Ice Age Floods Through the Mid-Columbia Region

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Chinese travel writers stand at maximum-flood level on Badger Mountain – one of the Lake Lewis Isles

Ice Age Floods Institute Annual Meeting Field Trip

Richland, Washington

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This field guide and road log covers Ice Age flood features mostly within the Pasco Basin, located midway along the 600-mile path of the Missoula floods (Figure 1). The ~150-mile road tour starts in the Tri-Cities at Richland, following the margins of the basin clockwise (Figure 2). Floods invaded the Pasco Basin from multiple directions including from the: 1) northwest via Sentinel Gap, 2) northeast via Ringold and Esquatzel Coulees, and 3) east down the Snake River. At the same time floodwaters exited the basin via a single narrow outlet at Wallula Gap. This hydraulic constriction caused floodwaters to back up to 900 feet deep over the Tri Cities forming temporary Lake Lewis. During each outburst flood Lake Lewis lasted for only a few weeks – the amount of time it took for all the floodwater to drain through Wallula Gap and the Columbia River Gorge (Denlinger and O'Connell 2010).

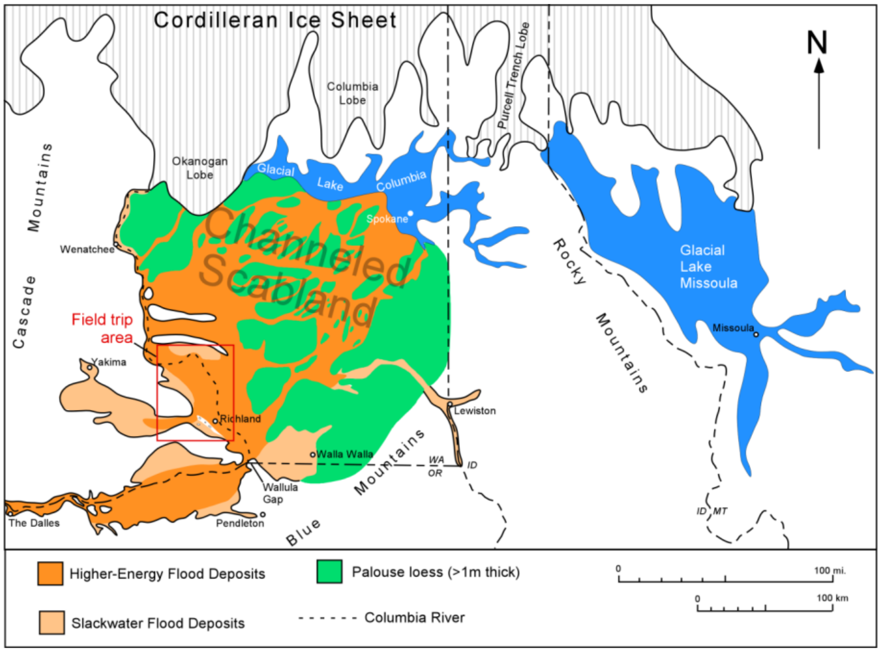


Figure 1. Most Ice Age floods were from periodic outbursts from Glacial Lake Missoula as recently as 15,000 years ago. One very last flood came from the breakup of the Okanogan Lobe releasing the contents of Glacial Lake Columbia a few centuries after the last Missoula flood (Bjornstad and Kiver 2012).

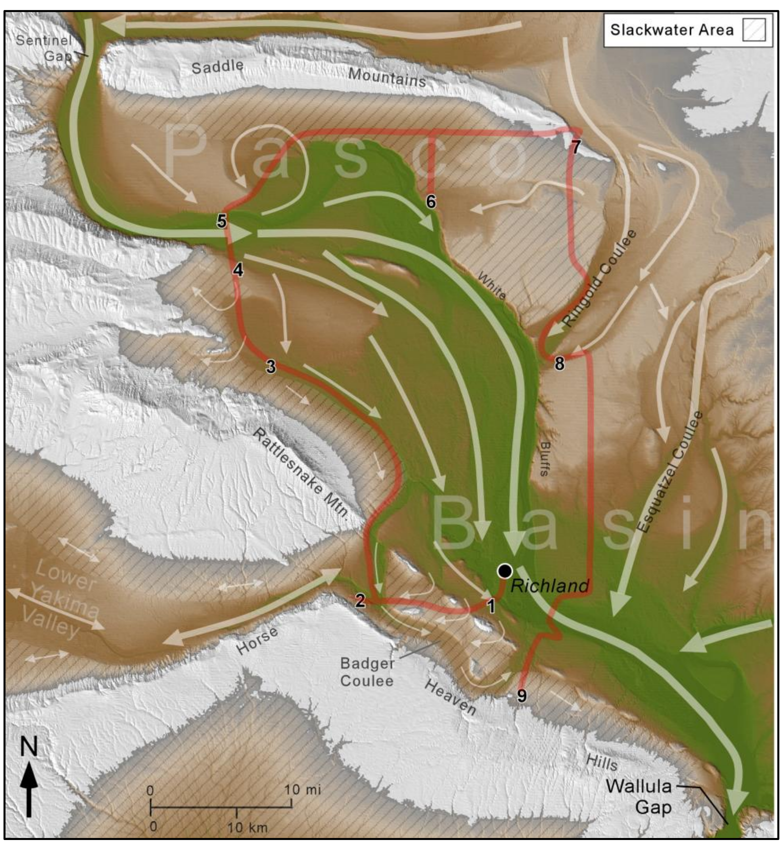


Figure 2. Location map showing field-trip route (red) and planned stops. White areas were above the maximum flood level (>1,200 ft elevation). Size of arrows is proportional to speed and force of Ice Age floods, which was greatest toward the center of the Pasco Basin and within scabland-derived coulees feeding into the basin Slackwater areas existed in the more-protected and backflooded regions inundated by the floods. These included the margins of the Pasco Basin as well as the Yakima and Walla Walla River valleys.

