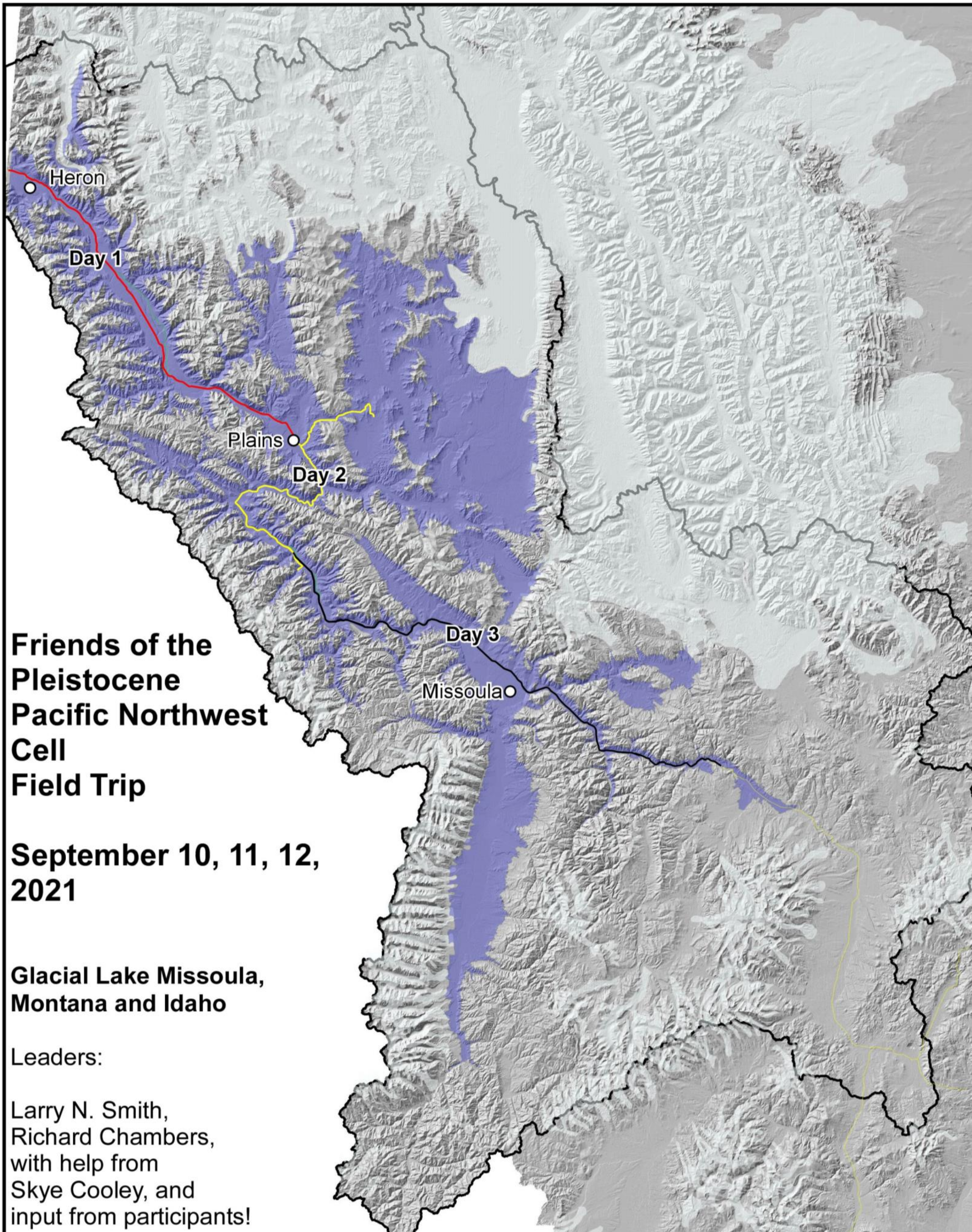

Friends of the Pleistocene Pacific Northwest Cell Field Trip

September 10, 11, 12, 2021

Glacial Lake Missoula, Montana and Idaho

Leaders:

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Richard Chambers,
with help from
Skye Cooley, and
input from participants!

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Where other guidebooks were directly quoted (or nearly so), that text is shown as single-spaced in the road logs.

December 2021 ver 1.1

Introduction

- Joseph T. Pardee (1910, 1942) described many features and relationships in the stratigraphy of Lake Missoula sediments and geomorphology of its landforms that have stood the test of time. His papers are important to read.
- The highest stand of the glacial lake has commonly been stated as 4,200 ft (1,280 m), however the highest strandline found is at about 4,250 ft (1,295 m) on Mt. Jumbo, just north of Hellgate Canyon in Missoula.
    - The inability to account for tilting in the former lake basin due to isostatic loading of the crust by the ice sheets and the lake itself complicates assignment basin-wide lake levels.
    - As detailed elevation data are currently being acquired (LIDAR), the imminent release of that imagery and data may allow lake basin-wide mapping of strandlines, which has not yet been possible.
- At its highest stand, the lake covered about 10-11,000 km^2 (3,860–4,250 mi^2).
    - A 3-day field trip cannot cover all lake subbasins and many features.
- The leaders of this trip do not have all the answers – much information on this trip is being presented to invite discussions.

Pacific NW cell FOP – Glacial Lake Missoula Field Guide Sept. 2021

Day 1: Friday, 10 September – Ice dam(s)

We will travel west along HWY 200 from Paradise, MT to the MT/ID border and work our way back. Along the way to Idaho, this guide points out a few features, but detailed mapping of Quaternary deposits in most of the area is not available.

The focus of today is to examine glacial deposits, their history, and glaciolacustrine deposits ("Lake Missoula beds" of Langton, 1935) within ice dam region, first described by Pardee (1910). We will discuss evidence for several terminal Purcell Lobe ice dam positions for the lake impoundment; gravelly alluvium likely deposited during lake draining events; Eddy Narrows site of Pardee's discharge calculations; and the preservation of glaciolacustrine deposits along the region, including at Heron, MT (near a late ice-dam position).

Miles *(approximate*- derived from Google maps, not a car)

0 – intersection of Willis Street & Hwy 200 in Plains. As the valley opens into Plains, extensive glaciolacustrine deposits are preserved NE and SW of the Clark Fork River. Pardee (1942) noted that gravel bars formed during high-velocity lake drainages are overlain by glaciolacustrine sediments, indicating that multiple, later lake stands drained more slowly than an earlier one(s). The "Plains loop" guide included after the Day 2 guide may be used at some point.

7.5 – Entering the Eddy narrows gorge where Pardee (1942, p. 1597) made the first lake drainage flow velocity calculations of 52-78 ft/s (35 to 53 mi/hr).

14 – Community of Eddy. Note glaciolacustrine sediments over gravel in roadcuts between here and Bull River Campground.

64.7 – Bull River Campground – The Bull River is a tributary from the north, along which a tongue of the Cordilleran Ice Sheet (CIS) flowed to near here. We'll get an overview of this later.

74.5 – Just east of Blue Creek, we cannot stop here due to parking limitations. Roadcut to west on right has a good exposure of a large clast gravel deposit overlain by ~1.5 m of glaciolacustrine deposits (at ~731 m elevation). 12 silt-clay couplets were counted beneath weathered deposits. OSL age from sand at the base of glaciolacustrine sequence (Fig. 1; Welk, 2019). The age from blue-light stimulation of quartz is 17.6±2.2 ka (USU-2129). This age is interpreted to be older than lake transgression due to the likely incorporation of older sand from the underlying deposit.

Figure 1. Blue Creek Road section OSL sample taken at the contact between sandy silt and sandy gravel (~730 m).

75.8 – ID/MT border - look for turnoff to Cabinet Gorge overlook.
76.1 – Turn left onto small road to Cabinet Gorge Dam Overlook – Park in parking lot near overlook at about 76.7 miles.

STOP 1-1 – Canyon Overview at Cabinet Gorge Dam Overlook

Location: 48.087170°, -116.059513°; elev. 2,280 ft (~695 m), CFR 2,073 ft (~632 m)

Description slightly modified from Smyers and Breckenridge (2003) and Breckenridge (2004)
"Cabinet Gorge dam on the Clark Fork River was completed in 1952 by Washington Water Power Company now AVISTA. The 600-footlong and 200-foot-high true arch dam is constructed in the 1.4 Ga Libby Formation of the Precambrian Belt Supergroup. This dam, in coordination with the Albeni Falls dam downstream, controls the water level of Pend Oreille Lake, normally 2062 feet. The prominent terrace south of the river is mostly Missoula Flood deposits but logs from monitor wells drilled in 1952 by WWP show cycles of clay till and interbedded lake deposits indicating multiple episodes of ice damming (H.T Stearns, oral communication, 1986).

Glacial erosion as well as till deposits indicative of an ice margin are found in this area, so many geologists have shown the ice lobe terminus near here. The bedrock bench on the north side of the valley has abundant till cover, interpreted to be ice-marginal deposits, possibly flood drainage was diverted to the south side of the valley by the ice from the north, at least in the waning stages of smaller late floods. The bench may represent the edge of the ice dam failure or the margin of subglacial flow. Just to the north, ice flowed through cols as high as 6000 feet in elevation across the Cabinet Mountains between the Bull River and the Purcell Trench.
… Old photographs of the lower Clark Fork valley reveal spectacular shorelines along the valley directly south of Cabinet Gorge perhaps as high as 4260 feet." (1298 m)

"Immediately east of Clark Fork, ID, large glacial grooves and ice striations can be seen along the road in the Wallace and Striped Peak formations. This is a very hazardous site to visit due to highway traffic, a drive-by is recommended. … The glaciated surfaces are preserved best when they are covered and protected by post-glacial talus. Unprotected scoured surfaces of the Precambrian Belt Supergroup quickly fracture and weather losing their evidence for glaciation."

76.1 – Return to Hwy 200
76.7 – Turn right to return to Montana, look for small sign on right for Heron, MT
80.7 – Turn right, cross reservoir and railroad tracks
82.1 – Turn left onto Harker Rd.
82.4 – Turn right onto Clark Fork Rd.
87.7 – Turn left onto Dry Creek Rd.
88.7 – **STOP 2 -** Dry Creek gravel pit, Idaho

Stop 1-2 - Dry Creek Gravel Pit

Location: 48.062765°, -116.092601°; 2,503 ft (763 m)

Of the gravel pits that Roy Breckenridge (Idaho Geological Survey, deceased) noted in multiple field guides, this gravel pit is the best preserved (Fig. 2). The main points here is to inspect:

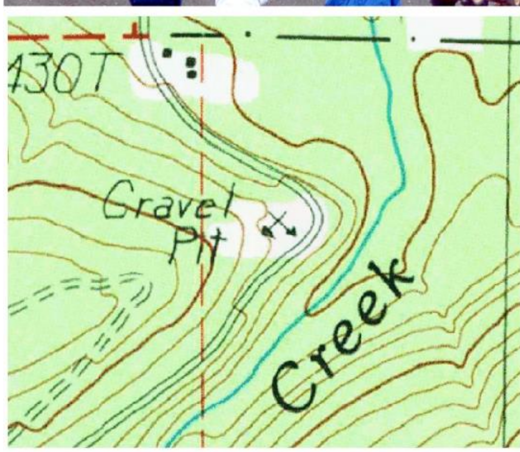
- Bedding and cross bedding orientations
- Clast lithologies and angularity
- Multiple hypotheses on the origin of these sediments.

Description modified from Breckenridge (2004)

"Foreset beds in the Dry Creek Pit - This site exposes a section deposited at the mouth of Dry Creek with the Clark Fork valley. The pit is at an elevation of 2680 feet [817 m] over 400 feet [120 m] above the present floor of the valley. The foresets are tens of feet high and dip *upriver* to the east. The clasts are poorly rounded, and some cobbles are striated. Although most of the clasts are of Precambrian Belt metasediments derived locally, some are from granite and diorite (Purcell sills) from rocks exposed in the Purcell Trench. The granules are cemented, and the pit walls must be ripped before the aggregate can be excavated. This gravel probably was deposited in latest-glacial time from the ice margin into Lake Missoula in the form of a pro-glacial delta. It is not to be confused with the so-called gulch fills or eddy bars of Pardee that formed in the side-valleys during Missoula Floods. Most of the drainages on the south side of the Clark Fork valley from Lake Pend Oreille upstream to nearly Thompson Falls contain these features. Thus, late glacial ice advanced upstream much farther than had been previously recognized. Furthermore, late phases of glacial Lake Missoula associated with this ice dam drained quiescently enough to leave the deposits preserved."

Cursory measurements I made of crossbed orientations show NW, E, and SE paleocurrent directions, suggesting a generally eastward transport direction.

Stereo pair of SW side of Dry Creek gravel pit in 2004



Roy Breckenridge (with arms outstretched) explaining how foresets are oriented to SE - away from the ice dam.

Figure 2. Photographs of Dry Creek gravel pit from a field trip with Roy Breckenridge in 2004. Topographic map shows an approximate outline of the pit.

95.0 – Return to Harker Rd, turn right towards Heron
96.1 – Turn right onto Elk Cr Rd.
97.1 – **STOP 3** Pull off on right side of road near curve to SW

STOP 1-3 - Elk Road Section

Location: 48.048275°, -115.967205°; 2,438 ft (743 m)

This ~9 m section of glaciolacustrine sediments was studied in detail by Welk (2019). The location is near the northern edge of glaciolacustrine sediments that were incised along a terrace on the north (Figs. 3 and 4). Glaciolacustrine sediments were found in excavations along Elk Creek Road from this location east to where the road turns to the north. The total thickness of the glaciolacustrine sediments here is unknown. Interpretation of water well logs suggests these sediments range in thickness up to 46 m (150 ft) with the thickest accumulations in valleys between gravel-cored bars ("Qgfl" in Fig. 3).

Welk (2019) described this section as consisting of rhythmically bedded sequences of sand, silt, and clay (Fig. 5). She described 12 rhythmites including basal sandy silt facies, each overlying a sharp, erosional contact. The basal facies grades upward into a silt-clay facies of microlaminated silt and clay. She notes soft-sediment deformation, both load and dewatering structures, and small normal faults; some sandy units are crossbedded.

One optical luminescence sample was collected in one of the sandy units and analyzed at the Utah State University Luminescence Lab. Because the quartz signal was dim and was interpreted to underestimate the burial age, a fading-corrected age from infrared stimulated luminescence (IRSL) of K-feldspar showed an age of 16.02 ± 1.08 ka (USU-2128) (Fig. 6).

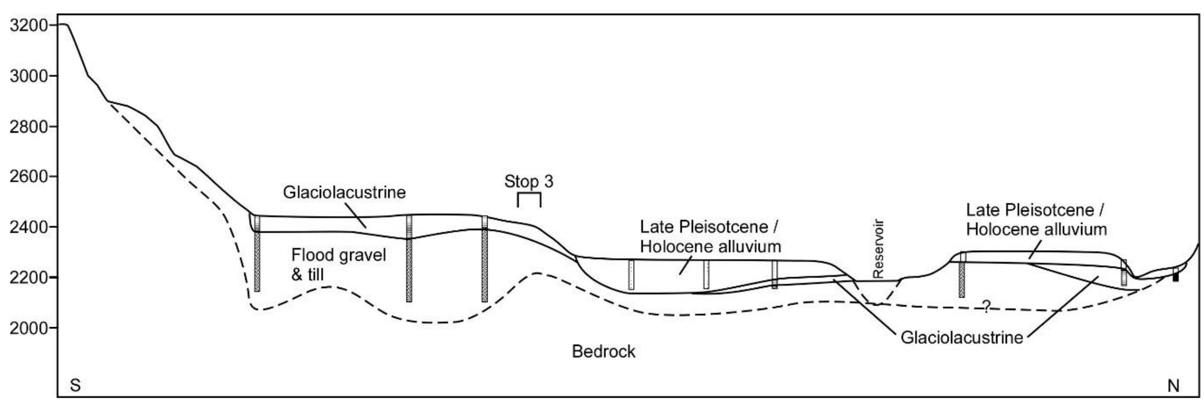


Figure 3. Cross section across Clark Fork River valley near Stop 3 from water well logs (vertical boxes) and geologic mapping of Welk (2019). The depths to bedrock are inferred from wells near to the cross section. It is possible that other glaciolacustrine sediments are included in the "Flood gravel & till" unit, but correlations are not possible from these logs.

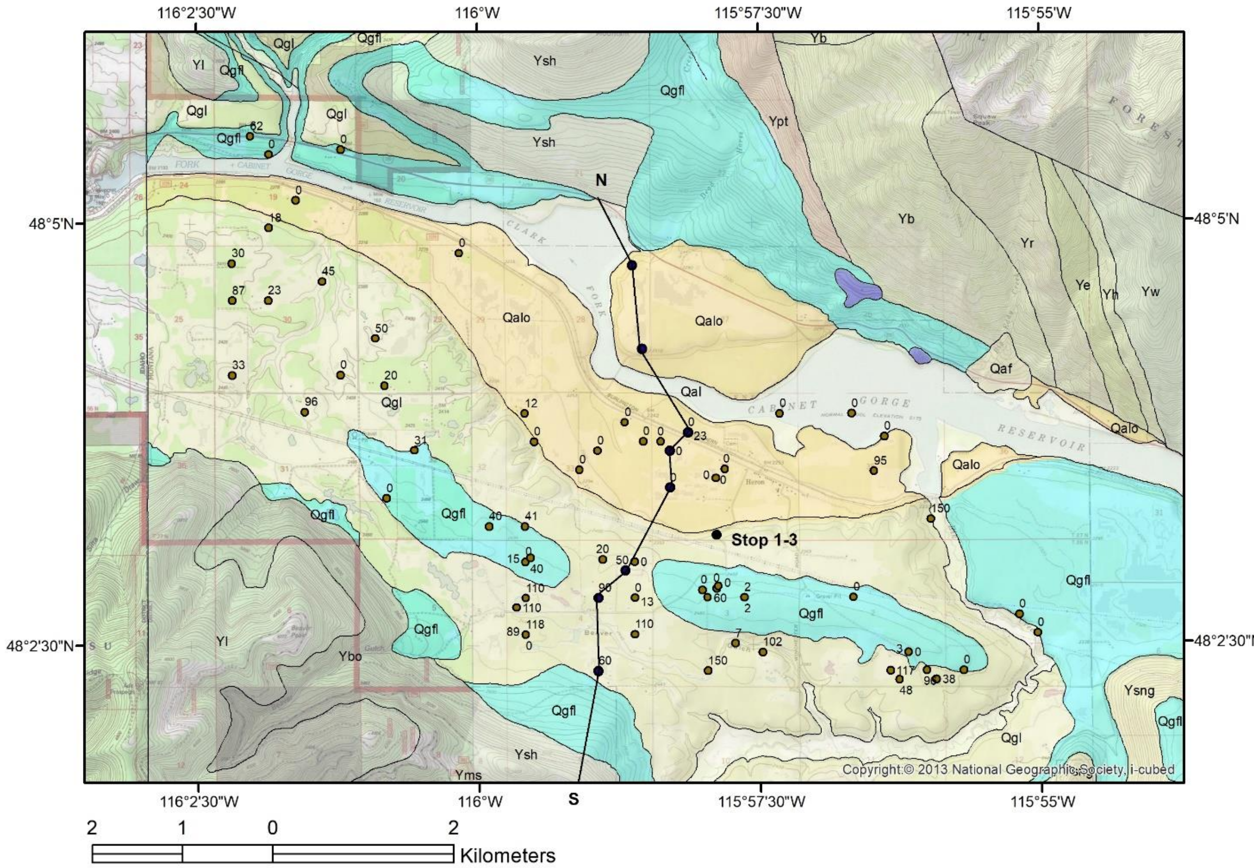


Figure 4. Geologic map of the Heron, MT area. Points show thicknesses of glaciolacustrine units interpreted from some water well logs. N-S line shows the location of the cross section in Figure 3. Glaciolacustrine (Qgl) over glacial flood deposits (Qgfl) in NW corner of map is the Blue Creek Road site of Figure 1. Geologic map modified from Welk (2019). Qalo-old alluvium; Qaf – alluvial fan; Yx – various formations of the Belt Supergroup.

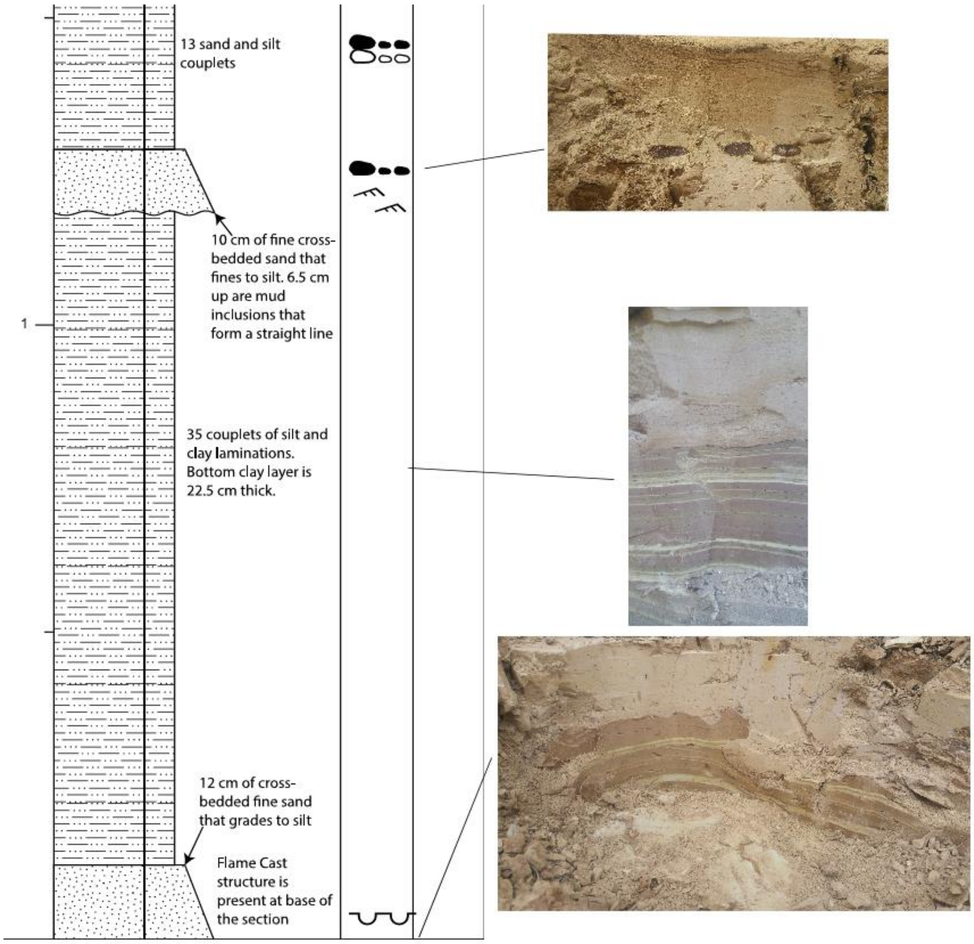


Figure 5. Simplified version of the lower 1.5 m of the Elk Creek section measured by Welk (2019). The lowest, and thickest, of the 12 rhythmites contains 35 silt and clay couplets (varves) above a crossbedded silty sand. The photographs show representative facies in the section (from Welk, 2019).

Figure 6. OSL sample from 3.7 m above the base of the Elk Creek Rd section. The end of the sample tube is above the hammer head. Dose rate sample was scraped from around the tube (from Welk, 2019).

The take-aways from this stop are:

1) Note how much fine-grained glaciolacustrine sediment is preserved so close to where the ice dam must have been.
2) Did failure of this late (or last?) ice dam result in only incising inner canyons along the Clark Fork River and very low-strength flow across most of the valley bottoms?
3) While the chronology of the glaciolacustrine sediments is poorly constrained, the date at the Elk Creek section overlaps that of Hanson et al. (2012), given the error bars, for the Ninemile section we will visit later.

Continue up Elk Creek Road. Note that you are traveling from glaciolacustrine deposits at Stop 3 onto an underlying gravel bar.
At the next intersection and turn, we can turn the caravan around.

97.5 – Turn around to return to Heron.
99.2 – Turn right on Upper River Road
100.0 – Gravel pits in Pleistocene “flood gravels” (Qgfl on Fig. 4); pebble to cobble sizes with a few outsized erratic boulders; Belt Supergroup and volcanic clasts; coarse sandy matrix around clasts; stratified bedding with large-scale crossbedding (Welk, 2019, appendix B). The topographic highs are gravel with glaciolacustrine deposits on both sides of the hills (Fig. 4).
100.5 – Continue on Upper River Road by veering to left
103.4 – Turn right onto Bartholomew Road
105.8 – Turn right to climb onto Smeads Bench for **STOP 4**
(no mileages) – Travel about 2 miles up switchbacks to a turnaround point near the top of the bench.

STOP 1-4a – Smeads Bench

The origin of Smeads Bench is not well constrained. Welk (2019) mapped a thin cover of glacial flood gravels across the top of the bench as she determined much of the hill is made up of Belt Supergroup bedrock (Fig. 7).

We have not mapped the deposits on the bench in detail. However, digging into roadcuts, it is likely that the bedrock is capped by till, which would be good evidence for advance of the Purcell Lobe to at least this position.

Return to the cars and stop about 1/3 mile from the turn around for an overview of the Clark Fork River Valley.

STOP 1-4b – Smeads Bench

Location: 48.018028°, -115.860633°; 2,740 ft (834 m)

The topography of the bench may be due to erosion by glaciation or catastrophic floods. However, the fact that the bench extends downstream (up-glacier) and ends abruptly upstream, argues against erosion by floodwaters.

This is the best view of the confluence of the Bull River with the Clark Fork River (NE). Note the forested hill NNW of the confluence, mapped as Qgfl (Fig. 7). This deposit was accurately mapped as Quaternary undifferentiated by previous workers (Harrison et al., 1992; Harrison and Cressman, 1993). This deposit is distinctive, as it has a topographic expression unlike other flood gravel deposits.

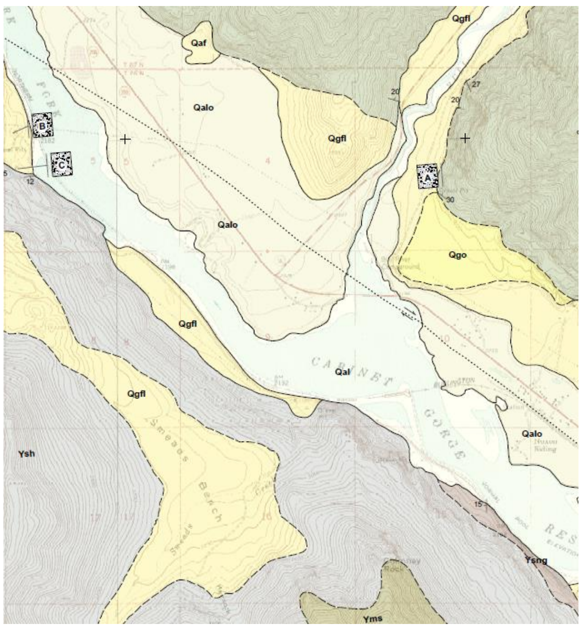


Figure 7. Geology of the Smeads Bench and confluence of the Bull River with the Clark Fork River. From Welk (2019).

Another interpretation is that it is a remnant of a terminal moraine of the Purcell Trench Lobe, marking an ice-dam position. More work needs to be done to find evidence of glacial transport of gravels.

RESET Trip Odometer to "0" Continue SE on Bartholomew (Railroad) Rd.
4.1 – Noxon, MT
4.7 – Turn left onto Klakken Rd
5.1 – Turn right onto Hwy 200
17.6 – Cross Clark Fork River
29.8 – Turn right onto Beaver Rd
32.0 – **STOP 5** Beaver Creek gravel pit

STOP 1-5 Beaver Creek Gravel Pit

Location: 47.714233°, -115.500939°; 2,590 ft (789 m)

This gravel pit is one of two upstream of the Dry Creek gravel pit that were highlighted by Roy Breckenridge as evidence for ice-dam positions (Breckenridge et al., 1989; Smyers and Breckenridge, 2003). Unfortunately, this pit and the nearby White Pine pit, have been severely excavated. Some outcrops of in-place gravels can be found to the north.

Description slightly modified from Smyers and Breckenridge (2003) and Breckenridge (2004): "This site exposes a section deposited at the mouth of Beaver Creek with the Clark Fork valley. The foresets are tens of feet high and dip *upriver* to the east. The clasts are poorly rounded, and some cobbles are striated. Although most of the clasts are of Precambrian Belt metasediments derived locally, some are from granite and diorite (Purcell sills) from rocks exposed in the Purcell Trench. The granules are cemented, and the pit walls must be ripped before the aggregate can be excavated. This gravel probably was deposited in latest glacial time from the ice margin into Lake Missoula in the form of a pro-glacial Gilbert-type delta. It is not to be confused with the so-called gulch fills or eddy bars of Pardee that formed in the side-valleys during Missoula Floods. Most of the drainages on the south side of the Clark Fork valley from Lake Pend Oreille upstream to nearly Thompson Falls contain these features. Thus, late glacial ice advanced upstream much farther than had been previously recognized. Furthermore, late phases of glacial Lake Missoula associated with this ice dam drained quiescently enough to leave the deposits preserved."

Take away from this stop:

1) It is now hard to evaluate whether these deposits represent flow away from an ice dam or eddy currents up Beaver Creek.
2) We must rely on other deposits at other locations to evaluate ice-dam positions.

34.2 – Return to Hwy 200 and turn right
70.0 – Plains, MT

Day 2: Saturday, 11 September – High-discharge sites along Flathead & Clark Fork Rivers and their tributaries

The focus of today is to visit classic lake drainage features including Markle Pass, Wills Creek Pass (Wilks Creek pass on today's maps – I do not know the history of the name), Camas Prairie, Rainbow (Dog) Lake, and the Clark Fork River from Paradise to Superior, MT, and possibly Tarkio at the end of today or the first stop tomorrow.

We hope to catch Markle and Wills Creek passes and the Camas Prairie dunes at early morning light; discuss flow velocities into Camas Prairie and Dog (Rainbow) Lake during lake-level lowering from near maximum levels, visit large imbricated boulders in canyon reach, and view eddy deposits in the St Regis, and Superior areas.

0 – Plains, MT – at Hwy 200 intersection with Willis St.
0.7 – Turn left onto Hwy 28
9.3 – We will visit Rainbow (Dog) Lake returning from Wills Creek Pass
17.0 – Turn right onto Hwy 382 towards Perma
18.5 – Markle Pass (present elev. 1,019 m [3,343 ft]). Note the scoured bedrock that formed as scabland during drainage of a high-stand glacial Lake Missoula southward through the pass.
18.8 – **STOP 1a** Pull off in overlook

STOP 2-1a – Markle Pass

Location: 47.545258°, -114.617737°; 3,315 ft (1,010 m)

This pull-off has one of the best views of dunes and expansion bars that formed during drainage from the Little Bitterroot Valley to the north into the Camas Prairie. Based a cross-valley profile, Lee (2009) estimated that the pass eroded about 60 m (200 ft) during flood discharge. So, the pass was possibly at about 1,070 m prior to catastrophic drainage events.

Return to Hwy 382, turn right
19.3 – Turn left onto Wills (or Wilks?) Gulch Rd
20.4 – **STOP 1b** Pull off along the road before the road curves to the left

STOP 2-1b – near Wills Creek Pass

Location: 47.546839°, -114.589018°; 3,195 ft (974 m)

Shorelines are evident in the distance to the SE. Schmitz Lakes (current elev. ~969 m [3180 ft]), up the road about 0.5 km, and nearby eroded bedrock were formed as scabland during catastrophic drainage and of glacial Lake Missoula.

In an unpublished report, Keenan Lee (Lee, 2009) updated Pardee's (1942) work on the Camas Prairie and its outlets to Rainbow Lake (to the west) and Perma (to the south). He included descriptions, photographs, and analyses of dune morphology and wavelengths. Based on dune morphology and the location of dunes, he postulated that antidunes formed adjacent to expansion bars as water depths decreased and Froude numbers increased as water-levels lowered but rapid velocities were maintained (Fig. 8)

Lee (2009) estimated that this pass eroded about 60 m (200 ft) during flood discharge (Table 1). At a maximum lake level of ~1,295 m (4,250 ft), the upper ~280 m of water would have spilled through this pass into Camas Prairie. However, the water also was spilling towards Plains first, through Rainbow Lake. After that direction a lowering of water level caused abandonment of that route, water only spilled into Camas Prairie through Markle and Wills Creek passes.

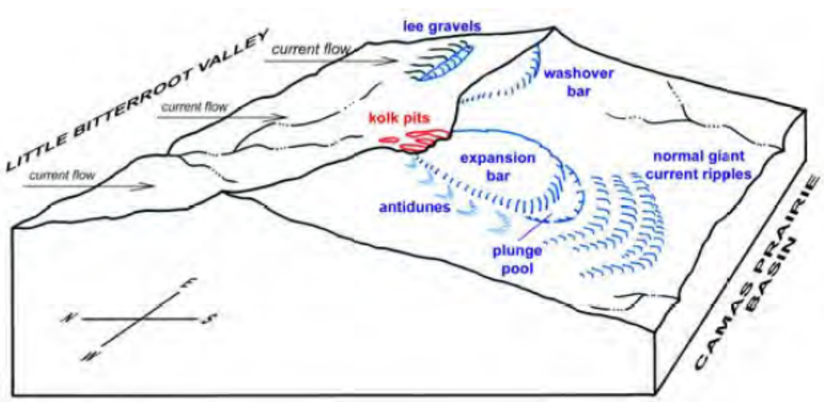


Figure 8—Generalized model of an inflow sublake notch.

Table 1—Inflow Sublake Notches at Camas Prairie

Sublake Notch[a]	Depth [ft] Highstand[e]	Depth [ft] Start of Flow 2[f]	Present Elevation
Duck Pond Pass[b]	800 [244 m]	200 [61 m]	3450
Big Creek Pass[c]	840 [256 m]	250 [76 m]	3410
Markle Pass	910 [277 m]	300 [91 m]	3340
Wills Creek Pass[d]	1070 [326m]	450 [137 m]	3180

[a] names used by Pardee [1942] [b] not labeled on topo map
[c] not labeled on topo map, at head of Big Gulch
[d] not labeled on topo map, at head of Wilks Gulch; site of Schmitz Lakes
[e] 4250 ft elevation [suggested by Pardee, 1942, although he used 4150 ft in his calculations; 4260 ft by GPS (Roy Breckenridge, 2003, pers.comm.)
[f] when Rainbow Lake Pass closed

Figure 8. Diagram showing terminology and positions of features related to catastrophic flows of water through passes in the Camas Prairie area. The table shows elevations and depths of flow through passes, based on present elevations and a lake stand of 1,295 m (4,250 ft). From Lee (2009).

Proceed to the driveway on the right 20.6 – Turn the caravan around and return to Rainbow Lake via Markle Pass

30.9 – **STOP 2** Pull off on dirt road at east end of Rainbow (Dog) Lake

Stop 2-2 – Rainbow (Dog) Lake overview

Location: 47.527581°, -114.744762°; 3,648 ft (1,112 m)

We are standing on Belt Supergroup bedrock that was plucked by kolking action during draining of a high-stand glacial Lake Missoula. As lake-level lowering reached the Plains Valley the shortest route for water to drain from the Little Bitterroot and Camas Prairie areas was through this area. The present drainage divide into the Rainbow Lake basin is about 1,100-1,120 m (3,600-3,680 ft) (Lee, 2009), higher than any of the passes into Camas Prairie (Pardee, 1942; Lee, 2009, Table 1). Lee (2009) estimated the Rainbow Lake pass was about 110 m (360 ft) higher before being eroded during one or more floods, or 1,230 m (4,035 ft). This clearly shows that this area withstood the earliest flood flows when lake-level lowering began in the Plains Valley. Once water levels fell below about 1,120 m, water could only flow through the various passes into the Camas Prairie Basin.

Return to Hwy 28 and turn right towards the way we came.
35.1 – As the highway turns to the south, on the right is the "Boyer Bar", an accumulation of gravels deposited where the valley widens. Some exposures along the highway suggest SW-directed large-scale cross stratification but stopping a caravan along this road is a bad idea. North of the bar, numerous pits were eroded into bedrock by high-velocity water.
36.7 – the southern tip of Boyer Bar is west of this location
44.7 – Turn left on Hwy 200 towards Paradise

50.9 – **Plains Loop (separate log at the end of Day 2) begins here, we may do this on the return trip if we have time today**

53.0 – Turn right onto Hwy 135 towards St. Regis
53.8 – As you look upstream, you will see rock stripped of soil cover inside (convex) bends of "point bars" and on the opposite banks, especially downstream. As floodwaters drained through these canyons, they took straight routes where possible, eroding the convex bends and the concave bends as floodwaters rushed through.
62.2 – Cross the Clark Fork River
67.8 – On the right (north) is a forested hill made up of gravel, an eddy bar near Toole, that is onlapped by a bench of glaciolacustrine deposits. This bar is the lowest I've recognized along the Clark Fork River (Figs. 9, 10).

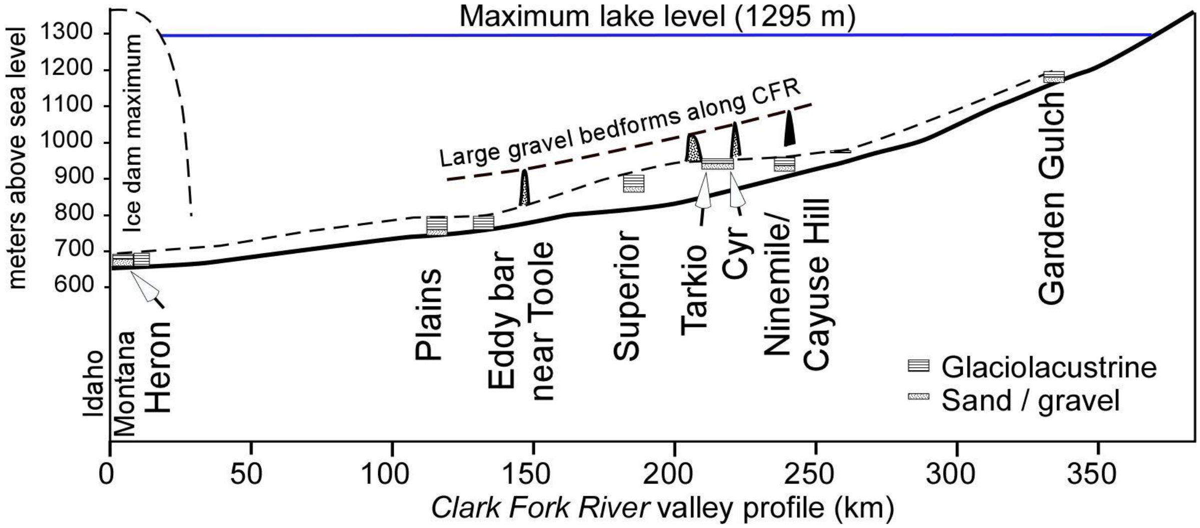


Figure 9. Longitudinal profile of the Clark Fork River in the field trip route showing the locations of mega-bars, glaciolacustrine sections I have studied, and sandy alluvium "basal sands" below glaciolacustrine deposits; VE = 133; modified from Smith (2006).

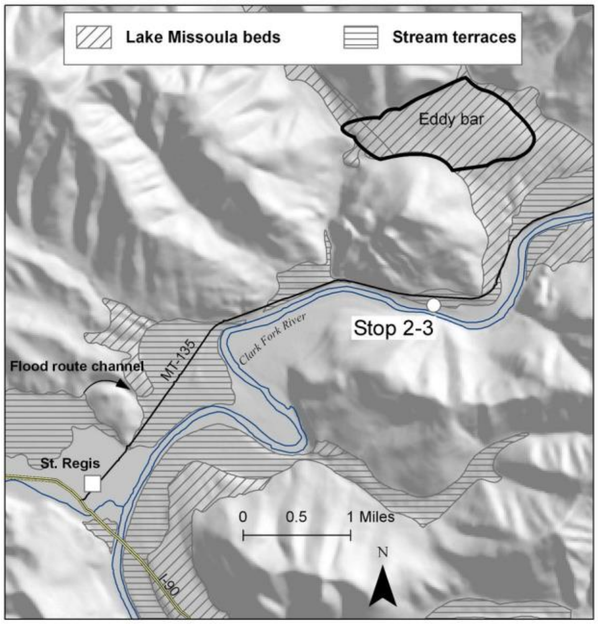


Figure 10. Geologic map of the area near Toole Siding (Stop 2-3); modified from Smith and Hanson (2014).

69.7 – Passing under power lines – SLOW DOWN for turn to the left!
70.2 – note the gap in the guard rail on the left – take the next HARD left turn onto a dirt road
70.3 – TURN LEFT onto dirt road to Toole Siding (I've missed this turn many times!)

Drive down the road about 0.1 miles. We will decide whether to park here and walk, or drive a bit farther.

STOP 2-3 – Imbricated boulders at Toole Siding

Location: 47.13716, -114.84827; 2,630 ft (802 m)

This location was shown to me (Larry) by Glenn Koepke (USFS, retired), in 2003 or 2004.

Description modified from Smith and Hanson (2014):

The rail line is active! Be aware of the possibility of trains coming from either direction!

This stop is at the top of a canyon reach of the Clark Fork River, downstream from St. Regis. Bedrock in the area is Revett Formation quartzite of the Belt Supergroup (Purcell Supergroup in Canada). The geology and landforms of the area are shown in Figure 10. The large accumulation of boulders with diameters of 2–6 m is unusual and represents a basal channel deposit of flood gravel; in places it is a lag gravel where smaller grain sizes have been swept away. Boulders are well exposed, and some are in original depositional position along the north side of the rail cut. These large clasts were deposited for an unknown distance above the rail grade and near the active channel of the Clark Fork River. Rough calculations of the fluid shear stresses required to transport the clasts shows they could not have been moved by normal-sized floods. Their position on the bank and within the channel suggests they originated from erosion of the upstream portion of the bedrock knob and accumulated where the channel widened slightly in this area. Their position near or at stream grade (2,600–2,630 ft; 792–802 m) here shows that the Clark Fork River has downcut very little, or not at all, at this location since the late Pleistocene.

Return to MT-135 by the same route. There's a chance we may turn around here and return to Plains depending on the time, if not, turn left, and proceed to eastbound I-90. Assuming, I've estimated the mileage correctly we'll keep with the cumulative miles:

74.8 – Pass under the I-90 freeway and travel east towards Superior, MT.
85.4 – Gravel pit across the freeway to the north exposes normal fluvial channel sequences underneath glaciolacustrine sediments. Three preliminary and unpublished OSL ages on quartz in sand below Lake Missoula beds were 28.5 ± 1.7 ka and 23.8 ± 2.7 ka (Smith, unpublished) and ~21 ka (Baker & Porat, unpublished).
88.2 – Exit I-90 at Superior, turn right and then continue onto Diamond Rd heading east.
93.3 – After rounding the turn into Trout Creek, park on the right (NW) near a dirt road that heads up a hill.

STOP 2-4: Flood gravels near the mouth of Trout Creek

Location: 47.13716, -114.84827; 2,800 ft (853 m)

In road cuts and the gravel quarry above this site, there are gravelly deposits that contain large-scale cross-stratification. Figure 11 shows the exposure in 2002; further mining of and sloughing at the site has obscured the cross stratification.

Description modified from Smith and Hanson (2014):

This eddy deposit is similar to others near confluences of the Clark Fork River and its tributaries. Stratification in many eddy deposits is not always evident; some exposures are composed of massive, very poorly sorted gravel. The sediment in this exposure, however, was deposited in a protected embayment by floodwaters flowing up Trout Creek, away from the main flood route, thus allowing for preservation of unidirectional stratification. Quarrying of the area above the road cut has made interpretation of the entire area difficult. Holocene colluvial deposits that may contain Mazama tephra, which has an age of 7,627 ± 150 cal ka BP (Zdanowicz et al., 1999), overlie gravel higher in the section.

We obtained permission from the landowner to wander around his property, so we can walk to the limited upper exposures of gravel and the suspected Mazama tephra. This tephra has not been studied in any detail, but based on its field appearance, I suspect it is the Mazama and not the Glacier Peak.

Figure 11. Gravel pit along Trout Creek in 2002. Beyond the car is large-scale cross stratification that shows transport to the left, up Trout Creek. These deposits are sediment that was transported away from the Clark Fork River during large-magnitude floods.

Depending on time, we may go ahead to the next stop to end the day. If not, the following stop will be the first for Day 3.
(if returning to Plains – travel ~48 miles)

98.3 - Retrace the route to Superior, turn right to travel east on I-90. Note the well-developed flat and rolling topography on top of the Lake Missoula beds. The rolling topography is especially evident east of the freeway in the half mile before Tarkio.
112.3 – Take Exit 61 off of I-90 at Tarkio
112.5 – veer right onto frontage road towards Tarkio Fishing Access site
113.4 - veer left and continue on the old rail grade. Travel ~0.3 mi to a wide spot near a driveway on the right.

STOP 2-5: Flood gravels and Lake Missoula beds at Tarkio rail cut exposure

Location: 47.00698, -114.73596; 2,930 ft (893 m)

Description modified from Smith and Hanson (2014):

The cut along the rail grade near Tarkio exposes large-scale cross-stratification developed in granule- to boulder-sized gravel capped by fine-grained Lake Missoula beds (Fig. 12). Open-work gravels with large-scale cross-stratification were deposited during catastrophic drainage and development of the huge gravel bar. Some of the gravel is cemented by calcium carbonate.

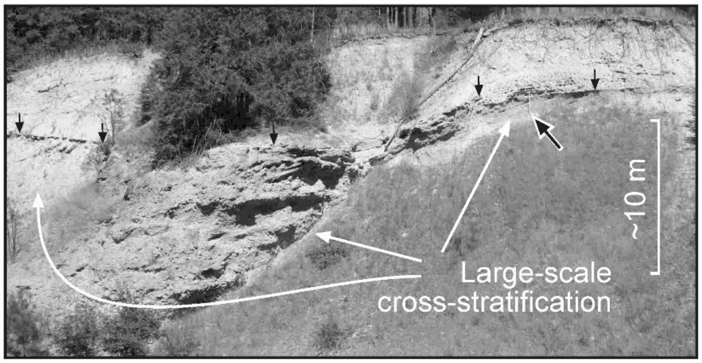


Figure 12. Gravelly alluvium with large-scale cross-stratification overlain by Lake Missoula silts at Stop 2-5; black arrows show contact between gravels and silts; 5 ft measuring staff at black and white arrow (from Smith, 2006).

A slump occurred in the gravel, causing minor movement and soft-sediment deformation in the fine-grained glaciolacustrine beds. The contact at the base of the Lake Missoula beds must represent a transgressive sequence where alluvial deposits are overlain by lake-bed deposits. Irregularities at this contact and within the gravel suggest that slumping of the gravel deposit occurred during transgression of the lake after one catastrophic flooding event.

Subsequent work at this site resulted in a preliminary chronology for the glaciolacustrine deposits and carbonate deposition in the gravels. Sand beds associated with Lake Missoula beds were sampled at four locations for OSL dating. TS-1a was a basal sand below the glaciolacustrine section, and above the gravel unit below. This sample was taken in an attempt to capture a transgressive sandy unit as the glacial Lake Missoula reformed after a catastrophic drainage, represented by the underlying gravel. I now recognize there are problems with this technique:

1) A mixing of material between the two units may result in the age tending towards an older value.
2) Determining the dose rate at a lithologic boundary is problematic as sampling the gravel below and the glaciolacustrine sediments above needs to be carefully done.
3) An in-place radiation measurement may be preferable to trying to bring representative samples back to the lab.

The remaining OSL samples were from sand beds low in the glaciolacustrine section (TS-2 a, b, c). TS-2a had insufficient sand for analysis.

U-Th dates on carbonate coatings of gravel below the Lake Missoula beds are significant. The morphology of the carbonate shows it must have formed beneath the water table, in saturated conditions. Therefore, this gravel unit had to have been saturated from ~9,000 yr to ~1,200 yr. This is a stratigraphic and geomorphic conundrum, that is:

1) When did the Alberton Gorge form?
2) When was the bedrock canyon cut?
3) Was the canyon filled with sediment, supporting a water table at least 60 m above water level until 1,200 yr ago?
4) What are the implications for the history of water content in the OSL samples?
    a. For example, raising the water content from 7% to 25% would result in the ages being about 4,000 yr older.

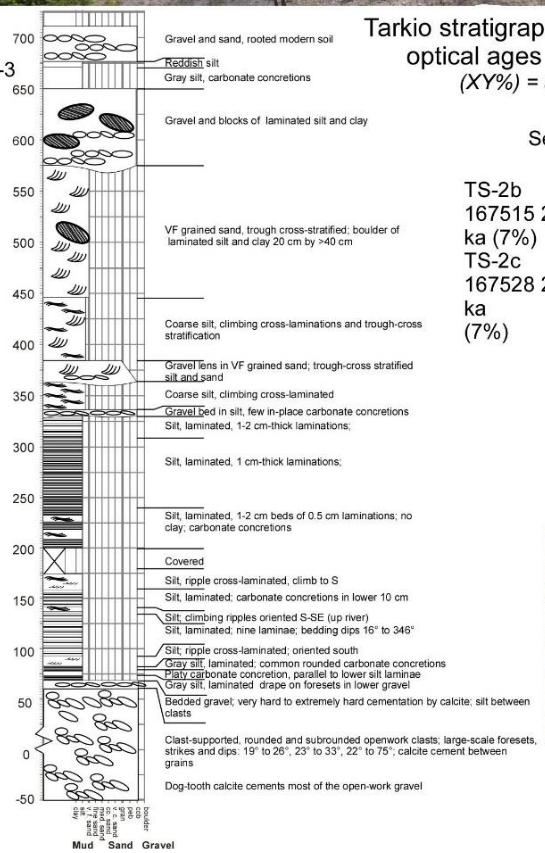
Thus, more work is needed here!

Figure 13. (Next page) Panorama of the Tarkio section with 3 stratigraphic sections and chronological information. All OSL dates are preliminary, and all dates are unpublished.

Tarkio stratigraphic sections and preliminary optical ages on quartz (unpublished)

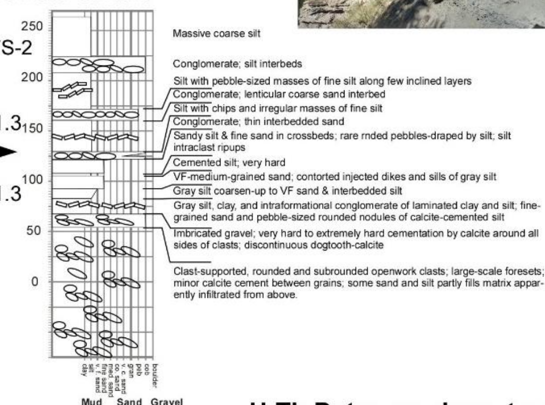
(XY%) = assumed water content

Section TS-3

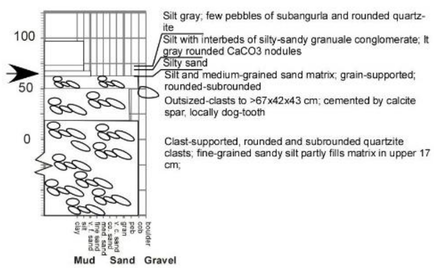


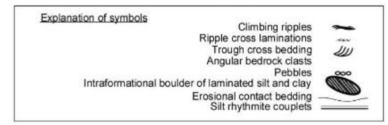
Section TS-2

TS-2b
167515 22.6 ± 1.3 ka (7%)
TS-2c
167528 22.4 ± 1.3 ka
(7%)

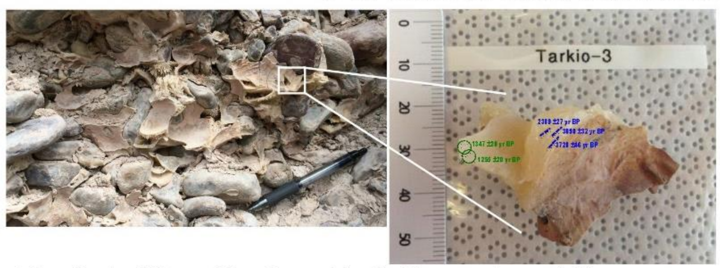


TS-1a
167510 20.4 ± 1.1
(7%)





U-Th Dates on clean, translucent carbonate cement (yr BP):



- Dates on three samples are in stratigraphic order in dense carbonate coatings on gravel
- Ages range from 8,917 ± 82 yr to 1,255 ± 20 yr
- ***Gravels were saturated***

Tarkio-3	Tarkio-2	Tarkio-1
1255 ±20	2433 ±26	8852 ±63
1347 ±20	3700 ±64	8917 ±82
2389 ±27	4634 ±63	
3090 ±32	5345 ±58	
3728 ±46		

Thanks to: Wang Xianfeng, Earth Observatory of Singapore

Return to I-90, go under the freeway, turn left on the Frontage Rd.
116.3 – Turn right onto Nemote Cr Rd 454
1170. – Pull over on the right shoulder near the crest of the low hills side of the road.

STOP 2-6: Rolling topography on Lake Missoula beds

Location: 47.04028, -114.73596; 3,120 ft (951 m)

Description modified from Smith and Hanson (2014):

"Along roads traversing the upper surface of the Lake Missoula beds, note the topography. At this location (A in Fig. 14), the east-west trending crests and troughs have been interpreted to have been dunes that developed during high-energy, north-flowing drainage events (Alt, 2001, p. 76–77). Aerial-photo interpretation of the hills and valleys shows dendritic patterns to the rolling topography, suggesting that they are not depositional landforms but networks of dry paleovalleys incised into the Lake Missoula beds (Fig. 14; Smith, 2006).

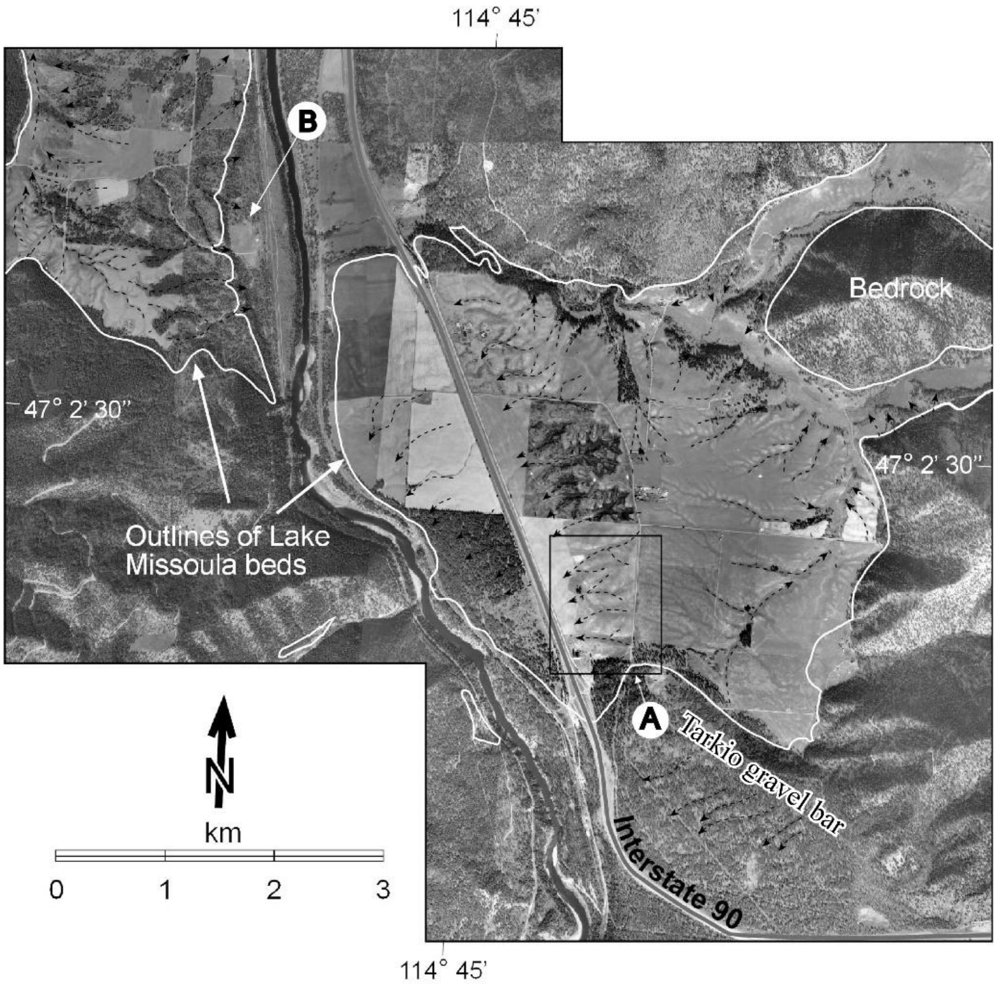


Figure 14. Digital orthophotos show the drainage networks that developed on the Lake Missoula beds in the Tarkio and Quartz flats areas and some of the drainage basins. Site "A" is rolling topography previously interpreted as a down-valley train of giant dunes. Site "B" is the location where drainage basins end in a depositional environment at a stream terrace remnant. The

alluvial fans in this area are minor compared to the amount of sediment eroded from the drainage basins; dashed lines with arrows show some of the channels in lake-bed silts (modified from Smith, 2006).

Key features to observe about the drainage basins and stream networks developed on the Lake Missoula beds are that most of the basins do not have active streams; if they do, the streams are underfit in much larger valleys. Where these small tributary drainage networks end at terraces along the Clark Fork River, alluvial fans are either not present, or they contain a much smaller amount of sediment than that expected to have been eroded from the stream network (at location B in Fig. 14). Thus, the side-valley systems appear to grade to terrace levels below the bench we are standing on (the upper surface of the Lake Missoula beds) and the alluvial sediments on these terraces were eroded before the terraces were abandoned. The lack of fans suggests that the drainage basins were mostly cut into the Lake Missoula beds during the final GLM flood. Another interpretation would be that the drainage basins are mostly Holocene gully systems and the sediments were carried off the terraces by unrecognized (filled-in?) channels."

117.2 - Return to I-90 and travel back to Paradise (if Day 2), or
Travel east to the freeway (if Day 3).

Plains area loop – Extra stops for when we have time

Intersection of Hwy 200 & River Rd E heading NW just south of the Paradise Bridge

0.6 – **STOP A** Pull off near this dirt road the on right (or at another spot) for an overview of the region.

Location: 47.38470, -114.80830°; road 2,490 ft top of knob 2,560 ft (758 m, 780 m)

If possible, walk up to the top of the bedrock knob for excellent views of the eddy bars on the north side of the CFR valley and water-scoured bedrock (the NW part of the knob is USFS land). Continue on River Road E to the NW
6.0 – near this turn to the W or the next at …
6.3 – where River Road turns W, stop for an overview across the CFR

6.3 – **STOP B Overview of the drainage from Rainbow Lake down Boyer Creek**

Location: 47.444136°, -114.874897°; 2,470 ft (753 m)

From this location the Boyer Bar of Pardee (1942) is not in view. Most of the lightly vegetated hills to the NE are below the level of the deepest GLM. Essentially all of the hills between Boyer Creek and the Plains Valley were underwater, except for the highest, Locust Hill, that is directly west of the Rainbow Lake channel.

I suggest walking up onto the small bedrock knob. At the top of this knob you can find a few depressions where bedrock blocks are missing. I interpret these depressions to have formed by plucking of bedrock blocks by high-velocity flows down the Clark Fork River during megafloods.

Continue along River Road E.
7.3 – Turn to the north to stay on River Road
7.5 – Turn to the west continue on River Road W
8.0 – Turn south to continue on River Road W
8.5 – Pull off on the left before climbing Sand Hill.

8.6 – **STOP C – Exposure of Lake Missoula beds over gravel**

Location: 47.4747°, -114.9404°; 2,467 ft (752 m)

At this typical, but not very impressive, outcrop we can view glaciolacustrine beds overlying sand and gravel. I agree with Pardee (1942) that the gravel was deposited during catastrophic lake drainage from an earlier stand.

Three OSL samples were taken along River Road (Fig. A):

Sample	Assumed water content	OSL age (quartz)	Sediment	Lab
ECC-01	7% ± 4%	24.0 ± 1.9	sand below lake beds	DTU
RR-01	7% ± 2%	20.9 ± 2.9	sand below lake beds	USU
RR-02	7% ± 2%	24.7 ± 4.0	sand within lake beds	USU

Figure A. Photographs of samples RR-01 and RR-02 taken 5/24/2016 analyzed by the USU Luminescence lab (USU-2355 and 2356, respectively). On 10/8/2015 I collected another sample in sand below glaciolacustrine a year at a farther SE location (ECC-01; DTU-167508).

Each of the ages for this area are unexpectedly old and take some explaining, therefore have not been published except being referred to in an abstract (Smith et al., 2017). However, considering their large error bars and the problems with accurately measuring dose rates in stratified sediments, they can be interpreted as consistent with other ages within the lake basin. The older USU age from a sand within the lake beds may indicate that the lake sediments were poorly bleached, resulting in an older age. The USU age of the “basal sand” (RR-01) is consistent with a lake transgression, possibly as young as 18 ka, after a catastrophic drainage event.

More work is needed on the ages at many sites.

Return to vehicles and continue NW on River Road W

10.3 – Intersection of Black Jack Road on left. In this area and to the north, River Road W runs along the east side of “Sand Hill” a ~100 m high accumulation of sand and gravel deposited by a catastrophic draining of GLM and onlapped by Lake Missoula beds. This hill was mapped as Pleistocene sand and gravel by Pardee (1942). To the NW it is bordered by outcrop of Belt Supergroup rocks that are sculpted into scabland-like topography.

Along the road you will find roadcuts exposing boulder gravel, some of which seem to make up ridges. In general, this looks like an expansion bar, but what flow expansion caused it is unknown. It is possible that down-Clark Fork River flow lessened as water entered Eddy Narrows, resulting deposition of the bar in this area. More work is needed to better explain this feature.

12.8 – near the top of the hill. Most of this land is private. To the NW and W are USFS properties.
13.3 – intersection of Swamp Cr Road; turn right to stay on River Rd W.
15.5 – turn left (W) to stay on River Rd W.
15.9 – Entering timbered area and Belt Supergroup bedrock that has been sculpted by floods.
17.0 – Approximate southern boundary of USFS half section. Exploring the topography and exposures can be done without asking landowner permission.
17.7 – River Beach recreational area where Swamp Creek enters CFR.

STOP C – Upper end of Eddy Narrows at River Beach

Location: 47.518399, -115.024119; 2,411 ft (735 m)

Explore this area for evidence of flooding.

Return to Plains via River Road to 5th Ave S across the CFR and Willis St (11.1 mi)

28.8 – Intersection of Willis St. and Hwy 200

Day 3: Sunday, 12 September – Chronology of floods and glaciolacustrine deposits

Reset odometer to 0 miles at Tarkio

4.8 – Exit 66, turn left on Fish Creek Road and then right on Old Hwy 10 to Cyr, cross the Clark Fork River bridge (to I-90 east)
8.0 – We are traveling over Lake Missoula beds that overly alluvium, possibly flood gravel in some areas. To the NE of this location, I processed 5 OSL ages from a single outcrop of sand below the Lake Missoula beds. If I assumed 7% water content for the sand, the ages range from 15.0 ± 1 to 16.9 ± 1 ka, averaging 15.9 ka. When I assumed a water contents half way between *in situ* and saturated for each sample (19-23%), the average age was 18.2 ± 0.7 ka (Smith et al., 2017). Thus, more work is needed to understand the cutting of the canyon and the water content history of these sediments.
8.8 – go under the freeway and park on the right in a field before the on-ramp.

STOP 3-1: Gravel bars and Lake Missoula beds – Cyr bridge over the Clark Fork River

Location: 47.00367°, -114.5767°; 2,978 ft (908 m)

Description modified from Smith and Hanson (2014):

"The widening of the Alberton Gorge into this valley led to the decreased flow velocities during the early phase of catastrophic lake drainages. The wooded ridge due south of the valley is a 300 ft-high (91 m) gravelly eddy bar deposited by currents flowing up the Sawmill Gulch tributary to the Clark Fork River (Fig. 15). In the exposure below the roadside along the east-bound on-ramp are boulders, some in-place. Alt (2001, p. 75) suggested that the sediment down to river level are of Eocene-to-Pliocene age. My interpretations are that these rhythmically bedded sediments are Lake Missoula beds that were distorted by slumping and possibly periglacial action between lake stands. The series of stream terraces cut into glaciolacustrine deposits on the south side of the river may have formed during, or after, the last drainage of GLM. A full understanding of the stratigraphy in this location requires more work."

Note at this stop the large boulders just below the lip of the (human-modified) flat area we are parked on. Some of these boulders appear to be in place and were deposited across what we interpret as deformed Lake Missoula beds.

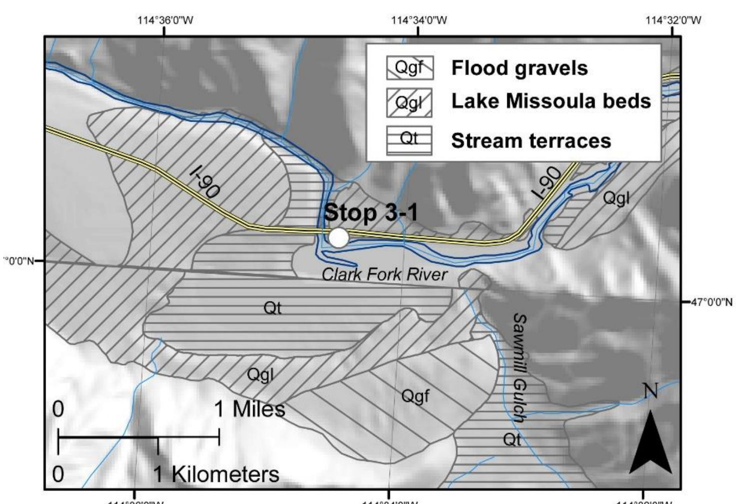


Figure 15. Geologic map of the area near Cyr, Montana, modified from Smith and Hanson (2014) (geology modified from Lonn et al., 2007).

Return to the onramp and head east on I-90

20.4 – Classic "reference" section of glacial Lake Missoula Beds at the I-90 roadcuts. Stopping along the north-facing highway roadcut in the Lake Missoula beds is worth it for a small group – but not for this caravan! This section of Lake Missoula beds is exposed on both the north-facing and the south-facing road cuts. The striking cyclic pattern of bedding is clear at a distance on both sides, however, the higher moisture on the north-facing side allows for better exposure of sedimentologic details.

21.0 - Continue east on I-90 to Exit 82 (Ninemile Road) and turn left to go beneath the freeway.
22.4 – Pull off on the left in the dirt lot – we will turn around after the stop.

STOP 3-2: Ninemile section of Lake Missoula beds

Location: 47.028117º, -114.384506º; 3,190 ft (972 m)

Description modified from Chambers (1971, 1984) and Smith and Hanson (2014):

This SW-facing outcrop (Fig.16) is hardened by desiccation of the fine-grained sediments. These exposures have long been recognized as a type example of fine-grained glaciolacustrine sedimentation in GLM. Published studies began with Dave Alt and his MSc student Richard Chambers from the University of Montana (Alt and Chambers, 1970; Chambers, 1971, 1984).

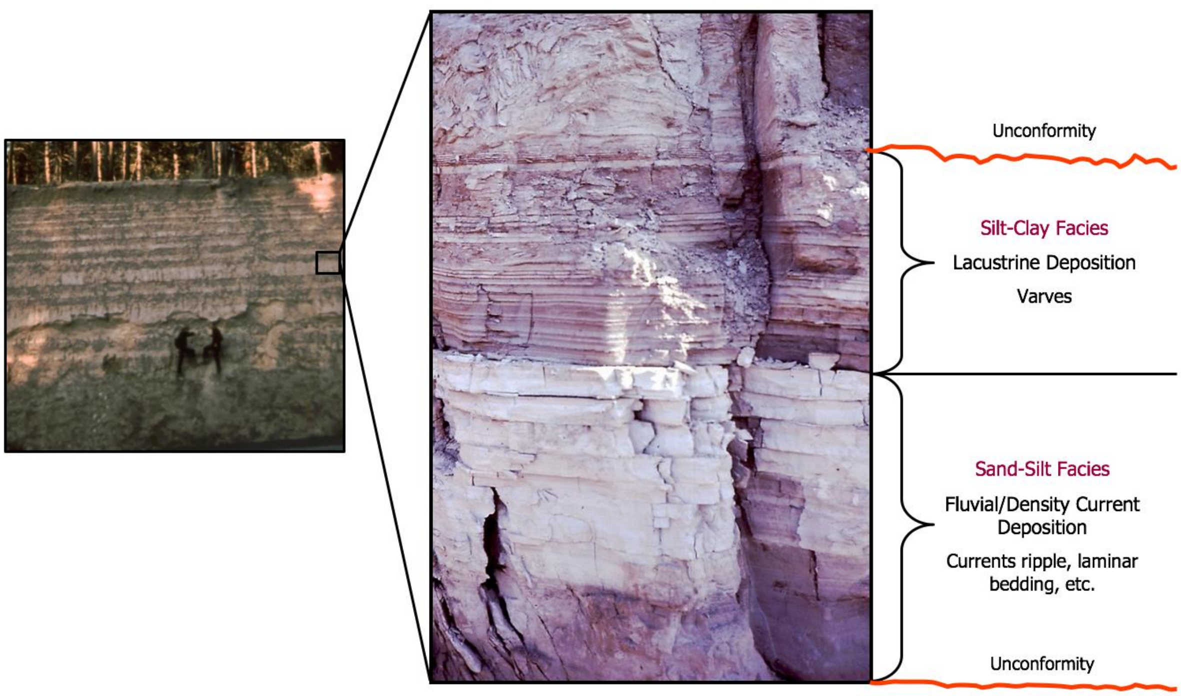


Figure 16. Ninemile Creek exposure of Lake Missoula bottom sediments.

The rhythmic nature of the units is so striking that Waitt (1980, 1985) theorized that a bed-for-bed correlation could be done with the flood slackwater sediments in central Washington, and Atwater (1986) attempted such a correlation to the flood deposits in Glacial

Lake Columbia based on varve counts. Additionally, if the rhythmic character of the Lake Missoula beds is due to filling and draining cycles of the lake, these beds should be correlative to other deposits within the lake basin. Indeed, these sediments likely overlap with sediments at the Rail line site (Stop 3-4) based on sedimentary characteristics and optical dating (Hanson et al., 2012).

This exposure consists of rhythmically stratified units of graded beds of fine sand, silt, and clay. These rhythmic beds overlie coarse-to-fine-grained sand and pebble-cobble gravel – exposed only toward the western end of the exposure along the freeway. The main sediments of this site can be divided into three lithofacies: a Pebble-Gravel facies, a Sand-Silt facies, and a Silt-Clay facies.

The Pebble-Gravel facies (Fig. 17) consists of thin beds of coarse sand and granule to medium pebble gravel and was likely deposited by non-channelized fluvial flow in shallow water on the lake floor before the lake began to fill (Chambers 1971; Hanson et al., 2012).

The lighter-toned basal Sand-Silt facies (Fig. 18), present in every rhythmite, is characterized by rippled or laminated very fine sand or silt. This facies was likely deposited by density underflows into relatively shallow water as the lake began to fill (Chambers 1971, 1984; Hanson et al., 2012).

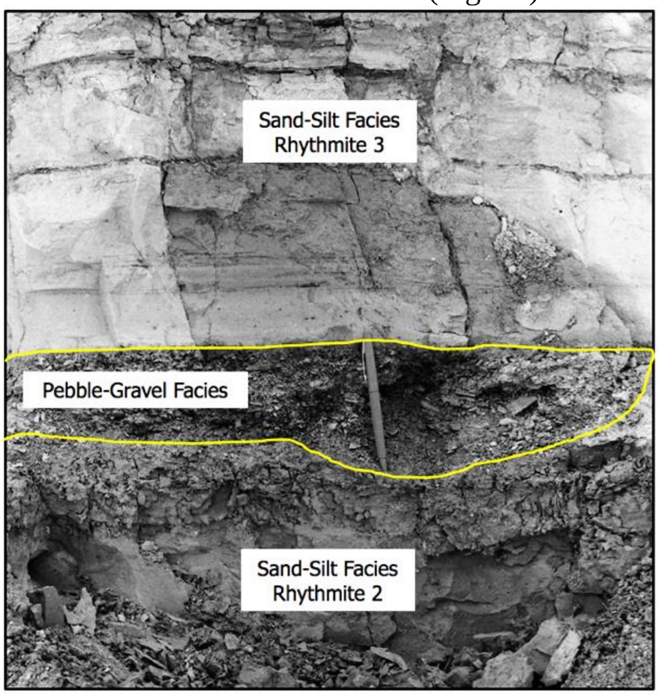


Figure 17. Pebble-Gravel Facies between Rhythmites 2 and 3.

Suggested depositional environments of this facies include shallow-water, high-energy currents generated by the complete drainage of GLM (Alt and Chambers, 1970; Curry et al., 1977).

As the lake water deepened, the Sand-Silt facies graded upwards into the Silt-Clay facies (Fig. 18). The couplets of silt and clay tend to decrease in thickness within each rhythmite due to an expanding lake floor as the lake continued to fill (Chambers, 1971, 1984; Hanson et al., 2012). These couplets and similar ones elsewhere in the GLM basins have been

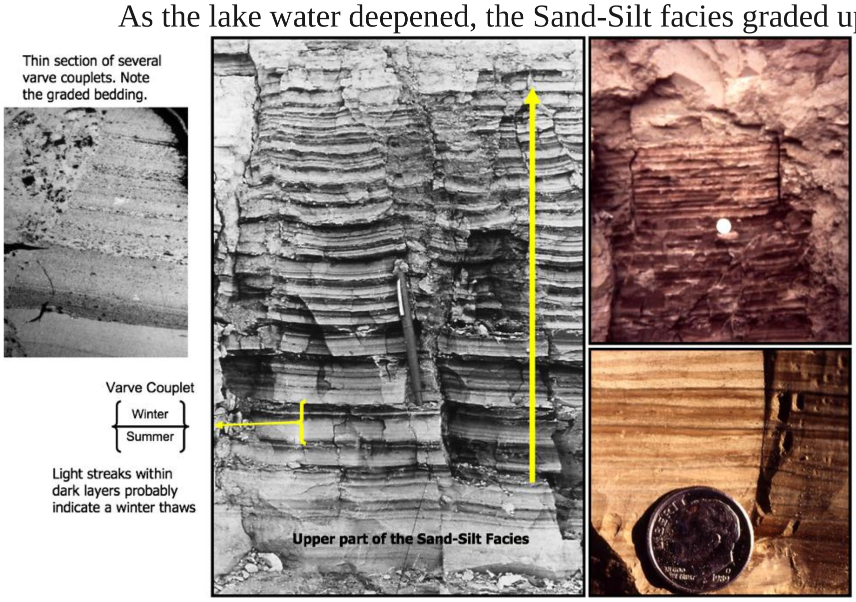
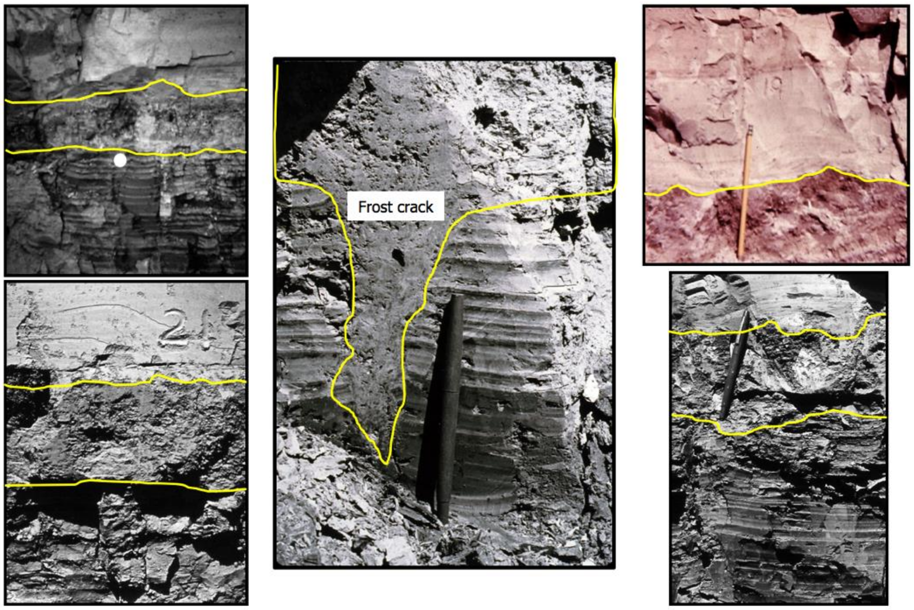


Figure 18. Silt-Clay facies illustrating the thinning upward trend as sediment is

spread over an expanding lake floor with increasing the water depth.

interpreted as varves (Alt and Chambers, 1970; Chambers, 1971, 1984; Waitt, 1980; Fritz and Smith, 1993; Levish, 1997; Hanson et al., 2012).



Evidence of exposure of the lake floor (Fig. 19) between rhythmic units (periglacial features or desiccation of the deposits) has led several researchers to conclude that there were multiple complete or partial drainages of the lake (Chambers, 1971, 1984; Hanson et al., 2012).

Figure 19. Weathered zones and frost cracks within the Silt-Clay facies are evidence of an exposed lake floor following a complete or partial draining of the lake prior to the formation of a new lake and deposition of another Rhythmite.

It is important to note that the base of Ninemile section is ~300 m above the base of the ice dam, ~200 km to the east. Thus, it is difficult to conclude from the stratigraphy and sedimentology of this exposure if: (1) the lake that drained was at full pool; and (2) the draining event was complete and catastrophic or if it only drained to some level below the base of the exposure. It is likely that these sediments would only be preserved during smaller, less energetic lake draining events (Chambers, 1984; Alho et al., 2010; Hanson et al., 2012), which is consistent with the fact that the optical age at the base of the exposure (15.1 ka) places it toward the end of the existence of GLM. The amount of time between each drainage event is difficult to estimate because of an unknown amount of erosion of the lake floor during drainage. Minimum estimates can be based on existing varve counts, which vary from two to 58 for individual units at this site (Chambers 1971 and 1984: Hanson et al., 2012)."

For additional information and photos about the Ninemile section go to
https://richchambers.wixsite.com/lake-missoula

23.1 - Return towards the freeway and turn left on Wildlife Dr (private road)
23.9 – Note along the road: (1) scattered cobbles and boulders, (2) outcrops of Belt Supergroup rocks, and (3) internally drained depressions – which we interpret as scabland topography that resulted from high-energy flood flow across this bedrock-cored hill.
24.3 – continue straight towards gravel pit.

STOP 3-3 – Rehbein Gravel Pit on top of Cayuse Hill

NOTE this is private land where we have graciously been granted entry. Everyone will need to sign a waiver to enter this stop. Do not approach steep slopes without being directed.

Location: 47.03534º, -114.36741º; 3,573 ft (1,089 m)

This gravel pit was first opened in 1998 and expansion to the south began in 2010 by its owner Mr. Dwayne Rehbein. He contacted me (Larry Smith) that there might be an interesting story here, so I first visited in 2017 (Fig. 20). Previously, I had mapped the hill as bedrock, noting a scattering of boulders and scabland topography on the eastern side of the hill. The top of the hill is about 170 m above local baselevel where scabland has formed near the present level of the Clark Fork River.

I calculated that there may have been ~800,000 m^3 of gravel in the deposit. The cross stratification suggests a gravel bar formed on the lee side of the hill and built ~300 m downstream during one or more catastrophic drainage events.

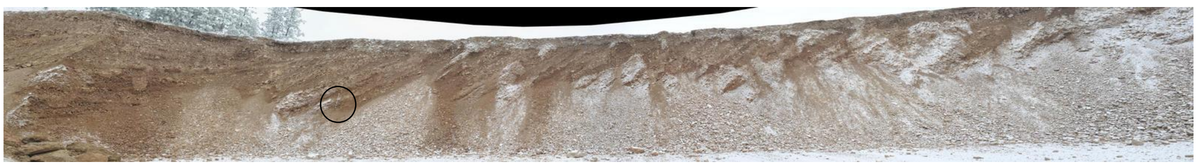


Figure 20. Outcrop of large-scale cross stratification in December 2017, looking north; 1.5 m long Jacob's staff is circled.

This location was a good place to test the applicability of new luminescence techniques to try to get ages of gravel deposition. Rock-surface luminescence dating, as opposed to sand-sized sediment dating, is growing in application (Sohbati et al., 2011; Chapot et al., 2012; Sohbati, 2016; Rades et al., 2018; Souza et al., 2021). Because many lithologies, including granites, gneisses, and arenites, contain translucent mineral grains, sunlight can penetrate mm's – cm's into rock surface and bleach luminescence in quartz and feldspars. Therefore, if a rock surface is exposed to sunlight and then buried, the luminescence signal builds again as a function of radiative dose rate and time.

To test the applicability of dating this deposit with rock surface luminescence techniques, the owner dug a sampling pit after sunset on a floor recently being worked (Fig. 21). From that, I extracted a few dozen rocks, wrapped each in aluminum foil and placed them in light-tight bags. I initially sent 8 rocks in 2018 to the Denmark Technical University-Risø Campus for dating at their luminescence lab. Those rocks that were well rounded, did not have broken faces, and were oblate in shape which are preferred as they would most likely have been sitting on one of two faces with the opposite faced toward the sun. As we had some success, in 2019, I sent 15 rocks each from two pits to the same lab.

Figure 21. Sampling rocks for dating work at dusk in June 2018.

All work was done in a darkroom with orange lighting. The flatter sides of each rock were cored with a 10 mm-diameter diamond bit in a bench press. The cores were sectioned into ~1 mm slices. Each slice was then placed in the reader carousel slot and run like more typical sediment aliquots.

From the first sampling, one side each of two rocks showed results that indicated the surfaces were well bleached by sunlight prior to burial. That is, of the 16 sides of 8 rocks, 12% were well bleached and resulted in preliminary ages (Smith et al., 2019). Further work on 15 samples each from two more sampling pits resulted in one more well bleached rock, one that was bleached on all sides. Most cobbles (63%) showed no evidence for recent exposure to sunlight, but 29% (11 cobbles) displayed partial bleaching on at least one surface.

For the three bleached cobbles, the distribution of equivalent doses (D_e) at the surface of each cobble was determined by measuring multiple surface slices. The effective total dose rate to the surface of individual cobbles was also estimated by modelling the variation of beta and gamma dose rates at the cobble-matrix interface. The burial age of each cobble was then calculated by dividing the mean surface D_e by the total dose rate. The infrared stimulated luminescence ages for feldspar of two cobbles were corrected for anomalous fading by both conventional g-value measurements and field-to-laboratory saturation (FLS) ratios. The third cobble was successfully dated with pulsing optically stimulated luminescence techniques for quartz to reduce the effect of feldspar. The resulting ages from all cobbles, from two widely spaced sample sites, are consistent within the error limits and converge at the age of ~18 ka (Smith et al., 2021). This age overlaps with a previously published age of 18.2 ± 1.5 ka determined by ^{10}Be cosmogenic nuclide dating of boulders for a large megaflood deposit in the Channeled Scabland (Balbas et al., 2017).

As the cobbles were collected from upstream and downstream portions of the landform, there is no sign yet that more than one megaflood is recorded at this site. The apparently oldest of the three ages was collected in the farthest downstream portion. Improvements in sampling techniques, especially if field OSL readers could be used, may increase the number of bleached clasts sampled.

Return to Ninemile Road.
25.5 – Turn left to return to I-90
26.0 – Continue east on I-90; Notice along the way the rolling topography on Lake Missoula beds.
43.0 – Exit onto Airway Blvd south. We will travel about 4 mi from here to Hiawatha Road.
43.3 – Turn right onto Airway Blvd
43.5 – Continue straight around the traffic circle
43.8 – Turn left onto W. Broadway St.
45.4 – Turn right (west) onto Flynn Ln, continue south as the road turns
46.8 – Turn right onto Mullan Rd
47.7 – JUST AFTER Roundup Dr, veer right onto Hiawatha Rd
48.7 – Turn around the caravan and park along Hiawatha Rd, being sure to not block the road or entry to the nearby homes.
NOTE – this is a private road. Anyone who wants to visit this area should get permission from the landowners, both north and south, of the end of the road.

Stop 3-4. Rail line exposure of Lake Missoula beds

Location: 46.89388º, -114.091736º; 3,170–3,200 ft (966–975 m)

Description modified from Smith and Hanson (2014):

"The Rail line site is an exposure along the abandoned Chicago, Milwaukee, St. Paul, and Pacific Railroad. Note, there are no known restrictions for accessing the exposure (it is on Missoula Airport Authority land), but you should ask permission from landowners to park your vehicle on Hiawatha Road as it is private property. The exposure continues for approximately 1.4 km but is best exposed closest to Hiawatha Road.

This exposure contains 29 upward-thinning units of rhythmically bedded fine sand, silt and clay. Three lithofacies are present: a sand facies, a silt facies, and a silt-clay facies. The sand facies, which resembles the pebble-gravel facies at the Ninemile site, occurs at the base of 10 units and comprises well-sorted, very fine- to fine-grained sand that is laminated or rippled. This facies was likely deposited as non-channelized fluvial sediments in shallow water on the floor of the lake before the lake refilled (Hanson et al., 2012). The silt facies, which resembles the sand-silt facies at the Ninemile site, consists of thinly laminated, coarse to fine silt with type-B ripple-drift cross-lamination. This facies was likely deposited by turbidity currents at relatively shallow depths as GLM began to fill (Hanson et al., 2012). The silt-clay facies is the dominant facies at this site and it consists of silt-clay couplets similar to those at the Ninemile site, which are interpreted to be varves (Hanson et al., 2012). Boundaries between all units are unconformable and show evidence of erosion and lake-bottom exposure in the form of desiccation and periglacial features (where ice-wedge cracks are filled with sediment from the walls; Fig. 17B).

Sedimentology and two optical ages (14.8 and 12.6 ka; Hanson et al., 2012) potentially place this exposure stratigraphically overlapping and above the Ninemile Creek exposure."

The two ages from this section are 14.8 ± 0.7 ka and 12.6 ± 0.6 ka midway through the rail line exposure (Hanson et al., 2012). The younger date cannot be rectified with regional stratigraphy where we know that the Glacier Peak tephra (~13.5 cal ka BP) draped post-GLM topography in the Mission Valley (Levish, 1997).

Take aways from this location are:

1) Note the fine-grained nature of the sediments (for comparison to the Stop 3-6 of this day and to the Heron area Elk Creek section Stop 1-3).
2) How convinced are we that there are subaerial exposure surfaces at cycle boundaries here?
3) Note the reported ages at this section.

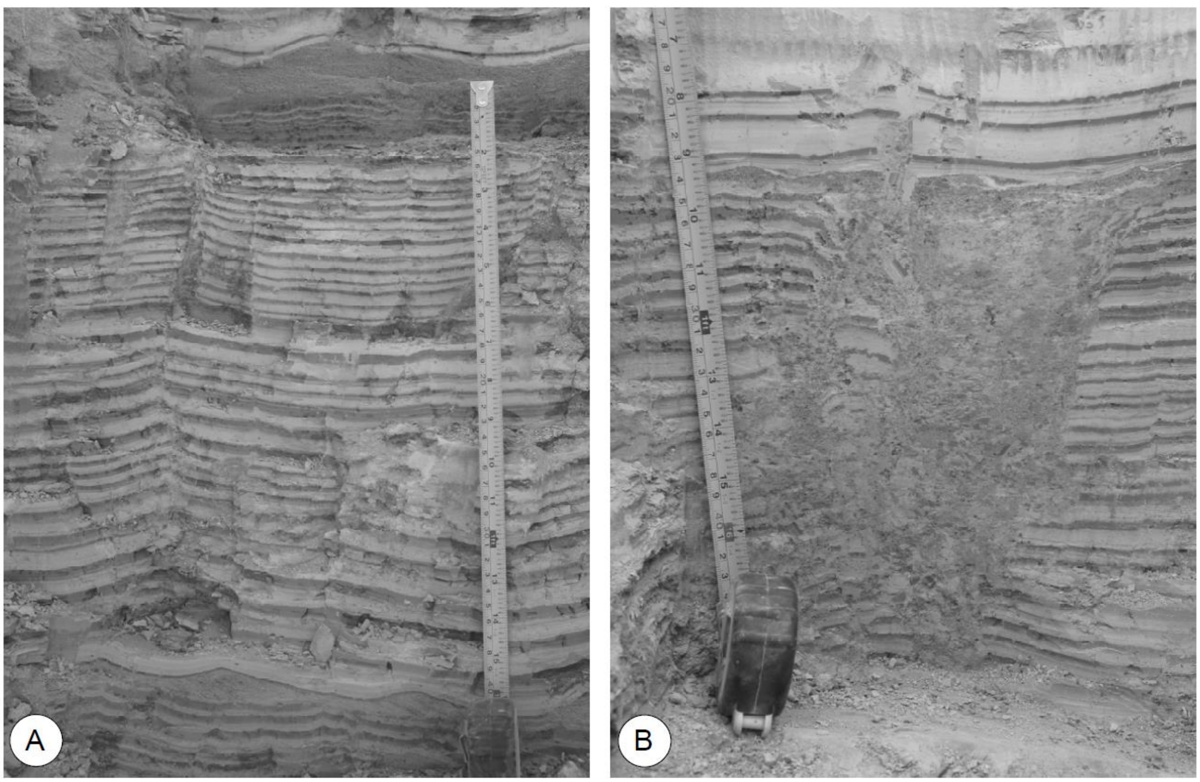


Figure 17. (A) A thinning-upward sequence of silt-clay varves, overlain and underlain by the rippled sand-silt facies at the Rail line section (tape is 40 cm long); (B) Downward-tapering periglacial feature, filled with brecciated sediment from the walls of the feature, in Lake Missoula beds at the Rail line section (tape is 43 cm long) (from Hanson et al., 2012 and Smith and Hanson, 2014).

49.6 – Return to Mullan Rd. We will pass by Flynn Rd and continue to N. Reserve

51.3 – Turn left on N. Reserve Rd

53.3 – Turn right onto I-90, traveling east.
56.9 – (*IF we are running late*, we may skip this exit and continue east) Exit I-90 at the Van Buren exit
57.3 – Turn right (west) onto E. Broadway St. and prepare to turn left (south) and cross the Madison St. Bridge.
57.8 – Continue straight onto Arthur Ave.
57.9 – Turn left (east) onto S 6th St. East
58.2 – Turn left (north) onto S. Van Buren Ave, then right onto Campus Dr. to get around campus
58.5 – Turn left (east) into the parking lot for the "M" trail. This is a good place to stop to talk about GLM shorelines, erratics plucked out of Hellgate Canyon, and subtle topography that shows a history of downcutting in the area.

STOP 3-5 – Shorelines and GLM lake-bottom features *(we may skip this stop depending on the time)*

Location: 46.862574°, -113.980601°; 3,219 ft (981 m)

While this is not the best place to view the shorelines due west on the "M" and north on Mt Jumbo, this is a good place to park for a short time.

The GLM shorelines are most prominent and in some ways, best preserved on Mt. Jumbo. The highest shoreline recognized is on Mt. Jumbo at 1,295 m (4,250 ft), the highest shoreline suggested by Lee (2009) and noted by O'Connor et al. (2020).

The land surface occupied by the University of Montana slopes away from Hellgate Canyon in a fashion that suggests alluvial fan deposition sourced from the canyon. These fan deposits eroded Lake Missoula beds a few km away, near the Missoula airport, and are not overlain by younger lake beds there, suggesting a post-glacial age. With inspection of building excavations and interpretation of subtle incision features Sears (2020) recognized a "chaotic layer contain[ing] large angular blocks, the largest of which exceed 10 ft in length." He postulates the "Missoula Valley alluvial fan" is actually the deposit of the final catastrophic draining of GLM, rather than outwash as suggested by Alden (1953). The lake-bottom surface is downcut by a series of river terraces, down to the floodplain (Sears, 2020).

59.7 - Return to I-90 via 5th St E and Madison St Bridge to travel east
62.3 (and 63.4) – when crossing the Clark Fork River – notice the large boulders in the river. These were likely transported during catastrophic draining of GLM.

92.2 – Exit I-90 at Bearmouth, turn left and cross under the freeway and over Clark Fork River and travel east on the Frontage Rd.
103.0 – Pull off on dirt road on right and park before the gate. We will walk from here.

Stop 3-6: Garden Gulch section of Lake Missoula beds

Location 46.710206°, -113.255514°; 3,850–3,890 ft (1,173–1,186 m)

This is private land that we have permission to cross. There are two landowners that can grant access to this property – I suggest contacting one or both for access in the future.

Description modified from Smith and Hanson (2014)

"The Garden Gulch section was measured on a 0.4 km-long, nearly vertical exposure of bedrock, sand and gravel, and silty lake sediments near the Clark Fork River. The exposure was formed in 1908 when a meander loop of the Clark Fork River was cut off during straightening of the Northern Pacific railroad (Taylor, 2020). The rail and subsequent highway routes were constructed parallel to the modified channel, which cuts into bedrock of greenschist-grade, metamorphosed mudstone and fine-grained sandstone of the Blackleaf Formation. During construction of the artificial channel, unconsolidated fluvial gravel and lacustrine sands, silts, and clays were left near the channel; minor amounts of spoils from the excavation were placed on top of the sediment. The silty sediments are periodically undercut during high-discharge events on the river, which has helped to maintain a nearly vertical exposure.

As described here, the Garden Gulch section is but one composite section on this large outcrop. It was measured from east-to-west up towards the major gulley that bisects the outcrop. The deposits include gravelly fluvial sediments of a paleo-Clark Fork River (2 m) that is overlain by ~9.5 m of fining-upward sequences of laminated silt and clayey silt with beds of rippled very fine sandy silt of mostly lacustrine origin (Figs. 23, 24). … Sand wedges and contorted bedding … provide evidence of 8–12 exposure surfaces in the outcrop, each representing a lake-lowering event. This record of lowering (which could be either partial or full lake drainings) from full, or nearly full-pool stands of GLM."

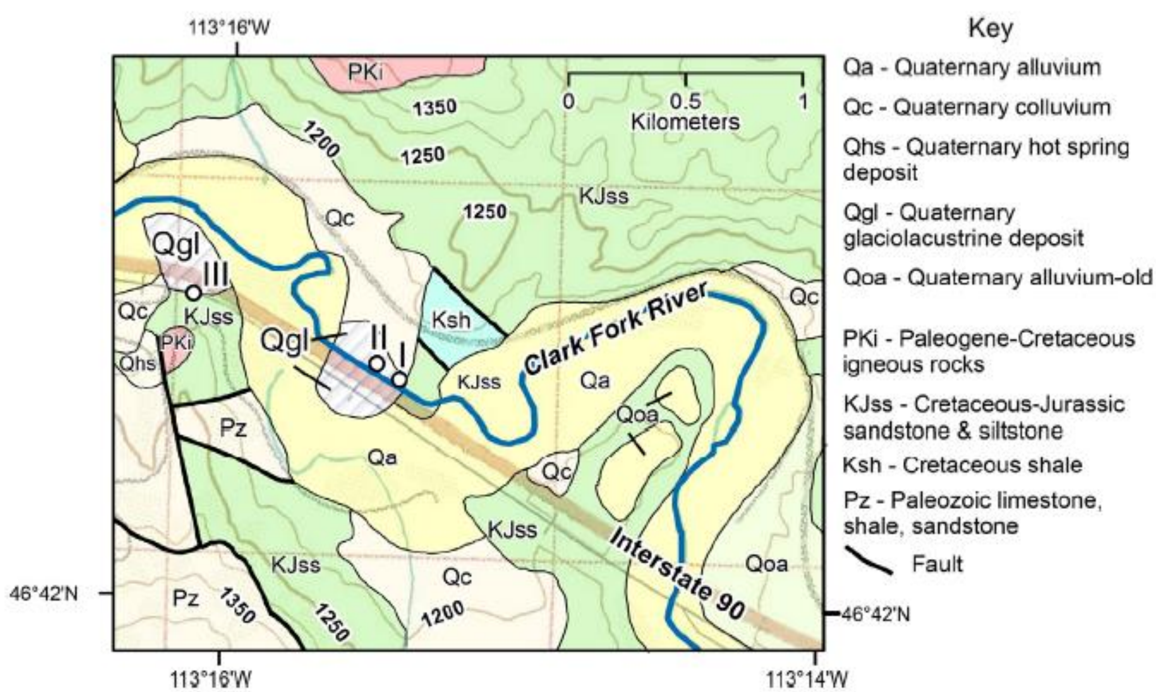


Figure 23. Geologic map of the Garden Gulch area. I, II, and III show locations of dated samples. The field trip will see locations I & II (from Smith et al., 2018).

After the 2014 field guide, I (Larry) did a great deal more work and sampling of horizons for OSL dating. The sedimentology is described in Smith (2017) and the ages, initially working with Olav Lian at the University of Fraser Valley (UFV), and then with the DTU lab were published in Smith et al. (2018). Additional unpublished dates from the DTU lab and from USU are included in Figure 24.

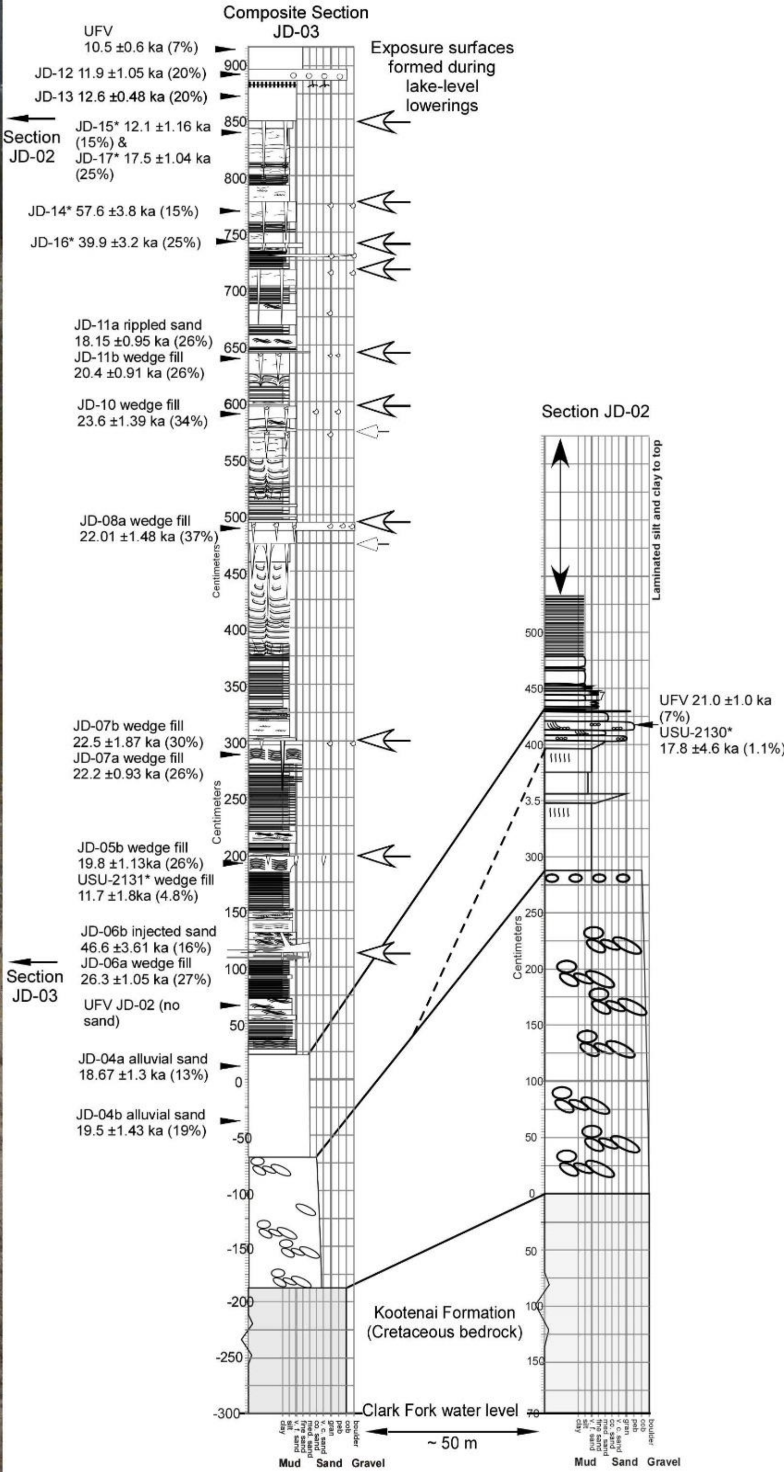
The major points of this stop are to:

1) Look at the initial transgression of Lake Missoula beds over gravels and determine whether an unconformity may or may not be at this contact.
2) Evaluate the periglacial processes shown by frost cracks
3) See evidence for lake level lowerings

Figure 24. (Next page) Summary of stratigraphic sections and chronology of the Garden Gulch area. The lower diagram compares estimated doses (De) from feldspar and quartz. The feldspar De's are about 70% of those of quartz, which is expected if the quartz is well bleached.

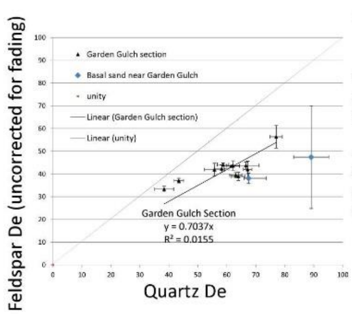
Garden Gulch stratigraphic sections and optical ages on quartz (Smith et al., 2017, 2018) and unpublished

*(xy%) = assumed water content; UFV = University of Fraser Valley; USU = Utah State University; all others DTU-NLL Risø; * - unpublished*



Comparison of estimated doses for K-feldspar and quartz

~70% $Q_{DE} = Kf_{DE}$



- The lower D_E values for feldspar (uncorrected for fading) are expected if bleached. Feldspar is more difficult to bleach, therefore the quartz is likely well bleached
- One sample (46.6 ±3.61 ka) is not shown as it is well above the chart, well above the 1:1 relationship. This sample s poorly bleached and interpreted as remobilized sublacustrine sand.

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Return to the frontage road, turn right to travel east back to I-90, or turn left to travel west back to I-90.

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REFERENCES CITED

Alden, W.C., 1953, Physiography and glacial geology of western Montana and adjacent areas: v. 231, 200 p., https://pubs.er.usgs.gov/publication/pp231.

Alho, P., Baker, V.R., and Smith, L.N., 2010, Paleohydraulic reconstruction of the largest Glacial Lake Missoula draining(s): Quaternary Science Reviews, v. 29, p. 3067–3078, doi:10.1016/j.quascirev.2010.07.015.

Alt, D., 2001, Glacial Lake Missoula and Its Humongous Floods: Missoula, Mountain Press, 208 p.

Alt, D., and Chambers, R.L., 1970, Repetition of the Spokane flood, *in* American Quaternary Association Meeting 1, Bozeman, Montana State University, p. 1.

Atwater, B.F., 1986, Pleistocene Glacial-Lake Deposits of the Sanpoil River Valley, Northeastern Washington: U.S. Geological Survey, v. 1661, p. 39.

Balbas, A.M. et al., 2017, 10Be dating of late Pleistocene megafloods and Cordilleran Ice Sheet retreat in the northwestern United States: Geology, v. 45, p. 583–586, http://geology.geoscienceworld.org/content/45/7/583?etoc= (accessed May 2017).

Breckenridge, R.M., 2004, Field Trip Guide to Glacial Lake Missoula and the Clark Fork ice dam area: Northern Idaho and western Montana: (IAFI field trip guide, unpublished).

Breckenridge, R.M. et al., 1989, Glacial Lake Missoula and the Channeled Scabland, *in* International Geological Congress, 28th, Guidebook, Washington D.C., American Geophysical Union, p. 72, doi:10.1029/FT310.

Chambers, R.L., 1984, Sedimentary evidence for multiple glacial Lakes Missoula, *in* McBane, J.D. and Garrison, P.B. eds., Northwest Montana and Adjacent Canada, Billings, Montana Geological Society, p. 189–199.

Chambers, R.L., 1971, Sedimentation in glacial Lake Missoula: Missoula, University of Montana, Missoula, 100 p.

Chapot, M.S., Sohbati, R., Murray, A.S., Pederson, J.L., and Rittenour, T.M., 2012, Constraining the age of rock art by dating a rockfall event using sediment and rock-surface luminescence dating techniques: Quaternary Geochronology, v. 13, p. 18–25, doi:10.1016/j.quageo.2012.08.005.

Curry, R.R., Lister, J.C., and Stoffel, K., 1977, Glacial history of Flathead Valley and Lake Missoula floods, *in* Smith, D.G., Curry, R.R., Lister, J.C., and Stoffel, K. eds., Glacial Geology of Flathead Valley and Catastrophic Drainage of Glacial Lake Missoula, Missoula, Geological Society of America, Rocky Mountain Section, p. 14–38.

Fritz, W.J., and Smith, G.A., 1993, Revisiting the Ninemile section: Problems with relating glacial Lake Missoula stratigraphy to the Scabland-floods stratigraphy, *in* EOS (Transactions, American Geophysical Union), American Geophysical Union, p. 302.

Hanson, M.A., Lian, O.B., and Clague, J.J., 2012, The sequence and timing of large late Pleistocene floods from glacial Lake Missoula: Quaternary Science Reviews, v. 31, p. 67–81, doi:10.1016/j.quascirev.2011.11.009.

Harrison, J.E., and Cressman, E.R., 1993, Geology of the Libby thrust belt of northwestern Montana and its implications to regional tectonics: Professional Paper, p. 42, doi:10.3133/PP1524.

Harrison, J.E., Cressman, E.R., and Whipple, J.W., 1992, Geologic and structure maps of the Kalispell 1 degree x 2 degrees quadrangle, Montana, and Alberta and British Columbia: U.S. Geological Survey Miscellaneous Investigations Series Map I-2267, p. Scale 1:250,000, https://ngmdb.usgs.gov/Prodesc/proddesc_10204.htm (accessed October 2019).

Langton, C.M., 1935, Geology of the Northeastern Part of the Idaho Batholith and Adjacent Region in Montana: Journal of Geology, v. 43, p. 27–60, doi:10.1086/624269.

Lee, K., 2009, Catastrophic flood features at Camas Prairie, Montana: More unusual currents in glacial Lake Missoula:, https://inside.mines.edu/UserFiles/File/Geology/Camas_red.pdf.

Levish, D.R., 1997, Late Pleistocene sedimentation in glacial Lake Missoula and revised glacial history of the Flathead Lobe of the Cordilleran Ice Sheet, Mission Valley, Montana: University of Colorado, 191 p.

O'Connor, J.E. et al., 2020, The Missoula and Bonneville floods—A review of ice-age megafloods in the Columbia River basin: Earth-Science Reviews, v. 208, p. 103181, doi:10.1016/j.earscirev.2020.103181.

Pardee, J.T., 1910, The Glacial Lake Missoula: Journal of Geology, v. 18, p. 376–386, doi:https://doi.org/10.1086/621747.

Pardee, J.T., 1942, Unusual Currents in Glacial Lake Missoula, Montana: Bulletin of the Geological Society of America, v. 53, p. 1569–1600, doi:10.1130/GSAB-53-1569.

Rades, E.F.F., Sohbati, R., Lüthgens, C., Jain, M., and Murray, A.S.S., 2018, First luminescence-depth profiles from boulders from moraine deposits: Insights into glaciation chronology and transport dynamics in Malta valley, Austria: Radiation Measurements, v. 120, p. 281–289, doi:10.1016/J.RADMEAS.2018.08.011.

Sears, J.W., 2020, Faults and floods of the Missoula Valley: Northwest Geology, v. 49, p. 103–

118.

Smith, L.N., 2006, Stratigraphic evidence for multiple drainings of glacial Lake Missoula along the Clark Fork River, Montana, USA: Quaternary Research, v. 66, p. 311–322, doi:10.1016/j.yqres.2006.05.009.

Smith, L.N., and Hanson, M.A., 2014, Sedimentary record of glacial Lake Missoula along the Clark Fork River from deep to shallow positions in the former lakes: St. Regis to near Drummond, Montana, *in* Shaw, C.A. and Tikoff, B. eds., Exploring the Northern Rocky Mountains, Geological Society of America, v. 37, p. 51–63, doi:10.1130/9780813700373.

Smith, L.N., Sohbati, R., Buylaert, J.-P., Murray, A., Jain, M., and Welk, E., 2017, Chronology of Montana's glacial Lake Missoula: Current status: GSA Annual Meeting in Seattle, Washington, doi:10.1130/ABS/2017AM-300238.

Smith, L.N., Sohbati, R., and Jain, M., 2021, Rock surface luminescence dating of flood deposited gravel determines the age of a glacial outburst megaflood, glacial Lake Missoula, Montana, USA, *in* AGU Fall meeting Abstracts, American Geophysical Union (AGU).

Smith, L.N., Sohbati, R., Murray, A.S., and Jain, M., 2019, First luminescence dating of flash-flood gravel clasts: Deposits from draining of glacial Lake Missoula, Montana, USA, *in* INQUA 20th Congress Abstracts, Dublin, Ireland, INQUA.

Smyers, N.B., and Breckenridge, R.M., 2003, Glacial Lake Missoula, Clark Fork ice dam, and the floods outburst area: Northern Idaho and western Montana, *in* Swanson, T.W. ed., GSA Field Guide 4: Western Cordillera and Adjacent Areas, Boulder, Geological Society of America, p. 1–15, doi:10.1130/0-8137-0004-3.1.

Sohbati, R., 2016, Encyclopedia of Scientific Dating Methods (W. J. Rink & J. Thompson, Eds.): Dordrecht, Springer Netherlands, 1–5 p., doi:10.1007/978-94-007-6326-5.

Sohbati, R., Murray, A.S., Jain, M., Buylaert, J.-P.P., and Thomsen, K.J., 2011, Investigating the resetting of osl signals in rock surfaces: Geochronometria, v. 38, p. 249–258, doi:10.2478/s13386-011-0029-2.

Souza, P.E., Sohbati, R., Murray, A.S., Clemmensen, L.B., Kroon, A., and Nielsen, L., 2021, Optical dating of cobble surfaces determines the chronology of Holocene beach ridges in Greenland: Boreas, p. 1-13, doi:10.1111/bor.12507.

Taylor, B., 2020, The Hellgate/Clark Fork Canyon 1908 Double Tracking and Rebuild: Mainstreeter, v. 39, p. 13–21, http://www.nprha.org/.

Waitt, R.B., 1980, About forty last-glacial Lake Missoula jökulhlaups through southern Washington: Journal of Geology, v. 88, p. 653–679, doi:https://doi.org/10.1086/628553.

Waitt, R.B., 1985a, Case for periodic, colossal jökulhlaups from Pleistocene glacial Lake Missoula.: Geological Society of America Bulletin, v. 96, p. 1271–1286, doi:10.1130/0016-7606(1985)96<1271:CFPCJF>2.0.CO;2.

Waitt, R.B., 1985b, Reply to Comment on "Periodic Jökulhlaups from Pleistocene Glacial Lake Missoula—New Evidence from Varved Sediment in Northern Idaho and Washington":

Quaternary Research, v. 24, p. 357–360, doi:10.1016/0033-5894(85)90058-4.

Welk, E., 2019, Quaternary geology of the Cabinet, Heron and Smeads Bench 7.5’ quadrangles, with emphasis on glacial Lake Missoula sediment: Montana Tech, 79 p., https://digitalcommons.mtech.edu/grad_rsch/199/.

Zdanowicz, C.M., Zielinski;, G.A., and Germani, M.S., 1999, Mount Mazama eruption: Calendrical age verified and atmospheric impact assessed: Geology, v. 27, p. 621–624, doi:10.1130/0091-7613(1999)027<0621:MMECAV>2.3.CO;2.