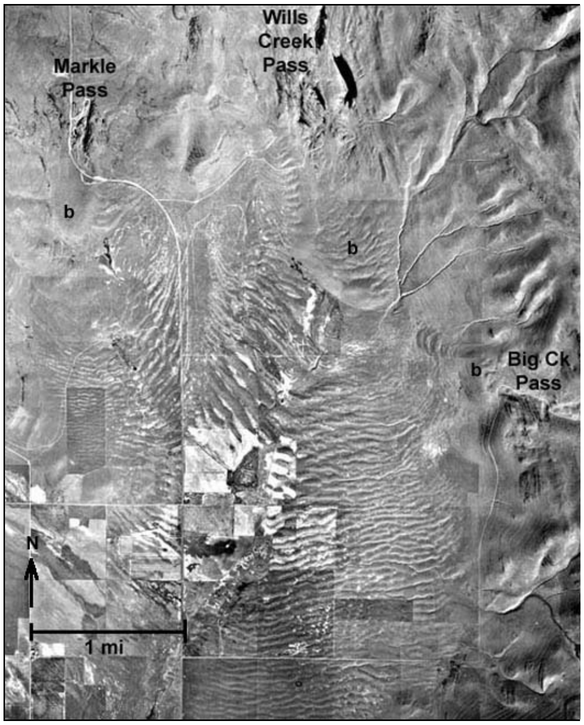


Figure 11—Aerial photo of Camas Prairie giant current ripple field. Black areas in each of the passes are kolk lakes. Lobate expansion bars [b] below each sublake notch.

Kolk pits formed in each of the sublake notches, many of them now lakes, with only two in Duck Pond Pass, half a dozen in Big Creek and Markle Passes, and 21 in Wills Creek Pass [Fig. 11]. Downstream from each of the notches is a large expansion gravel bar, the largest measuring 200 ft [60 m] thick below Wills Creek Pass, with the surface covered by giant current ripples [Fig. 11].

The valley constriction at Eddy Narrows slowed emptying of the lake for hours or days. Pardee (1910) calculated a flow through these narrows of 9.5 mi^3/hr [11 million m^3/s], with a velocity of 58 mph [26 m/s], which would have emptied the lake in about two days. Craig (1987), however, believes the velocity would have approached the theoretical limit of 172 mph [77 m/s] within minutes of the dam failure.

Examination of the damsite is disappointing; there is nothing to see. Glaciers occupied the site of the dam both before and after the Missoula floods, and Lake Pend Orielle covers the site today.

The divide between the Clark Fork River and the Spokane River is indistinguishable; it occurs in the Rathrum Prairie, a broad flat valley four to ten miles [6 – 16 km] wide that was the route of both the Purcell glacier lobe and the ensuing Missoula floodwaters. Rathdrum Prairie does contain a large gravel train of giant current ripples east of Spirit Lake. Spirit Lake itself, like several others along the margins of Rathdrum Prairie, was created by the deposition of a thick eddy bar that blocked the mouth of Spirit Creek. Spirit Lake has no surface outlet; it drains through the gravel bar.

FLOOD ROUTE AND DISCHARGE

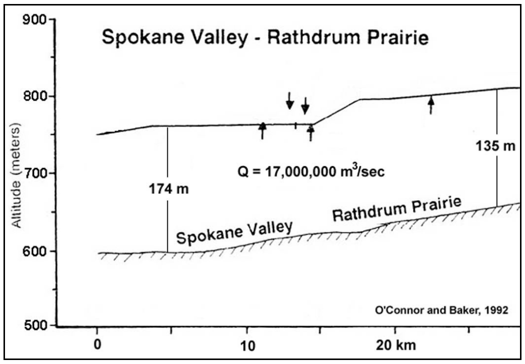


Figure 12—Flood discharge calculated from the longitudinal profile down the Rathdrum Prairie.