Miles

0 STARTING AT SHILO INN IN RICHLAND GO WEST TOWARD YAKIMA ON INTERSTATE I-182.

4 TAKE QUEENSGATE SOUTH EXIT (3A) OFF I-182. TURN LEFT ON COLUMBIA PARK TRAIL. PARK NEAR BOOKWATER WINERY AND TAKE SHORT WALK TO VIEW BOOKWALTER ERRATIC. RETURN TO I-182 WEST, THEN I-82 WEST TOWARDS YAKIMA.

Stop 1. Bookwalter Erratic

This out-of-place boulder near the Bookwalter Winery (Figure 3) was rafted in on an iceberg as recently as 15,000 years ago during an Ice Age flood. It lies at a relatively low elevation (~490') compared to many other erratics that go up to almost 1,200 ft elevation in the Pasco Basin. A coating of pedogenic calcium carbonate on one side of the erratic suggests the erratic was recently tipped up on it's side; in arid climates calcium carbonate typically accumulates from evaporation of soil moisture only on the undersides of rocks like this one.

Figure 3. Large ice-rafted erratic boulder of granodiorite between I-182 and the Bookwalter Winery in Richland. This is but one of thousands of erratics identified in the Pasco Basin.

Looking south from the erratic are Badger and Candy Mountain, separated by Goose Gap. Only the very tops of these hills protruded above the highest flood levels. These were once part of the Lake Lewis Isles.

Lake Lewis Isles

"'Lake Lewis' is only a general term for possibly several Pleistocene pondings of the Columbia and its tributaries in the southwestern part of the plateau."

Bretz, Smith and Neff (1956)

Lake Lewis Isles (Figure 4) is the name given to several hills south of the Tri-Cities whose crests rose above maximum flood level (~1,200 feet) during Ice Age flooding, making them islands in Lake Lewis (Bjornstad 2006). Only the top 380 feet of Badger Mountain and 190 feet of Candy Mountain poked out above temporary Lake Lewis (Figure 5).

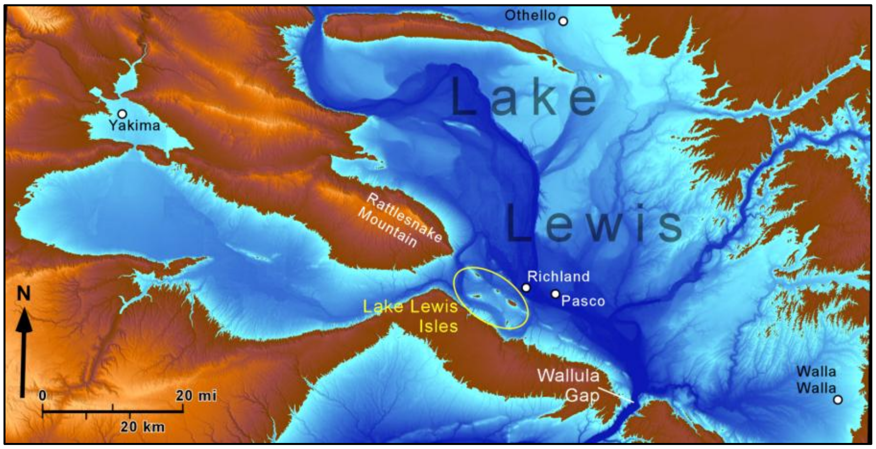


Figure 4. Lake Lewis and vicinity. During the largest Ice Age floods Red, Candy and Badger Mountains, as well as Goose Hill and Eagle Butte, were islands surrounded by a slurry of muddy, ice-laden floodwater. Darkest blue indicates deepest floodwaters; brown areas were above maximum flood level (>1,200 ft elev.).

Many light-colored, misplaced boulders like that in Figure 3, are scattered around the margins of the basin; these are ice-rafted erratics – calling cards left behind by the floods. Icebergs floating in Lake Lewis ended up getting pushed to margins of the Pasco Basin and collected in the quieter waters around these islands as well as within Badger Coulee where slackwater rhythmites also formed (see Figure 6). Strandlines, which mark former lake levels in some long-standing lakes (such as Glacial Lake Missoula), are weakly developed to nonexistent in Lake Lewis. That's because the lake was extremely short lived - lasting only a few weeks or less before all the floodwaters drained through Wallula Gap, down the Columbia River Gorge and on out to the Pacific Ocean.

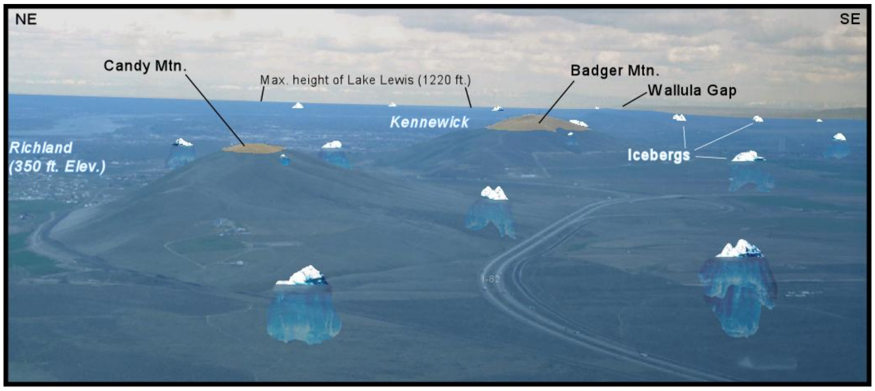


Figure 5. Two of the Lake Lewis Isles (Badger and Candy Mountain) within the southern Pasco Basin. Tri-Cities was submerged under as much as 900 ft of water during the largest Missoula floods. This is indicated by the level of highest ice-rafted erratics as well as erosion through Wallula Gap, which extends to ~1,200 ft elevation.

The combination of warm sun and fine soils laid down on the south-facing sides of Lake Lewis Isles, especially on Red Mountain, consistently produces nationally acclaimed wines.

Floods and Fine Wine?

Grapes grown on Ice Age flood deposits, like these on Red Mountain, produce excellent wine.

The Ice Age floods are largely responsible for the many fine wines produced in the Mid-Columbia Basin. Ninety percent of Washington vineyards are located in areas directly affected by glacial-outburst floods. Washington is second only to California in terms of wine produced in the United States. Currently, there are over 160 wineries within a 50-mile radius of the Tri Cities. The "terroir" of wine depends on the complex balance and interplay between a number of environmental factors such as climate, soil type, bedrock depth, drainage and aspect. Among these factors, the common denominator for vineyards in southeastern Washington is that most are underlain by soils developed in fine-grained slackwater flood sediments from Ice Age floods or from windblown sediment derived from reworking of the uppermost flood deposits. Soils containing slackwater flood deposits are nutrient poor and calcic with abundant fine sand and silt, which allow for good drainage, while simultaneously providing high moisture-retention capacity, all favorable wine grape-growing characteristics.

The most prolific and renowned wine-producing areas in the Mid-Columbia lie along the central portions of the Walla Walla and Yakima valleys and more recently, the southern margins of the Pasco Basin around Red Mountain. Not coincidentally, these areas all are blanketed by fine-grained slackwater deposits from the Ice Age floods. So next time you enjoy a glass of fine Mid-Columbia wine, make a toast to the cataclysmic floods that long ago inundated this region.

14 Take Benton City exit 96 off I-82 at Kiona and drive south on Webber Canyon Road before turning right on McBee Road. Proceed partway up McBee Grade to an irrigation canal, turn right, and park just past canal.

Stop 2. Badger Coulee

Badger Coulee is a streamless, 15-mile long valley that marks the former course of the Yakima River (see Figure 2). The tall Horse Heaven Hills form the coulee's southern boundary. During the Ice Age floods, the coulee became plugged with flood deposits, causing the Yakima River to be diverted north away from Badger Coulee (Bjornstad 2006). The most recent flood deposits consisted mostly of slackwater rhythmites. These rhythmites are exposed along many roadcuts in Badger Road where up to 20 rhythmites are exposed. Toward the top of the slackwater beds you'll also see a double layer of Mount St. Helens ash ("set S") that was deposited during a volcanic eruption near the end of Ice Age flooding (Figure 6).

Figure 6. Slackwater flood rhythmites in Badger Coulee containing the double-layered Mount St. Helens "S" volcanic ash. Ash was deposited between two of the last Ice Age floods about 16,000 years ago. Each graded rhythmite likely represents deposition during a single Ice Age flood event, separated by up to dozens of years.

Far below the slackwater rhythmites in Badger Coulee are gravel-dominated flood deposits when much faster floodwaters, from an earlier time, passed through Badger Coulee (Figure 7). At least two layers of gravel-dominated flood deposits are found 50 feet or more below the former land surface. The lower layer is browner - probably more weathered - than the layer immediately above it. Inclined, foreset bedding within the flood gravels indicates high-energy floodwaters flowed from west to east down the coulee. Fine-grained sediments sampled from the lower layer exhibit reversed magnetic polarity ("R" in Figure 7), while younger layers above show normal magnetic polarity (Baker et al. 1991; Bjornstad et al. 2001). Because the last magnetic reversal took place about 780,000 years ago, the magnetically reversed flood deposits near the bottom of Figure 7 must be at least 780,000 years old from much earlier Ice Age floods.

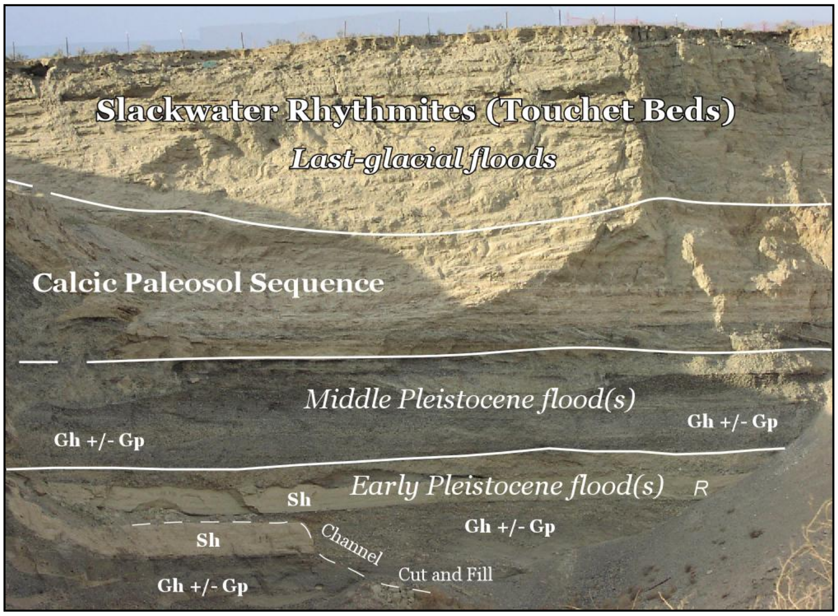


Figure 7. Sedimentary deposits exposed in borrow pit at west end of Badger Coulee visible from Stop 2 (see also Figure 9). Here is preserved strong evidence for some extremely old floods. Sh = horizontally laminated sand, Gh = horizontally bedded gravel and sand, Gp = planar-tabular cross bedded gravel and sand. Inclined beds in the gravel dip from left to right, indicating a paleoflow direction to the east. A thick paleosol sequence separates older flood gravels at base from slackwater rhythmites above. R = sediment sample with reversed magnetic polarity (>780,000 yrs).

Above the two layers of flood gravel is a thick zone of soil formation with layers of caliche, an ancient, buried soil containing a large amount of calcium carbonate. This paleosol is dated at more than 210,000 years old. This means that an Ice Age flood deposited the middle, flood-gravel layer between 210,000 years and 780,000 years ago. Most or all the slackwater deposits at the top of the exposure are from Ice Age floods associated with the last glacial cycle, which occurred between ~25,000 years and 15,000 years ago.

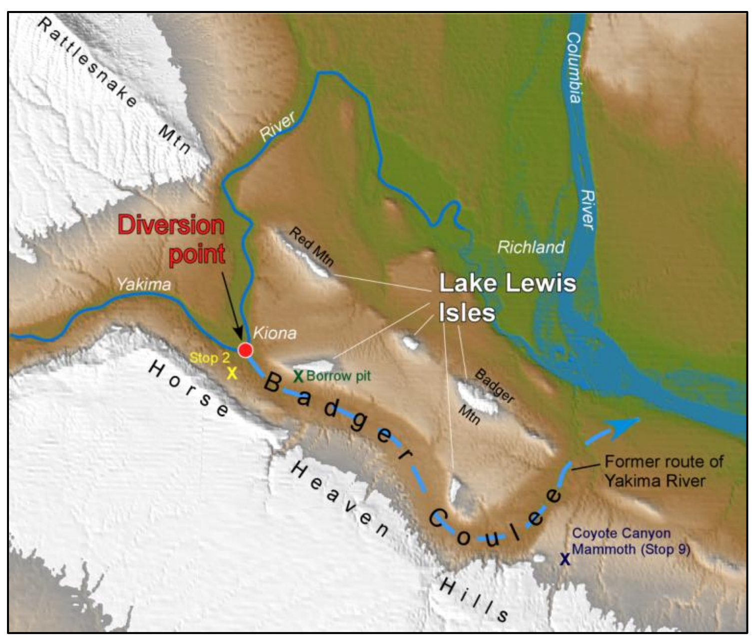
So why was there a sudden change in types of sediments laid at this location? The gravels in the lower layers were probably laid down when early floods were allowed to move unimpeded and thus more rapidly, through Badger Coulee (Bjornstad 2006). Over time, as the coulee became blocked with younger flood deposits, Badger Coulee was cut off from faster moving floodwaters. Blockage of the coulee also led to creation of the Yakima River Diversion (see below) out of Badger Coulee. A few icebergs also collected in this area that left behind ice-rafted debris along the coulee. The largest ice-rafted erratic found to date in the Mid-Columbia lies in Badger Coulee (Figure 8).

Figure 8. Largest ice-rafted erratic reported for eastern Washington. Left: This isolated, granodiorite boulder (circled) lies perched high on hillside about 300 vertical ft above the floor of Badger Coulee. Right: Michael Melford photographs the same erratic boulder in May, 2013 for a feature article on the Ice Age floods to be published in *National Geographic*.

Yakima River Diversion

Before the Ice Age, the Yakima River flowed through Badger Coulee, joining the Columbia River just below from where it enters today (Figure 9). Early in the history of flooding, the river was diverted north from Kiona after a build up of flood deposits blocked the coulee (Bjornstad 2006). Apparently, when these deposits accumulated to about 700 feet elevation, the Yakima River found a new, lower route into the central Pasco Basin through a saddle between Rattlesnake and Red mountains. Since that time, Badger Coulee became an area of strictly slackwater deposition during flooding, accounting for the extensive slackwater flood deposits that blanket the floor of the coulee (represented in upper part of Figure 7).

Figure 9. The former route of the Yakima River before the Ice Age is indicated by the dashed blue arrow. Since the Ice Age the Yakima River carved a new channel between Rattlesnake and Red Mountains after Badger Coulee became blocked with flood deposits. Areas in white were above maximum flood level.



Return to Kiona. Continue north through Benton City on SR 225 to SR 240.

26 Turn left (northwest) on SR 240. Travel up the Cold Creek Valley. Note lots of granitic, Ice-rafted erratics along road around MP 15.

37 Pull out onto wide area on the southwest side of SR 240 (MP 10).

Stop 3. Rattlesnake Slope Erratics and Bergmounds

" … isolated berg 'nests' and lone erratic boulders in so many places in the scabland, are irrefutable evidence for abundant floating glacial ice and, where closely spaced, are equally good evidence for the grounding of large numbers of these bergs. In Pasco basin, they obviously drifted ashore in a wide semiponded tract."

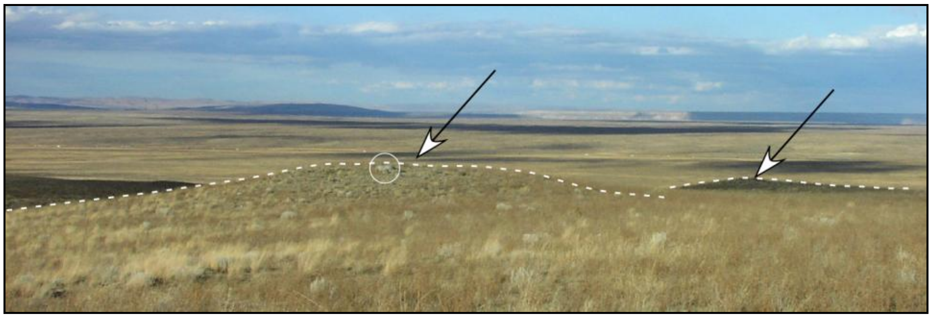
Bretz, Smith and Neff (1956)

Over the last 10 years over 2,100 erratics, erratic clusters and/or bergmounds have been identified and mapped on the northern slope Rattlesnake Mountain within the Hanford Reach National Monument (Bjornstad 2014). A proliferation of ice-rafted debris (Figure 10) is found here probably because icebergs tended to migrate to and concentrate in, slackwater areas such as Rattlesnake Mountain, just upstream of the first major constriction for Ice Age floods at Wallula Gap. Most erratics found in this area are smaller than a suitcase, but some as big as a car! Ninety-five percent are composed of rocks very different from the dark-colored Columbia River basalt, the only local rock type. About 75% are grantitic, a prevalent rock type near the ice dam that blocked Glacial Lake Missoula. Other exotic rock types that make up erratics on Rattlesnake Mountain include quartzite, diorite, argillite, schist, gneiss and gabbro. In particular, granitic rocks are easy to spot on Rattlesnake Mountain because of their light color. They stand out in stark contrast to the dark, local basalt and sparse, low-growing vegetation. Isolated erratics probably represent "dropstones" that melted out from free-floating icebergs before they became grounded or got carried farther downstream. Erratic clusters formed from the grounding of smaller icebergs and bergmounds (Figures 11 and 14) probably developed from larger, grounded icebergs (Fecht and Tallman 1978) containing lots of debris.

Figure 10. Ice-rafted erratics from Rattlesnake Mountain. Far left: Huge ice-rafted erratic of granodiorite in the Cold Creek valley visible from Stop 3. Total length of this granodiorite erratic, which is split in two, is 24 feet. Right: Cluster of banded argillite boulders in foreground likely derived from area of the ice dam in northern Idaho. Note bergmound in background.

Along the north slope of Rattlesnake Mountain erratics are found up to an elevation of 1,165 feet (Figure 12). This, in combination with the maximum elevation of flood erosion in Wallula Gap (~1,220 ft), indicates the largest floods within the Pasco Basin rose to 1,200 to 1,250 ft elevation (Bjornstad 2006). Most ice-rafted debris is concentrated between 600 and 1,000 ft elevation (Figure 13). Only a few erratics and bergmounds lie above 1,000 ft elevation indicating there were only a few very large floods, as suggested by Benito and O'Connor (2003), with most being relatively smaller. Three widely dispersed erratics on Rattlesnake Mountain, shown in Figure 12, were sampled and analyzed for cosmogenic-exposure dating (Keszthelyi et al. 2009); all three had an age of ~17,000 years. This is about the same age obtained on a radiocarbon sample of the Coyote Canyon Mammoth that we'll be visiting at the end of the field trip.

Figure 11. Bergmounds on the north slope of Rattlesnake Mountain. Note large erratic granodiorite boulder atop bergmound (circled).



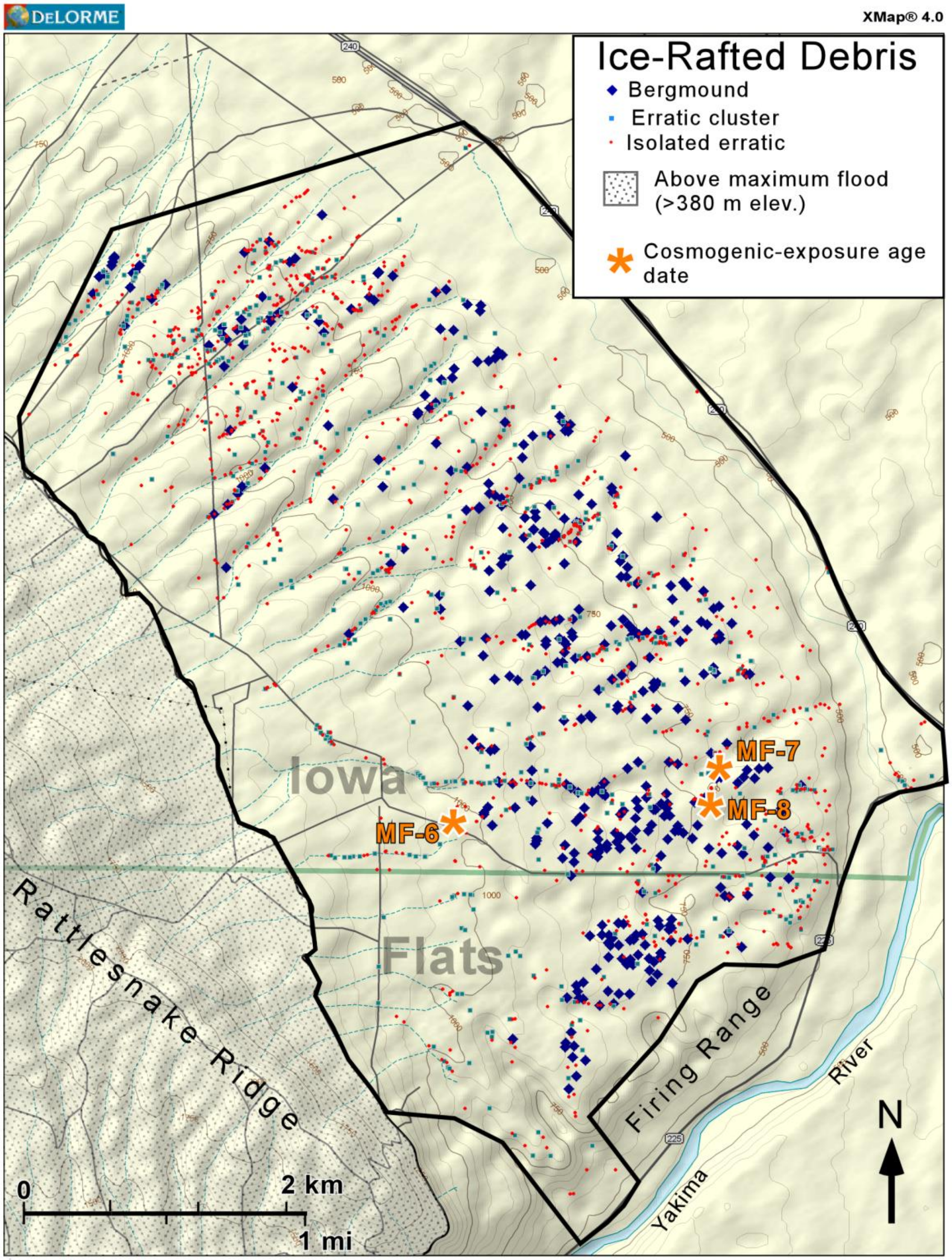


Figure 12. Ice-rafted debris on the northeast slope of Rattlesnake Mountain within the Hanford Reach National Monument. Floodwater flow was from upper left to lower right (see Figure 2). So far a total of ~2,100 isolated erratics, erratic clusters, or bergmounds have been mapped on Rattlesnake Mountain. Maximum elevation of ice-rafted debris is 1,165 ft. Note how many erratics are aligned with arroyos for reasons explained in the text. From Bjornstad (2014).

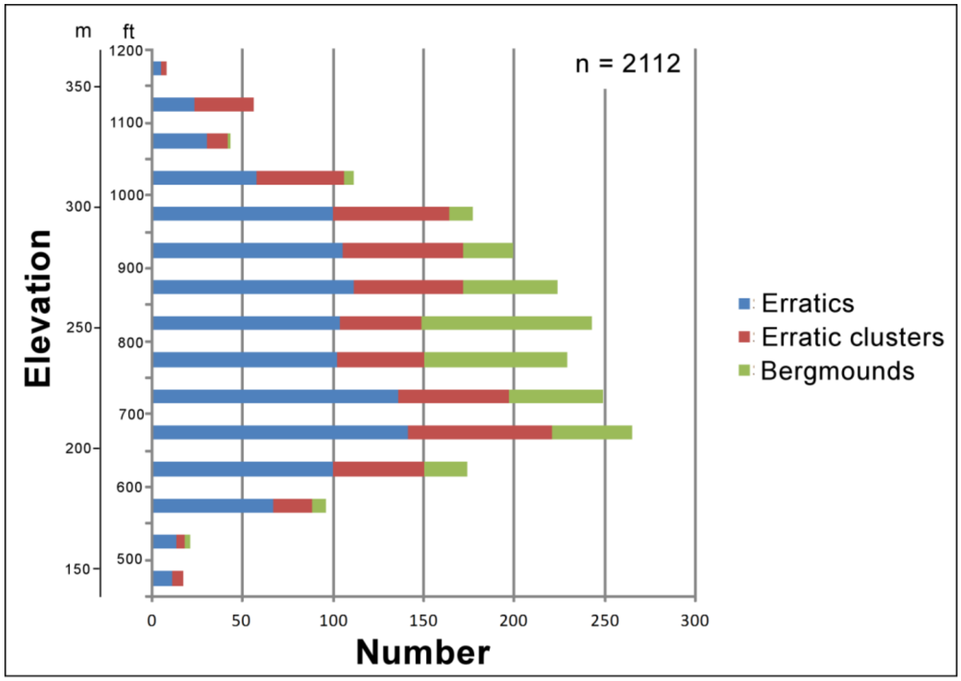


Figure 13. Vertical distribution of erratics, erratic clusters and bergmounds on Rattlesnake Mountain. Note how erratics and erratic clusters extend to near 1,200 ft yet bergmounds generally disappear above ~1,000 ft elevation.

On Rattlesnake Mountain erratics are found along the many parallel gullies that drain the mountain to the northeast (Figure 12). At lower elevations, erratics are concentrated along leeward, south-facing slopes of gullies. At higher elevations, they're found on gully bottoms. "Erratic behavior" in these gullies may be due to eddy currents during the Ice Age floods. That is, currents caused floodwaters to flow at slightly different speeds across the uneven surface. As floodwaters moved across the uneven surface of Rattlesnake Mountain, many erratic-bearing icebergs congregated into pre-existing gullies that trend crosswise to flood flow. Many erratics also have been found along roadways, apparently dug up during road construction. This means that many more erratics from older floods may lie buried beneath the surface.

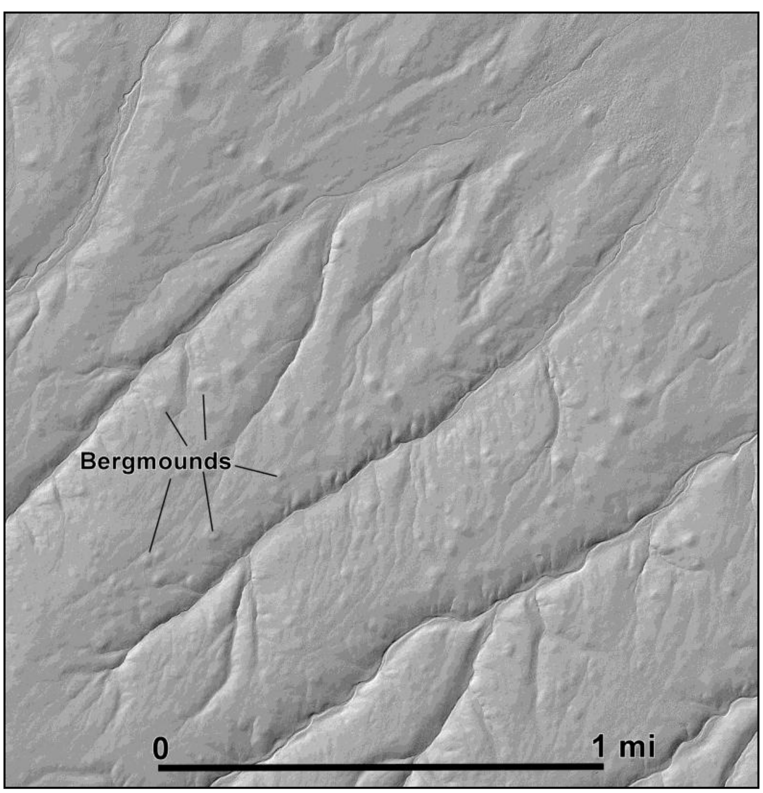


Figure 14. LiDAR (Light Detection and Ranging) image on Rattlesnake Slope. This new remote-sensing technique strips away above-ground structures and vegetation revealing a high-definition image of the underlying land surface. Clearly visible circular bumps are bergmounds left behind when large icebergs grounded against the hillside during Ice Age flooding.

Bergmounds are not seen above ~ 1,000 feet in elevation (Figures 12 and 13). Why only 1,000 ft if we know the floods went at least another 200 feet higher? Apparently, larger deep-rooted icebergs were forced to ground farther away from the ancient shorelines of transient Lake Lewis and when the icebergs melted, they left their debris at that elevation (Figure 15).

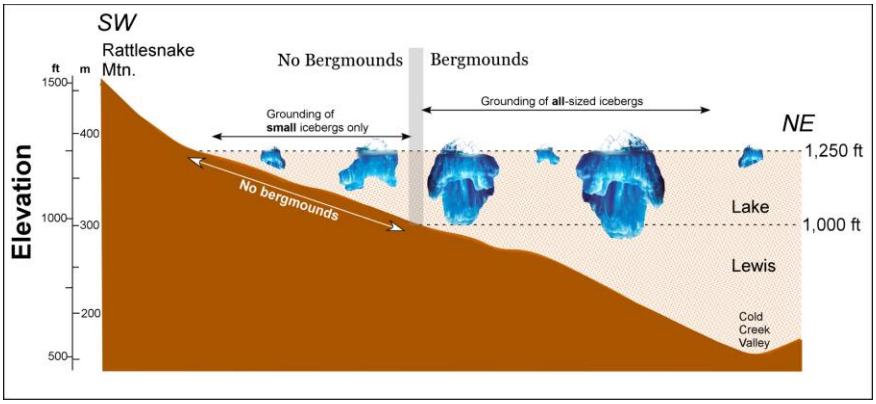


Figure 15. Explanation for the elevation limit observed for bergmounds. Apparently the largest bergmound-producing icebergs became grounded on the gently sloping lake bottom, farther from the ancient shores of Lake Lewis.

45 ASCEND TO FLAT ELEVATED SURFACE OF THE COLD CREEK FLOOD BAR

47 LOTS OF BERGMOUNDS VISIBLE HERE AT INTERSECTION OF SR 240 WITH SR 24. HERE ALSO IS THE YAKIMA BARRICADE - THE WEST ENTRANCE INTO THE HANFORD SITE. CONTINUE STRAIGHT (NORTH) ON SR 24 EAST.

Yakima Barricade Bergmounds

"This extraordinary display of hundreds of till mounds, up to 20 feet high and 100 feet or so in diameter, is unapproached by any other record of icebergs in scabland floods."

Bretz, Smith and Neff (1956)

During the Ice Age floods, large icebergs collected in backeddies as floodwaters swirled around and over the east end of Umtanum Ridge (Figure 16). When the icebergs melted, their contents of boulders, gravel, sand and silt collected into bergmounds (Figure 17). From the intersection of SR 240 and SR 24 (and a couple of miles west of intersection on SR 24), you'll see many more bergmounds on either side of the highway.

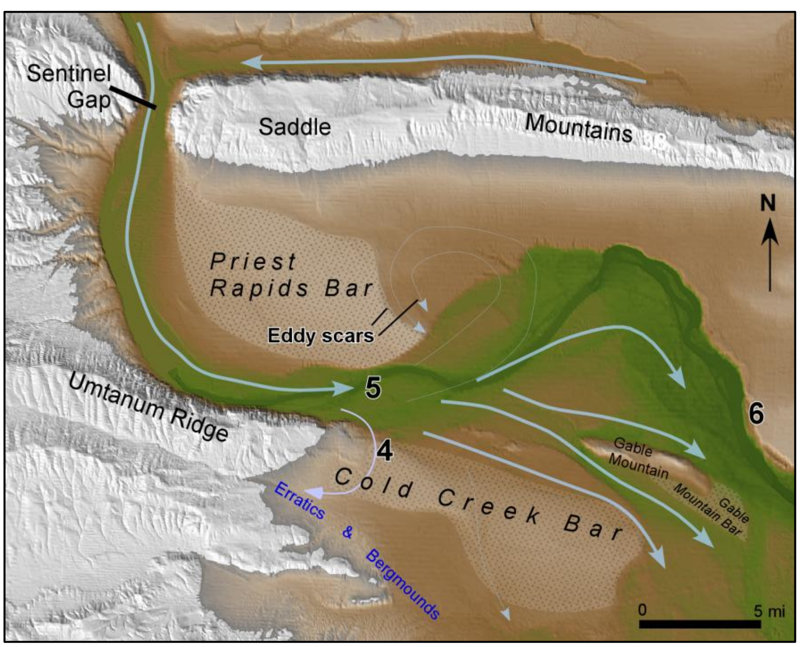


Figure 16. Flood features and flow through the northwestern Pasco Basin. Blue arrows show the changing directions of flow within the basin. Areas in white were above maximum flood level. Erratics and bergmounds concentrated in slackwater areas south of the Cold Creek flood bar. Field-trip stops are numbered.

Figure 17. Bergmound at west end of Cold Creek flood bar near the Yakima Barricade. View is looking south with Rattlesnake Ridge in the background.

48 STOP AT OVERLOOK ALONG NORTHERN EDGE OF COLD CREEK BAR. VIEWS OF PRIEST RAPIDS BAR, HANFORD NUCLEAR REACTORS, WHITE BLUFFS AND SADDLE MOUNTAINS.

Stop 4. Flood Bars Overlook

Flood bars downstream of Sentinel Gap represent the final resting place for the huge amounts of sediment transported by Ice Age floods (Bjornstad 2006). As floodwaters raced through the gap, two mechanisms were at work that led to sediment deposition and creation of these gigantic flood bars. First, there was a sudden change from a constricted flow to more open flow. As the flow expanded, it also slowed down, allowing suspended sediment to be deposited. Second was the dampening effect of Lake Lewis, as it quickly filled, on the speed of the floodwaters. The combination of these two factors resulted in total accumulations of up to 400 feet of flood sediment onto these compound bars.

At this stop is an expansive panorama of the Columbia River, Priest Rapids Bar (Figure 18), Sentinel Gap, Saddle Mountains, White Bluffs, Gable Mountain and the Hanford Site. Notice how Ice Age floods deposited huge flood bars on both sides of the Columbia River channel to about the same elevation (about 800 feet). Priest Rapids bar formed on the north side and Cold Creek bar on the south (Figure 16).

The Cold Creek flood bar on which we stand is composed of hundreds of feet of gravel and sand and classified as an expansion-shoulder-type bar. Floodwaters created the bar when they spread out and slowed in the area. Because of the expansion of the floodwaters here and their slower speed, they couldn't carry as much sediment, which resulted in deposition. With each flood more and more sediment was added to the bar. And at 12 miles long Cold Creek Bar is perhaps the longest flood bar anywhere along the Ice Age floods' path (Figure 16).

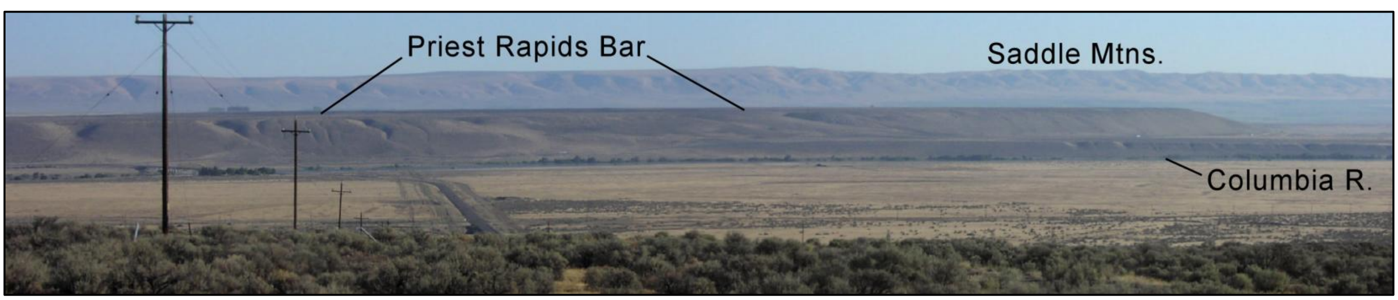


Figure 18. Overlook onto the Priest Rapids flood bar from the top of Cold Creek Bar at Stop 4. Looking north.

Sediments in the lower half of this flood bar retain a reversed magnetic polarity (Pluhar et al. 2006). The magnetism was preserved by tiny magnetic grains in the sediment, deposited when the Earth's magnetic pole was opposite of what it is today. Because the last magnetic reversal was 780,000 years ago, Cold Creek Bar must have started forming early in the Ice Age. This is probably true of many other flood features as well.

Cold Creek Bar has the distinction for being the most studied and best understood of all the Ice Age flood bars because most of the Hanford Site's radioactive and hazardous wastes are stored and/or reside in flood deposits within this bar (Bjornstad et al. 2007). In the 70 years since the Hanford Site was created, geologists have analyzed hundreds of boreholes to characterize and monitor the stored wastes. So understanding the strata and mechanisms behind the Ice Age floods is paramount to understanding the potential for migration of hazardous contaminants off the Hanford Site.

Twenty years ago while excavating a huge waste trench at Hanford, a series of six giant current ripples were unearthed about 25 ft beneath the surface of Cold Creek Bar (Figure 19). The asymmetric ripples are about 6 feet high and 200 feet apart. These are the same dimensions of giant current ripples found elsewhere. Geologists believe the ripples were created when fast moving floodwaters moved from west to east across the northern edge of the bar (Lewis et al. 1993). These ripples were subsequently buried beneath the deposits of one or more younger flood events.

Figure 19. Man-made excavation exposes cross section of several undulating giant current ripples at the Hanford Site. Here a 50-ft trench was dug into the top of Cold Creek Bar. Ripple shape is defined by vegetation, which preferentially grows in moister, fine-grained slackwater sediment that blankets the ripple train. T = ripple trough, C = ripple crest.

51 STOP AT VERNITA REST AREA FOR LUNCH.

Stop 5. Vernita Bridge Rest Area (lunch)

Here at the Vernita Rest Area floodwaters coming down from Sentinel Gap and ponding in Lake Lewis were up to 800 ft deep. The steep south face of Priest Rapids Bar (Figure 18) looms up more than 300 feet high just across the river. The floods flowed powerfully enough here to maintain a channel that scoured the area between Priest Rapids Bar and Cold Creek Bar (Bjornstad et al. 2007). From the Vernita Rest Area there's also a good view of the long, low and flat upper surface of Cold Creek flood bar to the south.

52 AFTER CROSSING THE COLUMBIA RIVER TURN RIGHT (EAST) ONTO SR 24 TOWARDS OTHELLO. NOTE GABLE MOUNTAIN – A TALL BASALT RIDGE TOWARD THE CENTER OF THE BASIN.

Gable Mountain Scabland

Gable Mountain is a Yakima Fold ridge of severely eroded basalt bedrock in the center of the Hanford Site. It received the full force of floods sweeping down from Sentinel Gap. Repeated Ice Age floods eroded Gable Mountain into a streamlined shape - tall and blunt at the upstream end (Figure 20), in contrast to the lower end, which is long and tapered with a tall pendant bar trailing in the downstream direction (see Figure 23). