THE MISSOULA FLOOD

Dry Falls in Grand Coulee, Washington, was the largest waterfall in the world during the Missoula Flood. Height of falls is 385 ft [117 m]. Flood waters were actually about 260 ft deep [80 m] *above* the top of the falls, so a more appropriate name might be Dry Cataract.

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CONTENTS

OVERVIEW

About 15 000 years ago in latest Pleistocene time, glaciers from the Cordilleran ice sheet in Canada advanced southward and dammed two rivers, the Columbia River and one of its major tributaries, the Clark Fork River [Fig. 1]. One lobe of the ice sheet dammed the Columbia River, 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, with a volume of water greater than that of Lake Erie and Lake Ontario combined [530 mi^3 or 2200 km^3]. Lake Missoula had no outlet [Fig. 2].

When the dammed water got deep enough, it started to *float* 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 [160 kph]. Discharge was about 600 million cfs [ft^3/s; 17 million 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 the largest flood discharge known.

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 Channeled Scablands of eastern Washington.

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 three ephemeral lakes [Fig. 4]. The floodwaters scoured scablands and coulees, ripped out huge blocks of bedrock, and dumped enormous loads of gravel in bars, often with giant current ripples. Titanic chunks of glacier rafted 100-ton rocks to the Pacific Ocean.

There was at least one such catastrophic flood, probably more than 25, perhaps as many as 89.

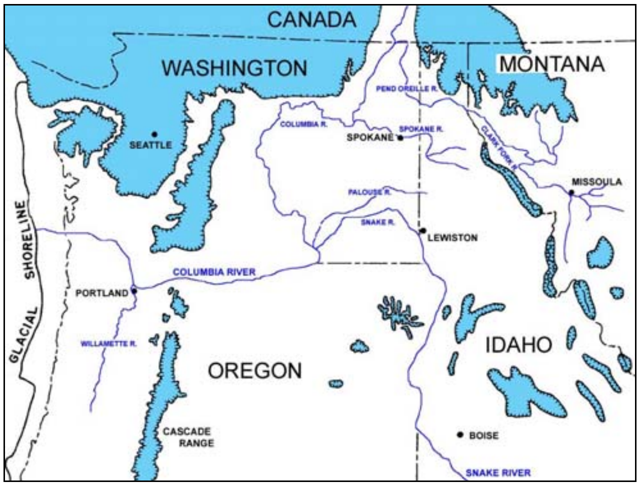

Figure 1—Columbia River drainage as the Cordilleran ice sheet advanced southward. Glaciers shown in blue.

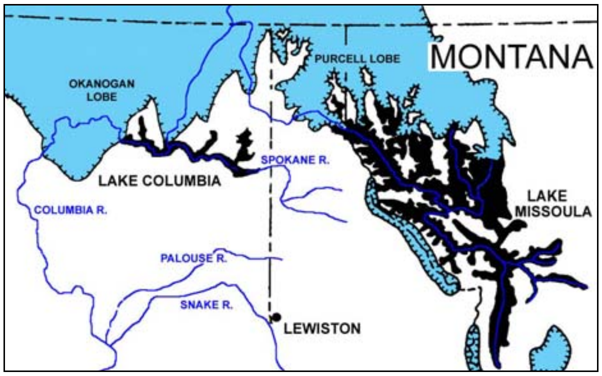

Figure 2—Lake Columbia and Lake Missoula created by ice dams.

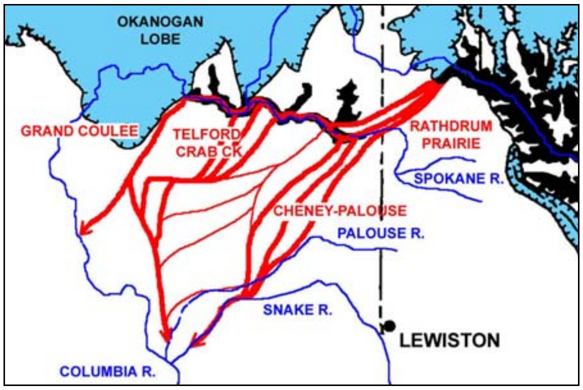

Figure 3—Lake Missoula floodwaters swept across Idaho and eastern Washington.

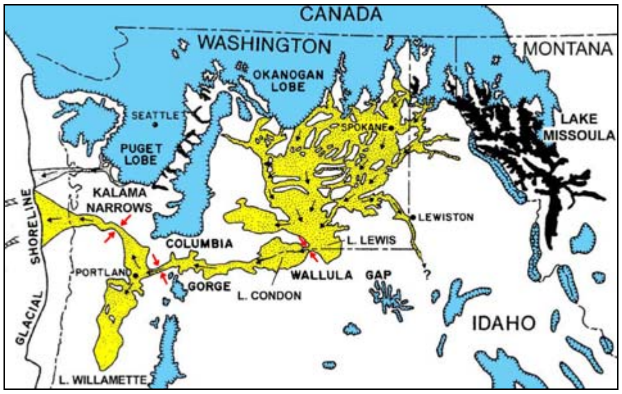

Figure 4—Flood discharge across Idaho, Washington, and Oregon.

THE GLACIAL DAM

Lake Missoula was created when the Clark Fork River was dammed by an advancing ice sheet from Canada. This occurred near the border of Montana and Idaho at the present Lake Pend Oreille [Figs. 5, 6], where the west-flowing Clark Fork River is bounded by the Cabinet Mountains on the north and the Bitterroot Range on the south. The main front of the Cordilleran ice sheet never quite reached the Clark Fork Valley, but an outlet glacier, or lobe, called the Purcell lobe because it led the ice advance down the Purcell Trench of northern Idaho, crossed the Clark Fork Valley and rammed into the north end of the Bitterroot Range [Fig. 7]. The left abutment of the glacial dam, where the ice ground against very competent bedrock, was formed by the Green Monarch Ridge.

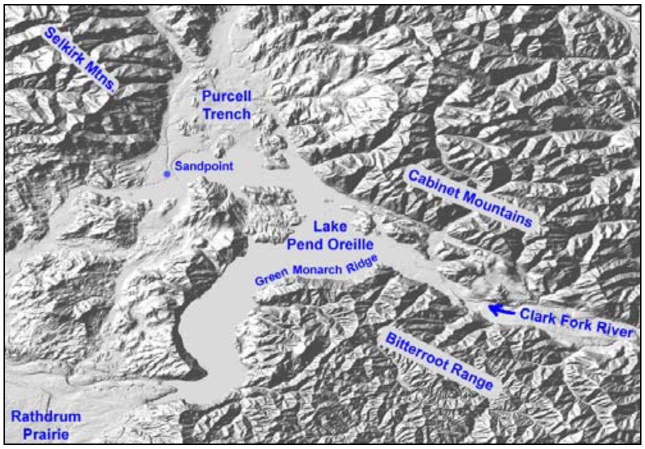

Figure 5—Glacial damsite area showing present topography.

Figure 6—View up the Purcell Trench, path of the ice lobe advance, from Green Monarch Ridge; Lake Pend Oreille fills the glacial furrow.

Although the Clark Fork River at first probably flowed around/over/under the thin distal edge of the advancing glacial lobe, relentless advance of the ice eventually sealed it against Green Monarch Ridge to create a formidable dam. Clark Fork River waters began to accumulate to create Lake Missoula [Fig. 8].

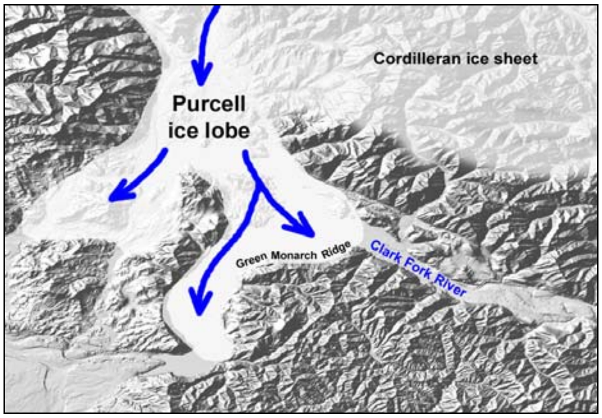

Figure 7—Advancing ice of the Purcell lobe ground against the Green Monarch Ridge, damming the Clark Fork River.

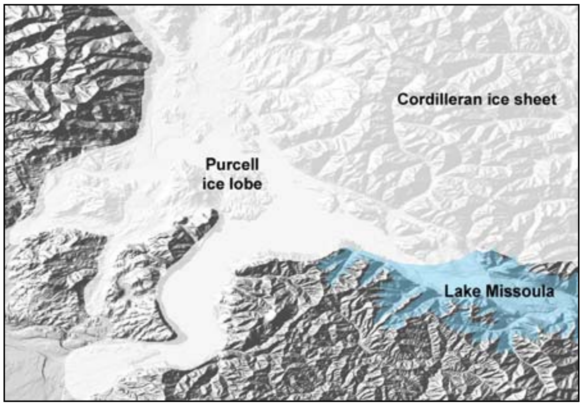

Figure 8—At the maximum ice advance Lake Missoula reached a depth of about 2000 ft at the dam. [Ice margin from Richmond and others, 1965]

When the waters of Lake Missoula rose behind the Green Monarch glacial dam to about 1100 ft deep, lake level reached a low point on the drainage divide at Pole Creek, through which the lake water spilled [Fig. 9]. Well rounded cobbles and pebbles of mixed rock types at the very top of the spillway [Fig. 9 inset] attest to river flow through the spillway. This spillway may have been active for some time, because the valley is considerably underfit; that is, it is larger than would have been created by its present stream [Fig. 10A, B].

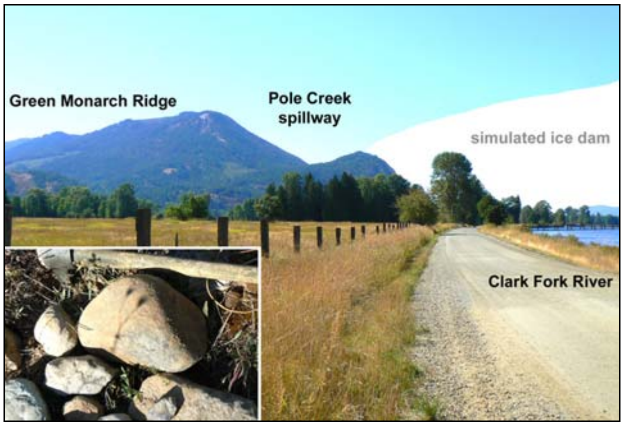

Figure 9— View down the Clark Fork River toward the ice dam. Early Lake Missoula waters spilled out through the Pole Creek spillway. Inset shows river gravels at the top of the spillway.

Continuing advance of the thickening glacier eventually blocked the Pole Creek spillway, forcing lake level higher. At a depth of about 1700 ft, a higher spillway opened [spillway 2, Fig. 10C], also indicated by river gravels at the top. Three more spillways opened successively, the highest at an elevation of about 4100 ft [Fig. 11]. There is no evidence that Lake Missoula stabilized at this elevation – that is, there is no prominent maximum elevation strandline around the lakeshore – but this elevation is close to the maximum known elevation of the lake.

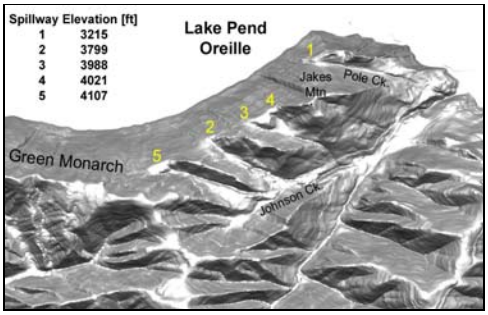

Figure 10A—Topography of the Green Monarch spillways.

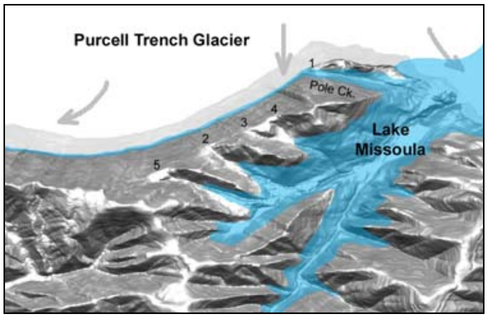

Figure 10B—Early Lake Missoula, at a depth of about 1100 ft, spilled out at Pole Creek.

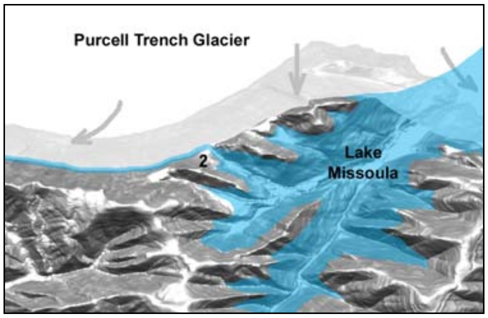

Figure 10C—At 1700 ft depth, a higher spillway opened.

Figure 11—Green Monarch Ridge viewed across Lake Pend Oreille, Clark Fork Valley at left. Numbers on spillways correspond to Fig. 10.

LAKE MISSOULA

Lake Missoula was created when the glacier dammed the Clark Fork River and water backed up as the lake grew for 50 or 60 years. Lake Missoula backed up to about Deer Lodge on the Clark Fork River, past Darby in the Bitterroot Valley, and up against the Flathead glacier lobe at Flathead Lake. The Clark Fork River flows through rugged, mountainous topography, so when this country flooded, Lake Missoula was very long, somewhat serpentine in map view, with deeply indented shorelines [Fig. 12].

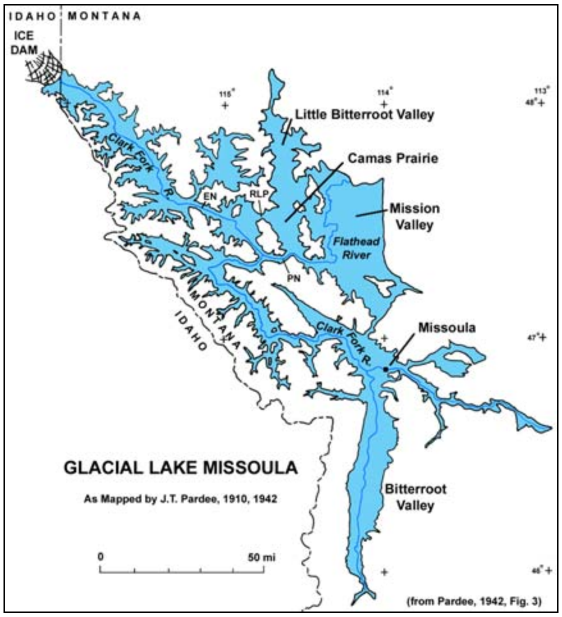

Figure 12—Glacial Lake Missoula at an elevation of 4150 ft. EN, Eddy Narrows; PN, Perma Narrows; RLP, Rainbow Lake Pass.

Lake Missoula eventually reached an areal extent of 2900 mi^2 [7500 km^2]. Shorelines around the perimeter of the lake [Fig. 13] show the lake reached an elevation of about 4250 ft [1295 m]. This made the water at Missoula about 950 ft [290 m] deep and an astounding 2000 ft [700 m] deep at the ice dam! Lake volume at highstand was an incredible 530 mi^3 [2200 km^3], more than the volume of Lake Erie and Lake Ontario combined.

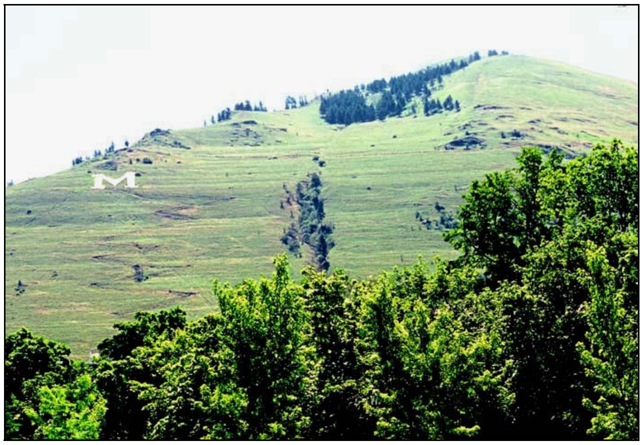

Figure 13—Lake Missoula shorelines above University of Montana campus at Missoula.

The geology of Lake Missoula is quite simple; almost all of the lake floor consists of Belt Supergroup metasedimentary rocks of Precambrian age [1.47 to 1.40 billion years]. The enormously thick sediments - perhaps as much as 12 miles [20 km] thick - were deposited in a rift basin by rivers heading in nearby [at the time] Siberia to the west and Australia to the southwest. Mostly sands and clays, these sediments were metamorphosed to quartzites and argillites, respectively, which are very tough rocks, resistant to erosion except where highly fractured. The metasedimentary rocks contain numerous intrusions of basalt. Conveniently, Belt rocks extend only a short distance beyond the site of the glacial dam, so that all of the boulders and cobbles of Belt rocks found across Washington and Oregon and, indeed, in the Pacific Ocean, can, with certainty, be attributed to transport by the Missoula Flood.

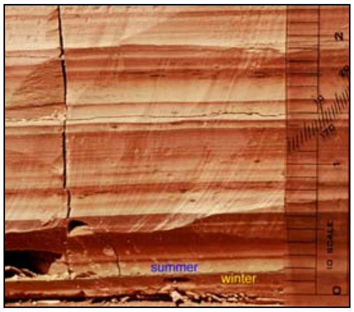

Figure 14—Varves in Lake Missoula sediments. One year of deposition is represented by a dark winter layer and a light summer layer.

Lake sediments accumulated at the bottom of Lake Missoula, many of which show sequences of varved sediments. Varves are annual layers consisting of a lighter summer layer of meltwater-transported sand and silt and a darker winter layer of clay and organic material that settled out when the lake was frozen over [Fig. 14]. A count of the varve couplets thus indicates how long it took to fill the lake up to the point where the glacier dam failed.

THE DAM FAILURE

Lakes are ephemeral features. Dams fail. Big dams fail catastrophically.

We don't know for sure quite how Lake Missoula's dam failed, but the most popular hypothesis is that the rising lake water floated the dam off its base. 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 started to float off its base, leading to catastrophic failure. The ice would have broken apart almost instantaneously, and Lake Missoula emptied immediately! *Immediately*, of course, took a finite period of time, probably about two days.

When one thinks of a dam failure, one usually thinks in terms of a wall of water rushing down the valley below the dam – logically so. What is not quite so intuitive, however, is the consideration of the flood that occurs *above* the dam. Most studies of the Missoula Flood have centered on the effects of the downstream flood that swept across three states on its rush to the Pacific Ocean. But another type of flood advanced *up* the Clark Fork Valley as the instantaneous drop in the lake's surface at the dam sped up the valley [Fig. 15].

Analogous to the water currents set up by pulling the plug in a bathtub, all of the water in Lake Missoula responded by rushing toward the damsite, creating flood currents that wreaked havoc on the lake bottom. These are the "unusual currents" that J.T. Pardee spoke of in his pivotal paper in 1942. Pardee went on to document flood features, especially in Camas Prairie, that resulted from these unusual currents in Lake Missoula.

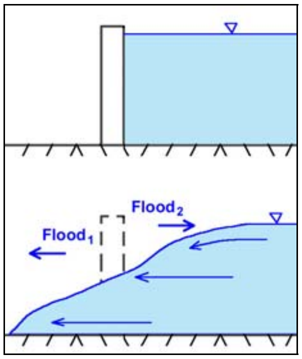

Figure 15—When the dam failed, a flood [F1] poured down the Clark Fork River. Another flood [F2] moved upriver as the falling water surface sped up the valley.

THE MISSOULA FLOOD ABOVE THE ICE DAM

Catastrophic Flood Features in Eddy Narrows

The topography of the Clark Fork drainage basin exerted extreme control on the flood currents that formed in Lake Missoula; wide, shallow valleys drained rather quietly, whereas narrow, deep reaches of the valley constricted flow and created immensely powerful flood currents that tore all unconsolidated materials from the lakebed and plucked out huge blocks of bedrock [Fig. 16].

When the ice dam failed, water impounded in the lower 60 miles of Lake Missoula below Eddy Narrows [Fig. 12], about a quarter of the total, was unimpeded and drained rapidly. The bulk of the water was above Eddy Narrows, however, and drainage was impeded by a hydraulic dam formed by the narrows – that is, flood water could not discharge through the constriction as fast as it arrived, and thus backed up above the narrows.

An appreciation for the magnitude of this flood is gained when one views Eddy Narrows [Fig. 17] and realizes this 'constriction' is about a mile wide at the present valley floor and about a mile and a half wide at the 1000 foot-deep flood level. Pardee [1942] estimated the flood velocity here at 45 mph [65 ft/s, 20 m/s], from which he calculated a flood discharge of 386.5 million cubic feet per second [10.9 million m^3/s]. Craig (1987), however, believes the velocity would have approached the theoretical limit of 172 mph [277 kph] within minutes of the dam failure.

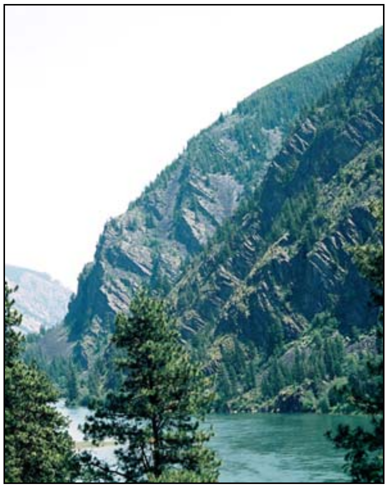

Figure 16—Denuded rock walls in Eddy Narrows. Note the 'trimline' between the flood-scoured rock and the forest-covered slopes above.

Figure 17—View down the Eddy Narrows from Eddy. The mile-wide valley is scoured up to about a thousand feet.

Catastrophic Flood Features On the Flathead River in Perma Narrows

Flood currents in Lake Missoula had immense power that enabled them to transport vast amounts of gravel [gravel is all unconsolidated material larger than sand, and includes pebbles, cobbles, and boulders]. Much of the gravel was carried in suspension, and some, including most of the larger boulders and cobbles, was moved along the bottom by the tractive power of the bottom currents. These currents were so strong they dragged a bedload of gravel not only along the valley bottoms, but in some cases up some fairly steep slopes. A unique type of deposit that illustrates this is the washover bar, an accumulation of coarse gravel that was carried up a slope and then dumped over the top of the ridge [Figs. 18 and 19].

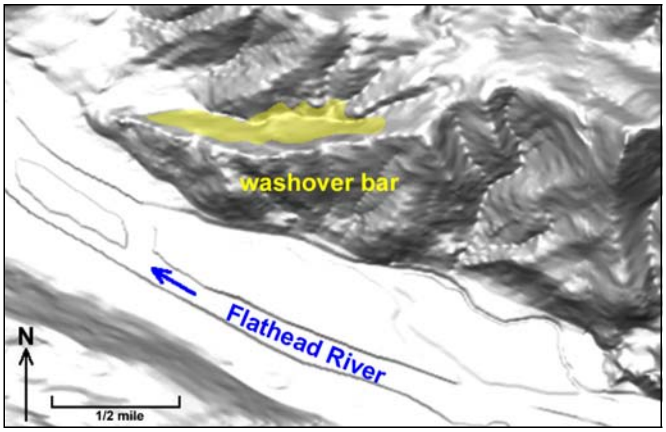

Figure 18—As floodwaters poured down the Flathead River above Perma, gravels were swept up and over the ridge and deposited as a washover bar.

Figure 19—Aerial view of the washover bar looking to the southwest.

In Perma Narrows, the main flood current ran through a straight reach of the Flathead Valley for about four miles, at which point the valley makes a right-hand turn at Burgess Lake [Fig. 20], and the flood current slammed into the steep left bedrock wall [Fig. 21]. This impact zone is here called the Burgess whamout zone, where the impacting currents tore out large kolk pits[1] and carved high rip walls in making its turn [Fig.22]. Burgess Lake now occupies the largest of these kolk pits [Fig. 23]. After ricocheting off the Burgess whamout, the current ran through another straight reach of valley that focused the main current into a narrow, straight [fault-controlled] tributary valley. Flood gravels, including large boulders, were dragged up this very steep valley, through a rip channel cut in the far ridge, and dumped in a washover bar on the other side [Fig. 24]. Today these gravels rest more than 1300 ft [400 m] above the Flathead River.

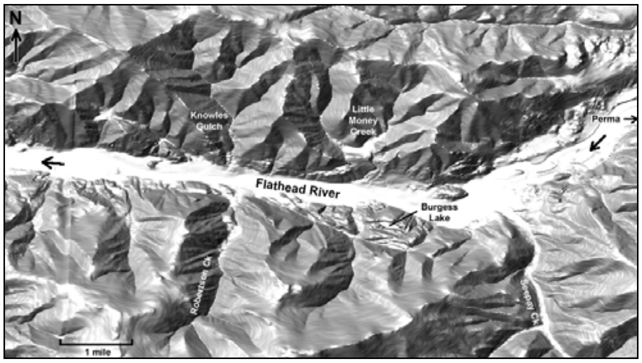

Figure 20—Topography of the Perma Narrows area.

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[1] *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.

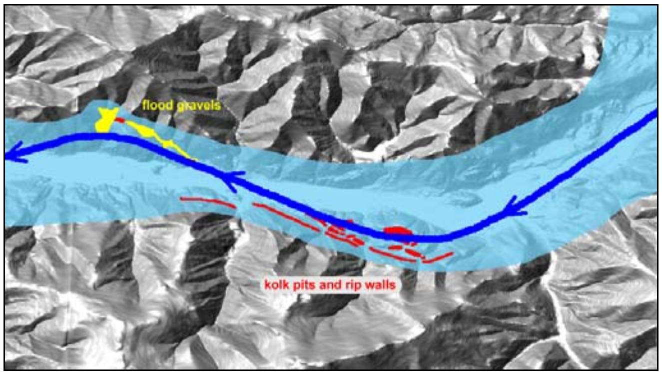

Figure 21—Flood waters hitting the bend at the Burgess whamout area were deflected against the north bank.

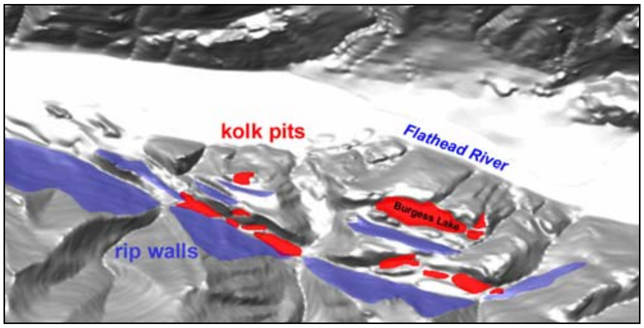

Figure 22—Flood currents in the Burgess whamout area carved rip walls and plucked out bedrock to form kolk pits. Burgess Lake, in the largest kolk pit, is 1800 ft long and 500 ft wide [550 x 150 m].

Figure 23—Aerial view of Burgess whamout shows Burgess Lake in a large kolk pit below one of the lower rip walls [lrw]. Upper rip wall [urw] is 400 to 900 ft high, 1100 ft above the Flathead River [120 - 275 m; 335 m].

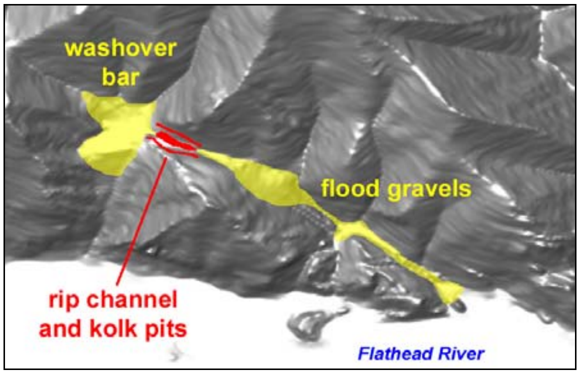

Figure 24—Flood gravels [probably including rocks plucked from the Burgess whamout] were driven up the slot-like tributary valley, over two divides, and dumped in a washover bar. Severe erosion occurred in the higher divide.

As the main flood tore down the Flathead River with depths of more than one thousand feet, the irregular topography of the mountain valley created numerous eddy currents, especially in tributary valleys that were nearly perpendicular to the main Flathead Valley. These eddy currents also carried flood gravels, usually smaller [mostly cobbles and pebbles] and rounder than gravels in the washover bars, that were deposited in the mouths of the tributary valleys, in some cases completely blocking the tributary. Numerous eddy deposits can be seen in the Perma Narrows [Fig. 25]. One of the largest eddy deposits is in Little Money Creek [Fig. 25 inset], where several hundred feet of gravel accumulated and built a valley-mouth bar [since breached] across the drainage [Fig. 26]. Numerous eddy gravels were deposited in Paradise Narrows, as well, especially on the north side.

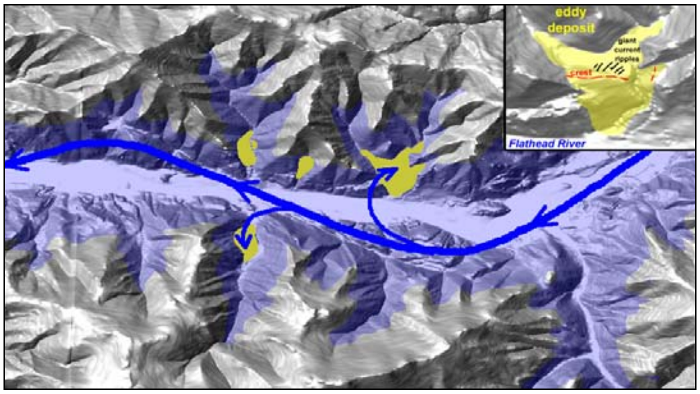

Figure 25—Eddy currents [smaller arrows] were created by the irregular topography and steep tributary valleys. Eddy deposits in yellow.
Inset: Little Money Creek, with giant current ripples on the up-valley side.

Figure 26—The breached eddy deposit at Little Money Creek.

Catastrophic Flood Features at Camas Prairie

Camas Prairie is in a simple drainage basin about in the middle of glacial Lake Missoula [see Fig. 12], where it was about a thousand feet deep [Fig. 27]. When Lake Missoula’s dam failed, water from Camas Prairie, Little Bitterroot Valley, and Mission Valley poured directly toward Eddy Narrows through Rainbow Lake Pass [Fig. 28]. The pass was under about 300 ft [90 m] of water initially, but flood waters eventually tore out about 360 ft [110 m] more of competent bedrock, primarily by kolk action [Figs. 29 and 30]. Flood currents carved a long, remarkably flat rip channel in very competent metasedimentary bedrock. Direct flow to Eddy Narrows, however, was impeded by Locust Hill, a wedge-shaped bedrock hill that split the flood current into northwest and southwest components [Fig. 31].

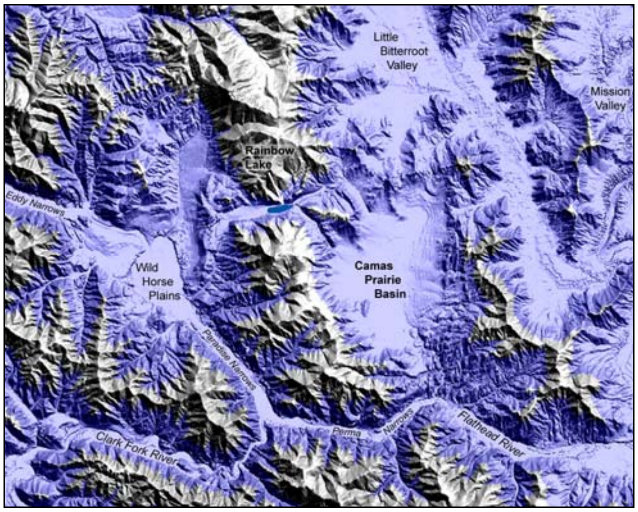

Figure 27— Camas Prairie region showing Lake Missoula at highstand [4250 ft elevation].

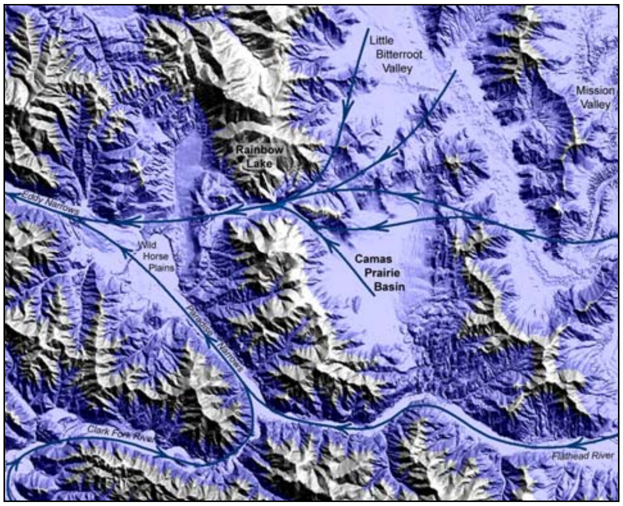

Figure 28—Lake Missoula emptied through the single outlet of Eddy Narrows, first ripping through either Rainbow Lake Pass or Paradise Narrows.

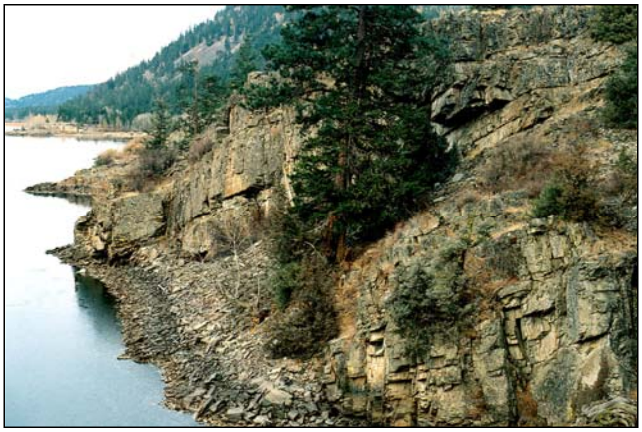

Figure 29—Bedrock plucked by kolk action at head of Rainbow Lake.

Figure 30—View east of Toolman Slough and Camas Creek rip channels converging at Rainbow Lake; rw, rip wall.

Flood currents from the Rainbow Lake outlet deposited coarse gravels at the end of the Rainbow Lake rip channel in several expansion bars. The Boyer bar is a huge expansion bar that contains most of the flood gravel from the Rainbow Lake rip channel. The bar is 11 000 ft [3000 m] long and 2000-4000 ft [600-1200 m] wide. Thickness is unknown, but it is about 360 ft [110 m] at the distal end [Fig. 32]. Constituents are boulder-cobble-pebble gravel with open-work structure, with some very large boulders suspended in finer matrix. Road cuts in the depositional front show crude foreset bedding [Fig. 32 inset].

When lake level dropped enough to close off the Rainbow Lake outlet, flood currents turned south through Camas Prairie to flow into the Flathead River Valley at Perma [Fig. 33]. All floodwaters coursing south through Camas Prairie tore across the Perma Ridge, a long ridge that formed the sublake divide between Camas Prairie and the Flathead Valley. In seeking the most direct route to the damsite, currents crowded the west bank, and bottom currents carved the ridge into a kolked scabland [Fig. 34]. As the lake drained, falling levels caused this erosion to progress down the ridge to the east, creating a series of rip channels as kolks cut near-vertical rip walls in the Belt bedrock [Fig. 35].

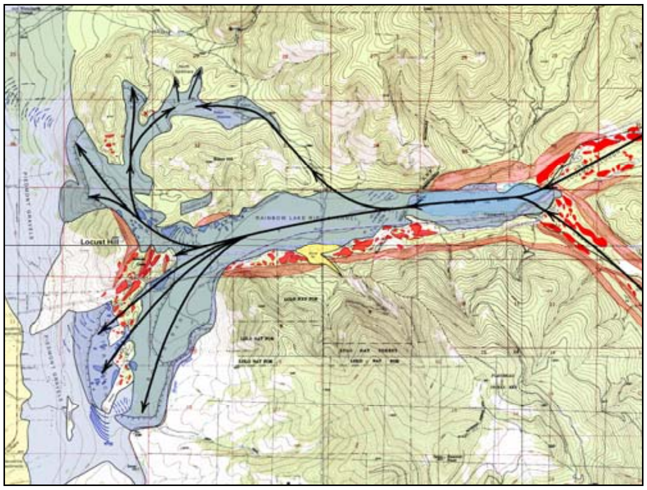

Figure 31—Main currents in the Rainbow Lake outlet system. Currents from Camas Prairie converged at Rainbow Lake to cut the Rainbow Lake rip channel. Locust Hill split this current. Red, erosion features; blue, flood deposits.

Figure 32—View northeast of the steep front of Boyer expansion bar. Roadcut exposes crude foresets and suspended kolk-derived blocks [inset].

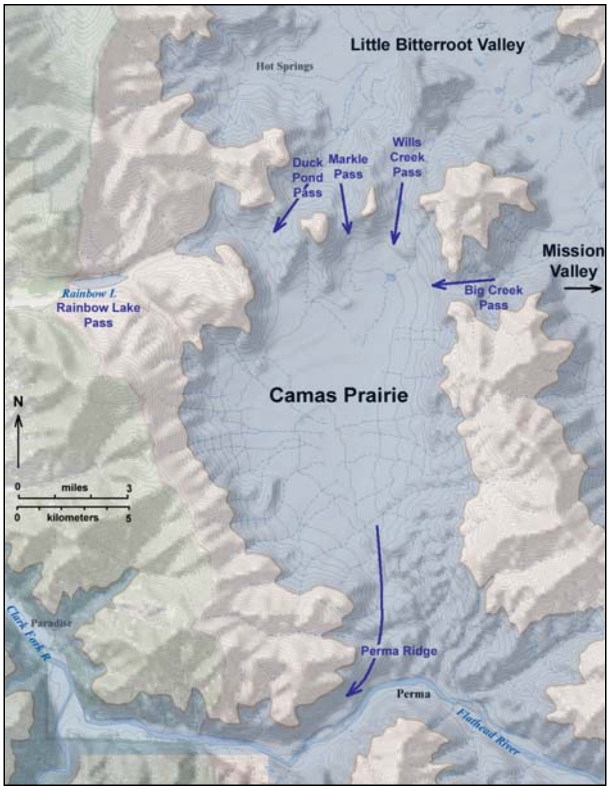

Figure 33—When Lake Missoula lake level dropped to 3650 ft elevation, all flow turned south through Camas Prairie to rip across Perma Ridge, while flow into the basin concentrated in four sublake notches.

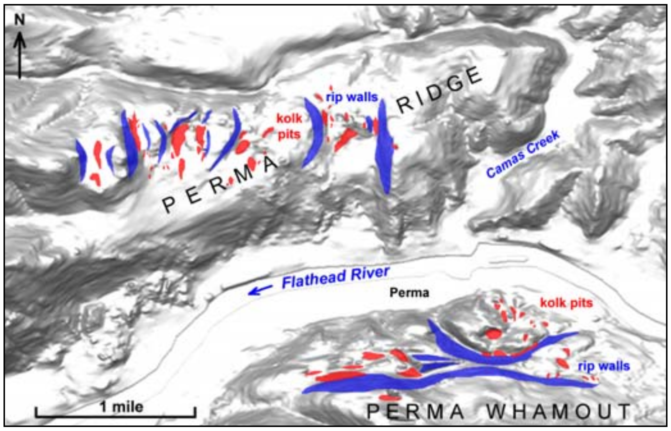

Figure 34— Catastrophic flood features in the Perma area.

Figure 35—View to south of rip walls on Perma Ridge.

Flood currents crossing Perma Ridge slammed into the Perma whamout, a severely impacted area on the far wall of the Flathead Valley [Fig. 34]. The most obvious features of the Perma whamout are the long, high [200 ft, 60 m] rip wall with numerous kolks and a lower semicircular rip wall with a 50-ft deep [15 m], circular kolk lake in the middle [Fig. 36].

Because Camas Prairie Basin is ringed by mountains on all sides except to the south, floodwaters coming into the basin from Mission and Little Bitterroot Valleys were forced through four narrow passages [Fig. 33]. Each of these passages was formerly, and is currently, a topographic pass through the mountains, but when under Lake Missoula they were unusual features, here called sublake notches. At this time, all of the lake-bottom currents were flowing uphill to enter Camas

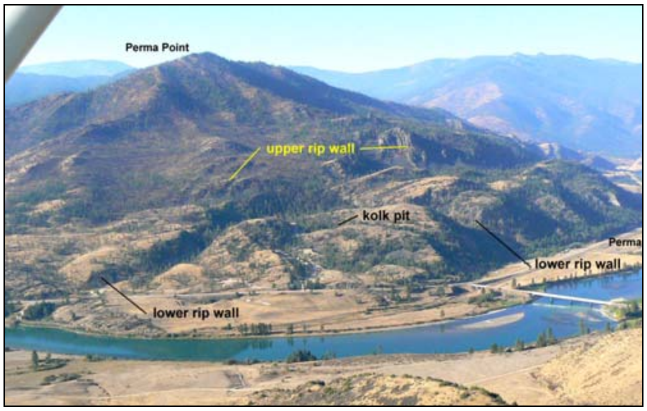

Figure 36—View south across the Flathead River to the Perma whamout area.

Prairie Basin, transporting bedload gravels upslope and over the divide. This inflow became progressively more restricted as lake level fell, with lake-bottom topography forcing flow to concentrate in the four sublake notches. The notches experienced unique, catastrophic currents that produced unique flood features [Fig. 37]. Figure 38 is a conceptual model of the landforms that developed from these unusual currents, and Figure 39 shows an aerial view of two notches.

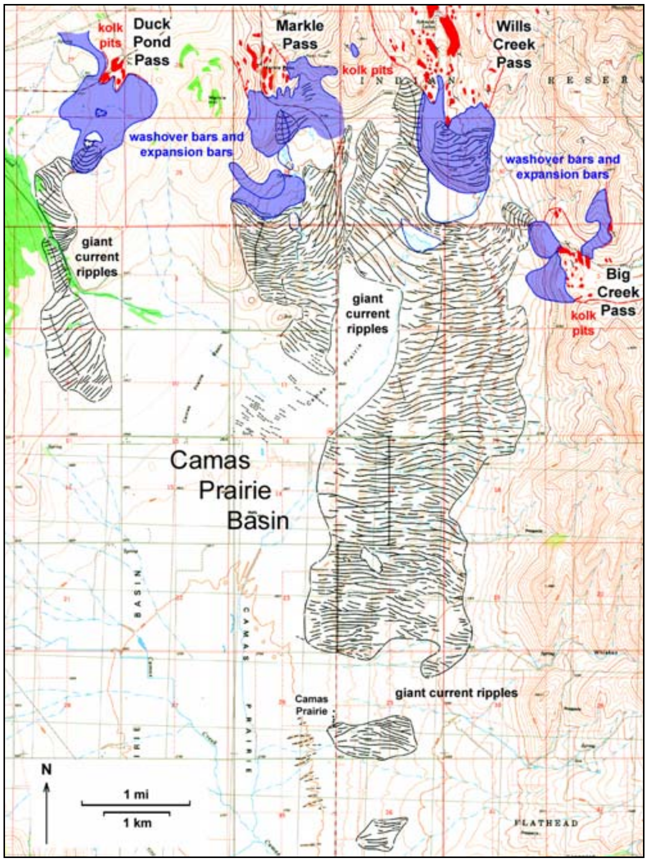

Figure 37—Catastrophic flood features of Camas Prairie Basin.

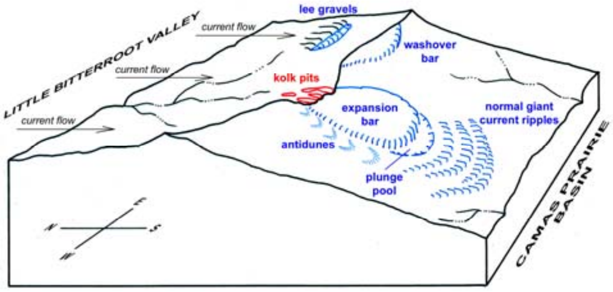

Figure 38—Generalized model of an inflow sublake notch.

Blocks of bedrock were torn out by kolks in each sublake notch, producing jagged bedrock floors in rip channels bounded by steep walls [Fig. 40]. This was truly catastrophic erosion, with billions of cubic feet of rock ripped out in what must have been a matter of hours. Most of this rock was deposited below each of the sublake notches in expansion bars [Figs. 41 and 42].

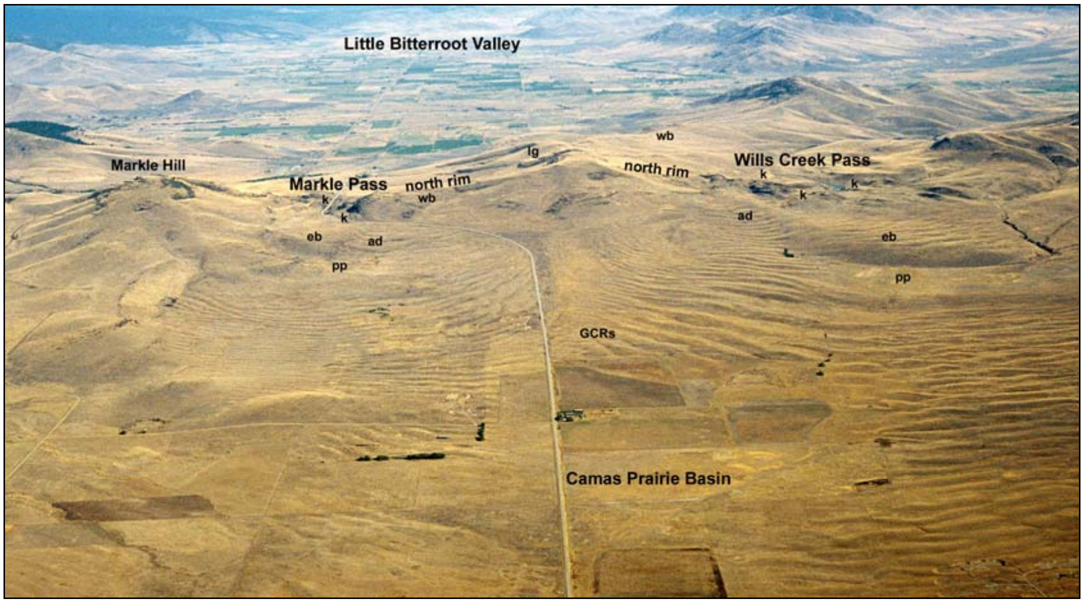

Figure 39–Aerial view to north of north rim of Camas Prairie Basin showing two sublake notches. ad, antidunes;eb, expansion bar; GCRs, giant current ripples; k, kolk pits; lg, lee gravels; pp, 'plunge pool'; wb, washover bar.

Figure 40—Kolk pit at Markle Pass.

Figure 41—Expansion bar deposited below Markle Pass.

Below the expansion bars, trains of giant current ripples [GCRs] stretch for about six miles to the south across the Camas Prairie [Fig. 43] and cover approximately 10 square miles [26 km^2] [Fig. 37]. These current ripples are hundreds of feet [tens of meters] to more than a half-mile [one km] long. In plan view they are convex downcurrent with central axes of ripple fields emanating from the sublake notches. The size of GCRs generally decreases away from the notches, and constituent gravels similarly decrease in size to the south.

Geologists classify these GCRs as large-to-very large, two-dimensional, flow transverse, sinuous, in-phase, subaqueous gravel dunes. This means the ripples are big, have very long repetitive shapes, formed perpendicular to the current, are sinuous in map view, are more-or-less parallel to each other, formed under water, and consist of sediments coarser than sand.

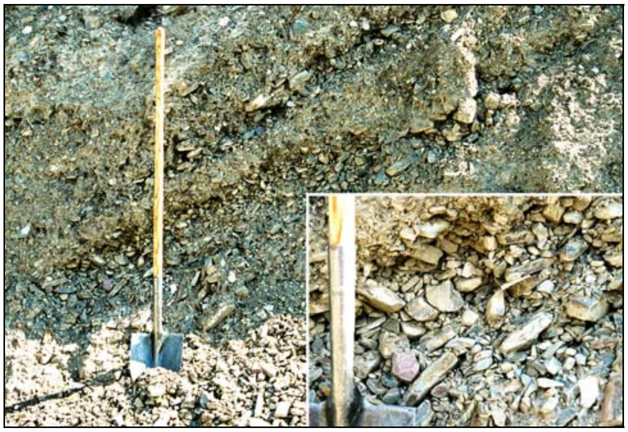

Figure 42—Gravels in expansion bar show crude foreset beds dipping 29°. Note open-work cobble-pebble gravel.

Figure 43—Giant current ripples in Camas Prairie Basin.

Giant current ripple wavelengths [distance from trough to trough] range from 90 to 951 ft [27-290 m] with a mean of 270 ft [82 m], and heights range from 1 to 57 ft [0.3-17 m] with a mean of 12 ft [3.7 m][Lee, 2009]. Most GCRs are asymmetric, with shorter, steeper sides on the lee slope, similar to sand dunes. Figure 44 shows profiles across several different trains of GCRs. Below each sublake notch is a single train of antidunes, which are notably asymmetric, with steeper upcurrent sides and with short, arcuate, convex-downcurrent shapes.

Giant current ripples at Camas Prairie are significantly different from normal ripples [like the ones seen on sandy stream bottoms] in more than just size. They show close correspondence to GCRs created by the Missoula flood below the ice dam in the scablands of eastern Washington [Fig. 45], even though they formed in different hydraulic regimes. Even more closely analogous, they are similar to GCRs formed on the floor of Lake Kuray-Chuya by the Altai flood in Siberia [Fig. 45]. In fact, these landforms created by catastrophic sublake currents have been described only in Camas Prairie and in Siberia [Baker and others, 1993; Rudoy, 2002; Carling and others, 2002; Lee, 2004; Herget, 2005].

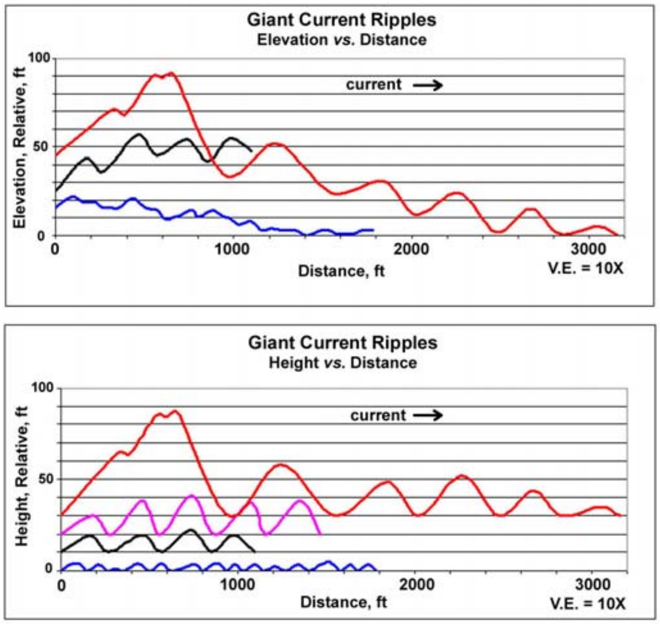

Figure 44—Profiles of giant current ripples from several different ripple trains. Lower profiles corrected for slope.

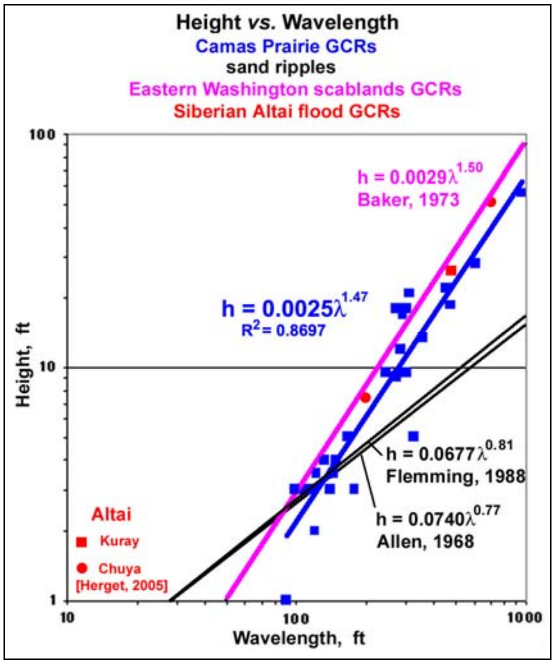

Figure 45—Height-wavelength relationship for giant current ripples at Camas Prairie is significantly different from sand ripples, but similar to GCRs in the scablands of eastern Washington and in Siberia.

The flood features at Camas Prairie document catastrophic sublake currents that have been described only here and in Siberia.

THE MISSOULA FLOOD BELOW THE ICE DAM

Rathdrum Prairie and Spokane

When the ice dam at Green Monarch Ridge on Lake Pend Oreille failed, the lower Clark Fork River Valley below the dam was still filled with glacial ice. The catastrophic wall of water that escaped from Lake Missoula tore over the low divide between the Clark Fork River and the Spokane River and headed down the broad, flat Rathdrum Prairie [see Fig. 3].

Within three minutes of the dam failure, velocities in Rathdrum Prairie would have reached 76 mph [129 kph] and increasing, 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 443 to 571 ft [135 to 174 m], a valley width of 3½ miles [6 km], and a slope of 0.01, velocities were calculated to be from 56 – 100 mph [90 - 161 kph], with a power of 200,000 W/m^2, and a minimum discharge of 600 million cfs [17 million m^3/s] [Fig. 46]. These were 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; Fig.47].

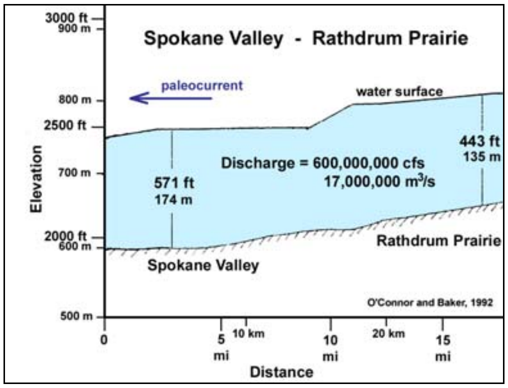

Figure 46—Flood discharge calculated from the longitudinal profile down the Rathdrum Prairie.

Cheney - Palouse Scablands

Much of the floodwater surged out onto low rolling hills of Palouse Loess, a geologic term for deposits of wind-blown dust. Prior to the Missoula Flood, a mantle of loess several hundred feet thick covered the basalt bedrock of the Columbia Plateau. In this semiarid climate, loess develops a fertile mollisol soil favored by wheat farmers. Where flood waters had stripped away the loess down to black basalt, the resulting barren areas were referred to by early farmers as *scablands*.

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. 47], and the extent of anastomosing channels across the plateau demonstrates to any casual observer the full scale of the Missoula flood. If satellites were available 80 years ago, J Harlan Bretz would have had an easy time of it!

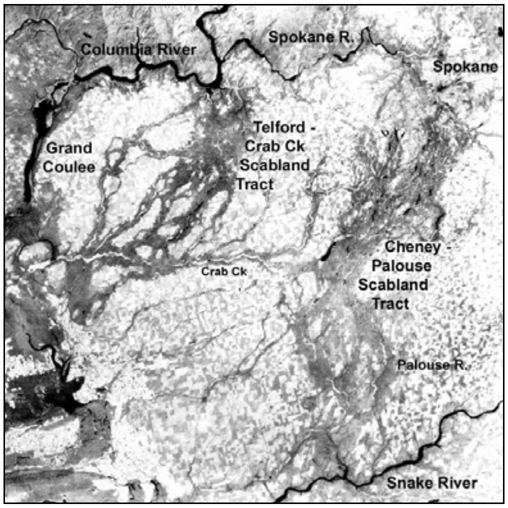

Figure 47—Dark basalt scablands of eastern Washington show clearly where the lighter Palouse Loess was stripped away by the Missoula Flood. Landsat MSS image.

Most of the flood headed directly southwest toward the Palouse River, but the floodwaters surged right across the Palouse River Valley and up 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.

Floodwaters crossing the divide cut new channels and created an immense cataract at the Snake River Canyon that quickly eroded back several miles to its present location at the picturesque Palouse Falls [Fig. 48]. 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!"

Flood debris was deposited primarily as streamlined 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. 49]. They may be several kilometers long and up to 100 ft [30 m] high, and where exposed they show well sorted foreset gravels [Fig. 50].

Figure 48—Palouse Falls at a huge plunge pool cut by flood-waters 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.

Giant current ripples formed at depth by foreset deposition of gravels. About sixty trains of giant current ripples have been recognized below the ice dam; from measurements of 40 ripple trains (Baker, 1973):

the number of GCRs varies from 3 to 60,
mean heights 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:

$h = 0.0029\,\lambda^{1.5}$ where h is height and λ is wavelength.
[GCRs at Camas Prairie are very similar].

Figure 49—Pendant bar with giant current ripples just below the confluence of the Palouse River with the Snake River.

Figure 50—Fore-sets of open-work cobbles in pendant bar dip 26°.

Grand Coulee

With the Okanogan glacier blocking the Columbia River near the present Grand Coulee Dam, Lake Columbia was draining into Grand Coulee [see Fig. 3]. When the Missoula flood hit the lake, about a quarter of the flood 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. The flood through Grand Coulee was about 260 ft [80 m] deep, and it carved Dry Falls [see Frontispiece]. 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. 51].

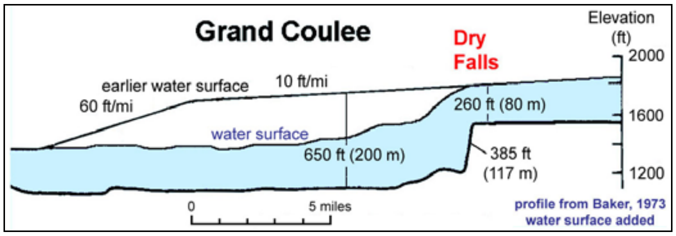

Figure 51—Dry Falls in the Grand Coulee floodway. The falls would have been more like a giant cataract.

Dry Falls today represents the position of the cataract at the terminal stage of flood erosion in the Grand Coulee. Previous positions were farther south, and headward erosion caused the escarpment to retreat to the north. As Figure 52 shows, Dry Falls is actually several miles wide; the view seen from the overlook [Frontispiece] is only a small part of the entire cataract.

Wallula Gap and the Columbia River Gorge

All of the Missoula flood routes converged just above Wallula Gap [see Fig.4]. Wallula Gap [Fig. 53] 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 total flood discharge, so it created a hydraulic dam that ponded the floodwaters into a vast ephemeral lake, called Lake Lewis.

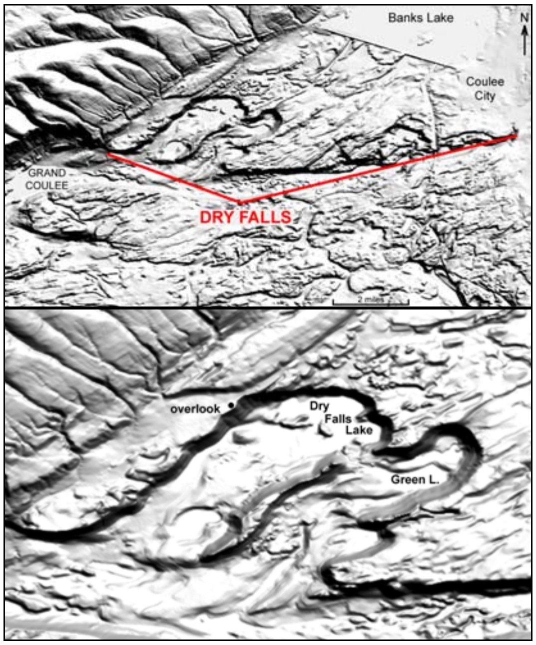

Figure 52—Topography of Grand Coulee around Dry Falls cataract.

Figure 53—Mile-wide Wallula Gap was unable to transmit the Missoula Flood, forming a hydraulic dam that backed up floodwaters for more than a week; view downstream.

Maximum discharge through Wallula Gap was about 10 million m^3/s, with a velocity of 56 mph [90 kph] and a power of about 100,000 W/m^2 [O'Connor and Baker, 1992]. It probably took more than a week for these waters to drain through Wallula Gap.

The narrow Columbia River Gorge above Spokane similarly created a hydraulic dam that ponded Lake Condon at the upstream end {Fig. 4]. Flood depths were about 900 ft [270 m] through the Gorge [Fig. 54] as discharge reached 10 million m^3/s, about the same as through Wallula Gap. Peak velocity in the constrictions of the Gorge reached 78 mph [126 kph]] [Benito and O'Connor, 2003].

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. 55].

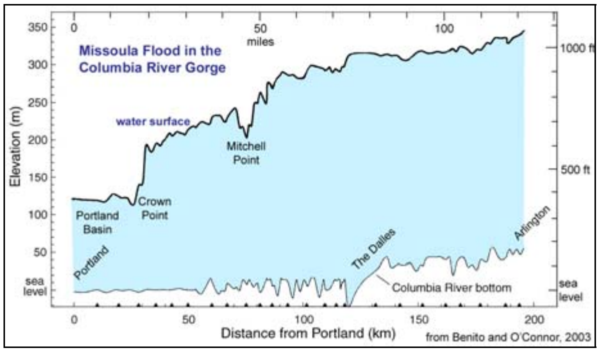

Figure 54—Flood profile through the Columbia River Gorge. Water was about 900 ft [270 m] deep through most of the Gorge and velocities reached 78 mph [126 kph].

Portland to the Pacific Ocean

Floodwaters shot out of the mouth of the Columbia Gorge as a wall of water 400 ft [120 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 the Columbia River to the Kalama Narrows, where another hydraulic dam ponded waters back up into the Willamette Valley, forming Lake Willamette [Fig. 4; aka Lake Allison]. Much of the loess scoured from the Washington scablands was deposited in the lake, contributing to Oregon's fertile farmland valley. The shores of Lake Willamette extended as far south as Eugene and are marked by numerous iceberg-rafted erratics.

Two ice-rafted flood erratics in the Willamette Valley are particularly interesting. The Bellevue Erratic [Fig. 56] is a large block of Belt metamorphic rock 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 tonnes]. It would have taken a very large iceberg to carry this from Montana! The Willamette Meteorite, found nearby among other flood debris, most likely fell on the Cordilleran ice sheet in Canada, was carried to the damsite in the glacier, and was likewise ice-rafted to the Willamette Valley in the Missoula flood. Thus the largest meteorite ever found in the U.S.A. may be just another Canadian import.

Floodwaters continued past Astoria on the present coast out to the margin of the glacial continent, where they dumped sediment into the Pacific Ocean. Discharge was so great, and so much sediment was entrained in the floodwaters, that turbidity currents were generated that carried flood debris along the seafloor for 700 miles [1100 km], crossing the Gorda submarine ridge and flowing up into the rift valley [Fig. 57]. A turbidite sand bed in the rift valley, deposited nearly instantaneously, is 190 ft [60 m] thick with a volume estimated at 20 cubic *miles* [84 km^3] of sand [Zuffa and others, 2000]!

Figure 55—Multnomah Falls in the Columbia River Gorge was created when floodwaters incised the main canyon.

Figure 56—The Bellevue Erratic in the Willamette Valley, OR. The 160-ton block of Belt argillite was rafted across four states in a huge chunk of glacier torn from the ice dam.

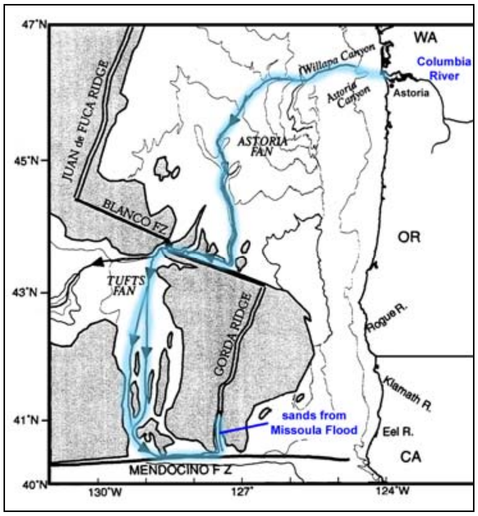

Figure 57—Floodwaters and entrained sediments created turbid currents that swept across the Pacific Ocean floor for 700 miles [1100 km][Zuffa and others, 2000].

MULTIPLE MISSOULA FLOODS

Lake Missoula filled many times and emptied catastrophically in many Missoula Floods. Rhythmite sequences [a series of repeated beds of similar origin] at numerous localities provide this evidence: slack-water rhythmites in backflooded tributary valleys below the dam indicate multiple floods, and varved rhythmites in Lake Missoula attest to multiple fillings of the lake.

Below the dam, most slack-water rhythmites are graded beds deposited by flood bores surging up tributary streams. They grade upward from coarse sand and gravel to silt, with occasional ice-rafted erratics [Figs. 58, 59]. The tops of some rhythmites are marked by thin paleosols, or buried soil horizons, which indicate a period of subaerial exposure. Thus, each rhythmite represents a separate flood event, and each deposit records multiple floods.

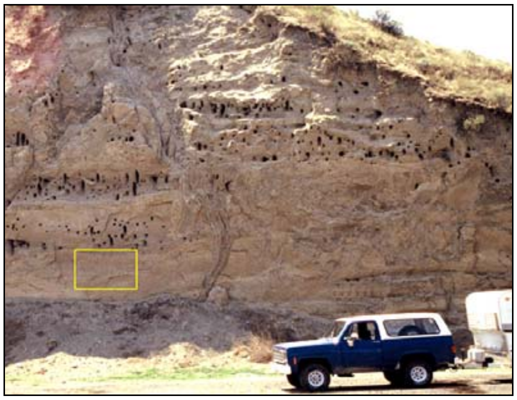

Figure 58—Slackwater rhythmites [Touchet Fm.] at Lowden, WA. About 11 rhythmites exposed here. Rectangle shows area of Figure 59.

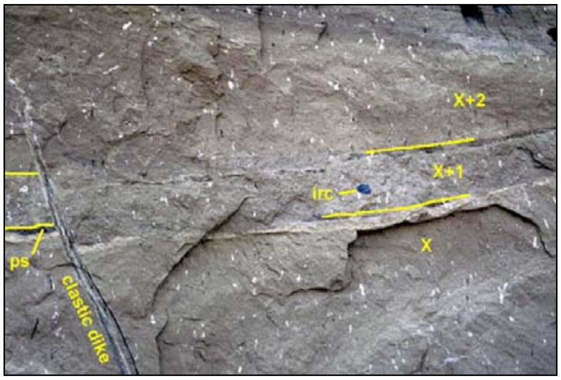

Figure 59—Three sand-silt graded beds offset at a clastic dike [infilled dessication crack]. Bottom two beds show weathered tops with thin paleosol [ps]. Ice-rafted cobble [irc] of Belt metaquartzite shows glacial faceting.

The most complete record occurs at Sanpoil Valley [Atwater, 1986], an embayment on the north side of Lake Columbia, where varved rhythmites document 89 flood events, with the period of time between floods initially increasing to a maximum of about 50 years and then decreasing to less than 10 years [Fig. 60].

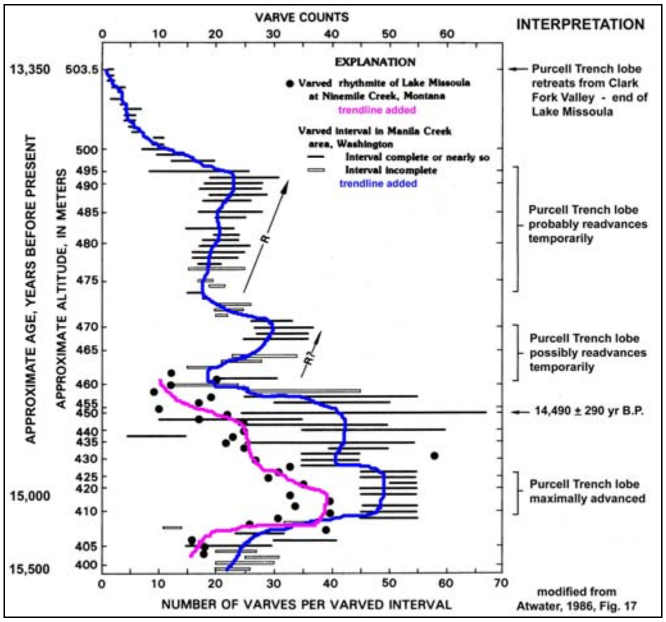

Figure 60—Slackwater rhythmites in Sanpoil Valley indicate about 89 different Missoula Floods. Earlier floods were separated by 20-30 years, the intervals then increased to a maximum of about 50-60 years, after which floods became more frequent [and presumably smaller].

Thousands of varves were deposited in Lake Missoula. At the best-known Ninemile locality near Missoula, about 40 rhythmites consist of varves overlain by a sand/silt layer [Figs. 61, 62]. The varves were deposited on the floor of Lake Missoula, and the sand/silt layers represent subaerial exposure and deposition in a stream. The number of varves in each rhythmite varies from 9 to 40, decreasing regularly upward, and the total number of varves is just less than one thousand.

An interpretation of these data would suggest: [1] Lake Missoula filled and emptied [in a catastrophic flood] about 40 times, [2] it took 9 to 40 years to fill the lake, each successive lake requiring less time, and [3] the process was repeated over a period of about one thousand years. Because Ninemile is about in the middle of the very long lake, the record here would not provide a complete history of the lake. Correlating Ninemile with the downstream record would suggest these events were in the latter half of the entire flood history.

Figure 61—Lake Missoula rhythmite sequence at Ninemile, MT. Each rhythmite consists of alternating fluvial silts [light color] and varves [dark]. About 26 rhythmites here appear to thin upward.

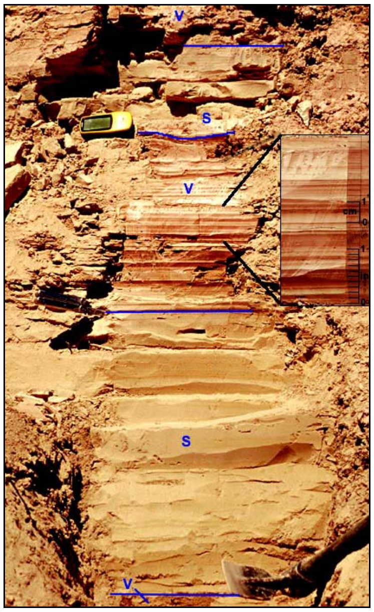

Figure 62—About 38 varves [v] in the middle rhythmite are bounded by lighter silts [s].

Putting these observations together suggests there were scores of Missoula Floods and Lakes Missoula. Early lakes and floods were relatively 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 relatively small because the thin distal lobe of the initial glacier dammed little water before the dam failed [Fig. 63, stage 1]. 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. 63, stage 2].

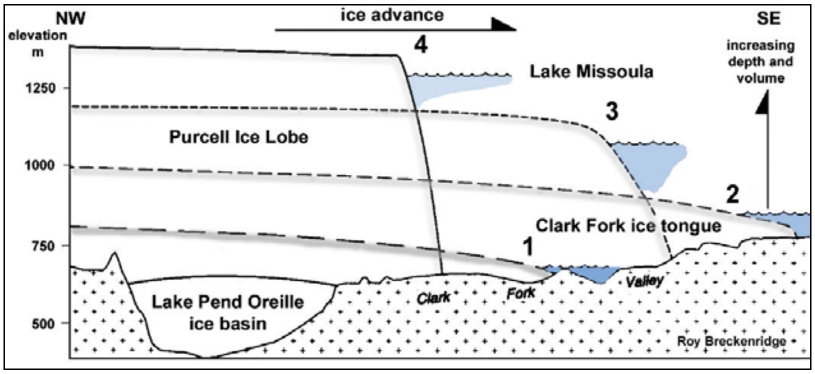

Figure 63—Successive Purcell glacier advances would have dammed successively larger Lakes Missoula.

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

AGE OF MISSOULA FLOODS

The age of the Missoula floods is not well constrained. If there were early Pleistocene floods, no direct evidence remains. Slack-water rhythmite studies indicate a range for the floods from about 15,500 years ago to about 13,500 years ago [Waite and Atwater, 1989]. The turbidite sands in the Pacific Ocean range in age from 16,000 to 11,000 years, with the large, single-flood sand dated at 15,600 years ago [Zuffa and others, 2000]. Study of flood gravels in the Columbia River Gorge indicate all flooding was less than 19,000 years ago, and many floods occurred more recently than 13,000 years ago [Benito and O'Connor, 2003].

All indications are that Missoula floods occurred between 11,000 and 19,000 years ago. The largest Missoula flood probably tore across Montana, Idaho, Washington, and Oregon about 15,000 years ago.

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