Within three minutes of the dam failure, velocities in Rathdrum Prairie would have reached 76 mph [34 m/s] and climbing, and the wall of water would have reached Spokane within 20 minutes (Craig, 1987).The discharge through Rathdrum Prairie was calculated by O'Connor and Baker (1992) using step-backwater modeling. With a depth varying from 440 to 570 ft [135 to 175 m], a valley width of 3½ miles [6 km], and a slope of 0.01, velocities were calculated to be from 56 – 100 mph [25-45 m/s], with a power of 200,000 W/m^2, and a minimum discharge of 17 million m^3/s [Fig. 12].

These were, at the time, the largest known freshwater flows ever calculated, and they lasted about three days.

All of Lake Missoula discharged through Rathdrum Prairie and dumped into the upper end of Lake Columbia in the Spokane Valley. This has been likened to a hippo jumping into a swimming pool – the displacement waves were tremendous. Vast amounts of water surged over the south bank into three major flood spillways – from east to west the Cheney - Palouse scablands, the Telford - Crab Creek scablands, and Grand Coulee [see Fig. 3].

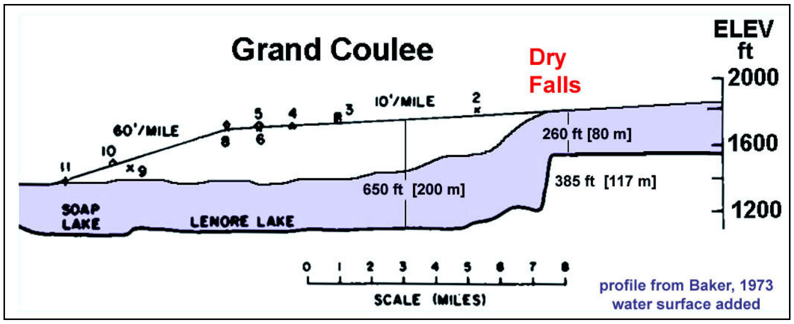
Much, if not most, of the floodwaters surging into the Cheney-Palouse scabland tract, eroding and sculpting loess-covered plains and gouging out the underlying basalt. Floodwaters followed pre-existing drainages to some extent, but crossed many local divides, creating anastamosing channels cut into bedrock, with streamlined islands of loess in between.

Most of the flood headed directly southwest into the Palouse River where the valley curved to the west, but the floodwaters surged right across the Palouse River Valley and over the divide into the Snake River to the south. The flood reaching the Snake River was so great that floodwaters surged *up* the Snake River for more than 100 miles [160 km], dumping gravels on top of Bonneville flood gravels near Lewiston, Idaho.

The Snake River captured the Palouse River in a matter of hours by creating immense waterfalls at the Snake River Canyon that quickly eroded back several miles to their present location at the picturesque Palouse Falls [Fig.13]. Palouse Falls is a world-class example of an underfit plunge pool; the current falls, 184 ft [56 m] high, are not even as high as the apparent depth of the plunge pool. It has been reported that when James Gilluly, one of the better known of Bretz's numerous antagonists, arrived here, he stood for a long time looking at the falls before muttering, "How could I have been so wrong!"

Lake Columbia drained from its western end into Grand Coulee. When the Missoula flood hit the lake, about a quarter of the Missoula flow, or about 5 million m^3/s, surged into this outlet. Grand Coulee itself did not have the capacity to convey this flow, so the floodwaters spread out and scoured the area to the east as well, before dumping into the Quincy Basin near Ephrata. The flood through Grand Coulee was about 260 ft [80 m] deep, and it carved Dry Falls [see Frontispiece], the largest waterfall in the world, currently inactive because it is on an intermittent stream [not expected to flow again until the next glacial period]. Actually, Dry *Falls* is a bit of a misnomer, as the true scale of the flood would have made this more like a colossal *cataract* [Fig. 14].

Figure 13—Palouse Falls at a huge plunge pool cut by floodwaters dumping into the Snake River. Falls are 184 ft high [56 m]; top of falls has been cut down 400 ft [120 m] below the preflood surface, seen on skyline.



profile from Baker, 1973
water surface added

Figure 14 –Dry Falls in the Grand Coulee floodway. The *falls* would have been more like a giant cataract.

Figure 15—Mile-wide Wallula Gap was unable to transmit the Missoula Flood, forming a hydraulic dam that backed up floodwaters for weeks [view downstream].

Debris from the Grand Coulee excavation was dumped onto the enormous gravel fan at the head of the Quincy Basin, the Ephrata bar, joining with the tremendous load carried down Upper Crab Creek from both the Telford-Crab Creek spillway and some of the Cheney-Palouse outflow.

All of the Missoula flood routes converged into the Pasco Basin just above Wallula Gap. Wallula Gap [Fig. 15] is a mile wide [1.6 km] and more than 800 ft [250 m] deep, but even this huge opening had the capacity to transmit only half of the flood discharge, so it created a hydraulic dam that ponded the floodwaters into a vast, ephemeral lake, called Lake Lewis.

Maximum discharge through Wallula Gap was about 10 million m^3/s, with a velocity of 56 mph [25 m/s] and a power of about 100,000 W/m^2. It probably took weeks for these waters to drain through Wallula Gap.

The Columbia River Gorge similarly created a hydraulic dam that ponded Lake Condon at the upstream end. At the lower end of the Columbia Gorge, floodwaters shot out as a wall of water 500 ft [150 m] high that roared into the Willamette Valley at Portland, scouring the valley floor and surrounding hills and heading south up the valley. The main flood continued down to the Kalama Narrows, where another hydraulic dam ponded waters back up into the Willamette Valley, forming Lake Willamette. The shores of Lake Willamette extended as far south as Eugene and are marked by numerous iceberg-rafted erratics up to 400 ft elevation.

Floodwaters continued past Astoria on the present coast out to the margin of the glacial continent, where it dumped sediment onto the Astoria fan and formed turbidity currents that carried flood debris along the seafloor for hundreds of kilometers in the Cascadia Channel.

FLOOD EROSION

The geology of the flood area is usefully very simple. Lake Missoula lies primarily in Precambrian Belt Series metasedimentary rocks with minor outcrops of Mesozoic granitic rocks. Miocene Columbia River Basalt is the primary bedrock throughout the flooded area. Wisconsin Bull Lake Palouse Loess forms a 160-ft thick [50 m] blanket over the basalt [this is an ideal medium for mollisol development and grain cultivation, so the extent of loess is readily apparent as large wheat fields]. Floodwaters pouring over Palouse Loess sculpted it in places and completely removed it in others. Loess islands – streamlined hills with upstream prows and downstream tails – are surrounded by scablands. Much of the loessal soil was carried to the Willamette Valley south of Portland, where it created that valley's fertile farmland.

Scablands refer to those areas of denuded basalt, so named by early farmers because they lack tillable soil. Kolks were the dominant agents that eroded the scablands, so these basalt areas show extensive evidence of plucking and very little evidence of abrasion. The dark basalt contrasts strongly with the light Palouse Loess, so scablands stand out clearly on space images [Fig. 16], and the extent of anastomosing channels across the plateau demonstrates to any casual observer the full scale of the Missoula flood. If satellites were around 80 years ago, J Harlan Bretz would have had an easy time of it!

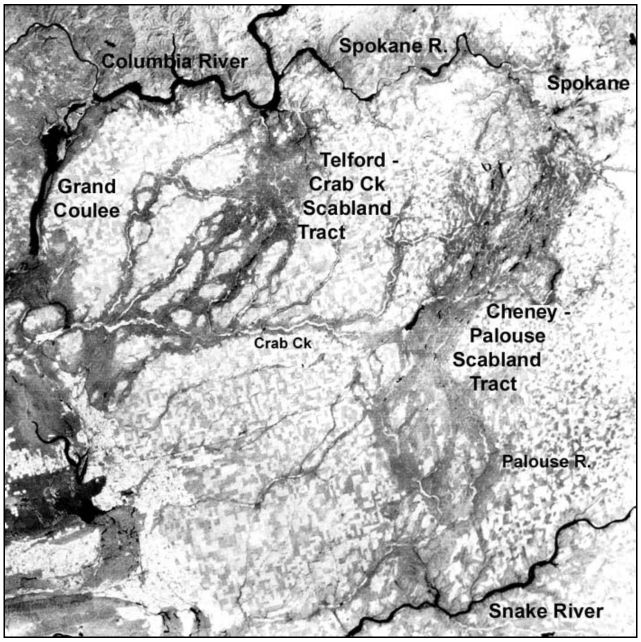


Figure 16—Dark basalt scablands of eastern Washington show clearly where the lighter Palouse Loess was stripped away by the Missoula Flood. Landsat MSS image.

Although the anastamosing channels give the impression of braided drainage, not only is the scale vastly different, but the process is, as well. The loess islands between the channels were created by erosion, not by deposition.

Extensive scour through the Columbia Gorge deepened the channel and left near-vertical walls of bare, plucked basalt. Many tributary streams were left hanging, and, similar to glacial hanging valleys, form spectacular waterfalls like Multnomah Falls [Fig. 17].

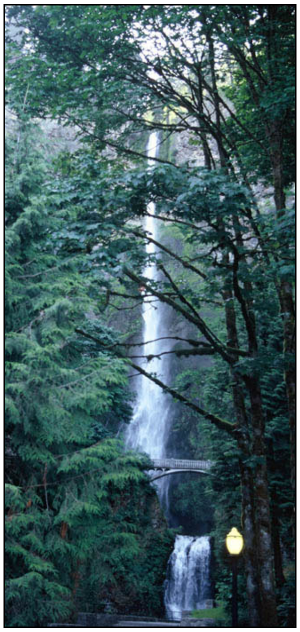


Figure 17—Multnomah Falls in the Columbia River Gorge was created when floodwaters incised the main canyon.

FLOOD DEPOSITION

Depositional landforms in flood channels are primarily streamlined, subfluvial gravel bars and giant current ripples. Gravel bars are relatively matrix-free deposits of pebble-cobble gravel, with boulders and occasional blocks. Pendant bars formed downcurrent of obstructions under about 100 to 200 ft [30 to 60 m] of water [Fig. 18]. They may be several kilometers long and up to 100 ft [30 m] high, and where exposed they show well sorted foreset gravels [Fig. 19].

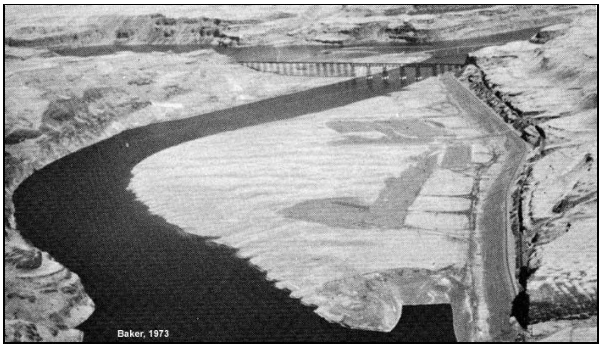


Figure 18—Pendant bar with giant current ripples just below the confluence of the Palouse River with the Snake River.

Figure 19—Fore-sets of open-work cobbles in pendant bar dip 26°.

Expansion bars were deposited downcurrent of constrictions. These are foreset-bedded gravels deposited by decelerating flows. The deposits often contain large angular blocks plucked from the constriction, and the surfaces of many expansion bars show armoring and scour channels.

Eddy bars formed at the mouths of tributary streams or alcoves [Fig. 20]. These deposits are generally poorly sorted, and crude bedding may dip in many different directions. Lower, coarser gravels may dip away from the channel and finer upper gravels may dip back toward the channel reflecting backcurrent deposition.

Figure 20—Eddy bar [breached] at the mouth of a canyon tributary to the Flathead River below Perma, MT.

Figure 21—The Bellevue Erratic in the Willamette Valley, OR. The 160-ton block of Belt argillite was carried across four states in a huge chunk of glacier torn from the ice dam.

Slack-water sediments were also deposited in tributary drainages downstream in Washington and Oregon by flood bores surging upstream. The foresets dip upstream, although some later beds may dip back toward the main channel, and average grain size decreases upstream. Many of these are rhythmite sequences.

Giant current ripples are analogous to normal current ripples, but at a colossal scale where amplitudes are measured in meters and wavelengths in tens of meters. They formed at depth by foreset deposition of gravels. About sixty trains of giant current ripples have been recognized; from measurements of 40 wave trains (Baker, 1973):

the number of giant ripples varies from 3 to 60,
mean amplitudes vary from 1.3 ft to 22 ft [0.4 m to 6.7 m],
mean wavelengths vary from 60 ft to 425 ft [18 to 130 m],
the relationship of these variables is given by the regression: $A = 0.0029\ \lambda^{1.5}$
[the giant current ripples measured in the Camas Prairie also fit this relationship exactly]

The amplitude of the waves is at a maximum in the center and decreases outward, and the ripples are asymmetric, steeper on the downstream side. They have been classified as out-of-phase catenary ripples.

Two ice-rafted flood erratics found in the Willamette Valley are particularly interesting. The Bellevue Erratic [Fig. 21] is the basis of a state park, which exhibits this large Belt metamorphic boulder 21 ft x 18 ft x 5 ft [6.4 m x 5.5 m x 1.5 m] with an original weight of 160 tons [145 metric tons]. The Willamette Meteorite, found nearby among other flood debris, most likely fell on the Cordilleran ice sheet and was likewise ice-rafted to the Willamette Valley by the Missoula flood. Thus the largest meteorite ever found in the U.S.A. may be just another Canadian import.

MULTIPLE MISSOULA FLOODS

Lake Missoula filled many times and emptied catastrophically in many Missoula Floods. Rhythmite sequences at numerous localities provide this evidence: varves in Lake Missoula attest to multiple fillings of the lake, and slack-water rhythmite deposits in backflooded tributary valleys indicate multiple floods.

Thousands of varves were deposited in Lake Missoula. At the best-known Ninemile locality near Missoula, there are about 40 rhythmite sequences that consist of varves overlain by a sand/silt layer [Figs. 22, 23]. The varves were deposited in Lake Missoula, and the sand/silt layers represent subaerial exposure and fluvial deposition. The number of varves in each sequence varies from 9 to 40, decreasing regularly upward, and the total number of varves is just less than one thousand.

Most downstream slack-water rhythmites are sequences of graded beds, grading upward from coarse sand and gravel to silt, with occasional ice-rafted erratics [Figs. 24, 25]. The tops of some sequences are marked by thin paleosols, and most show evidence of subaerial exposure, indicating multiple, separate floods. The number of such sequences ranges from 50 to 89.

Fig 22—Lake Missoula rhythmite sequences at Ninemile, MT. Rhythmites are alternating fluvial silts [light color] and varves [dark]. About 26 sequences visible here appear to thin upward.

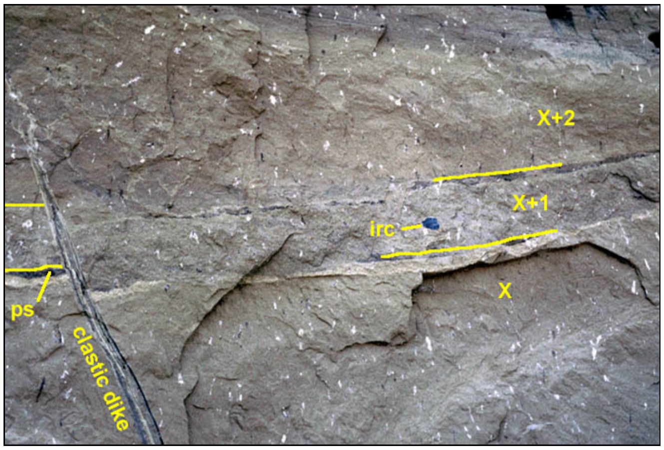


Figure 25—Three sand-silt graded beds are offset slightly along a clastic dike [perhaps a dessication crack]. Bottom two beds show weathered tops with bits of thin paleosol. Ice-rafted cobble [irc] of Belt metaquartzite shows glacial faceting. Area shown is the rectangle in Figure 24.

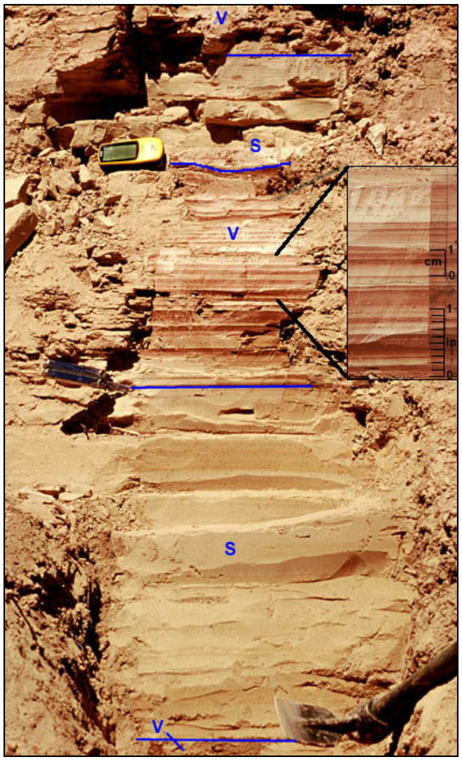


Figure 23—About 38 varves [v] in the middle sequence are bounded by lighter fluvial silts [s].

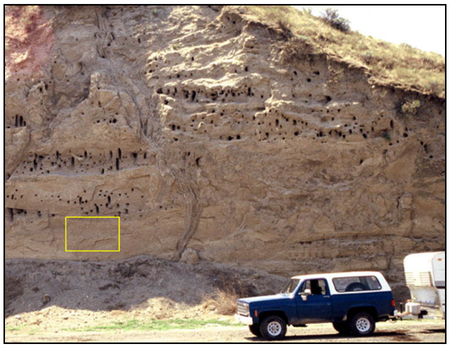


Figure 24—Slackwater rhythmites [Touchet Fm.] at Lowden, WA. About 11 sequences seen here.

Putting these observations together suggests there have been scores of Missoula Floods and Lakes Missoula. Early lakes and floods were small; they apparently increased regularly to a maximum, and then waned in the later stages of the glaciation. The first lake and its flood were small because the thin distal lobe of the initial glacier advance dammed little water before the dam failed. The resulting flood truncated the distal edge, however, leaving a thicker glacier front to advance and make a higher dam that dammed more water before failure released the second flood [Fig. 26].

This progression would have led to larger and larger lakes and floods until such time as the glacier started to diminish in response to climate change. The late lakes and floods may have been quite small.

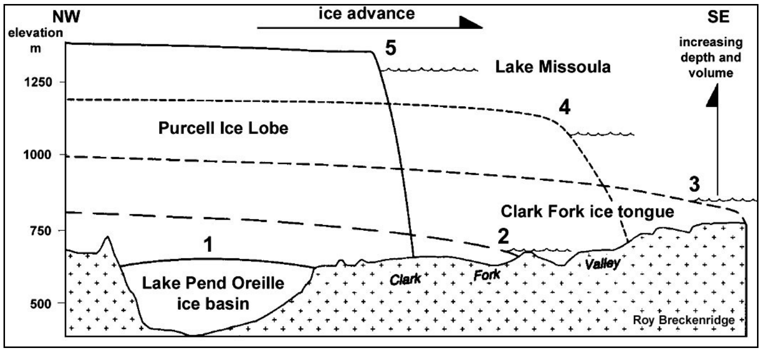


Figure 26—Successive Purcell glacier advances would have dammed successively larger Lakes Missoula.

AGE

The geologic history of the Missoula floods is poorly constrained compared with the Bonneville flood. If there were early Pleistocene floods, there is no direct evidence. The Bull Lake Palouse Loess is a good time marker; major flooding stripped this loess in Pinedale time. Some Missoula flood gravels were deposited in the Snake River on top of 14,500 bp Bonneville gravels. Toward the top of the rhythmite section in Burlingame Canyon near Walla Walla ,Washington [on top of sequence 29 of 40], is Mt. St. Helens double ash Set S, dated at 13,000 bp. The main Missoula flooding probably occurred between about 14,500 and 12,800 bp.

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Keenan Lee
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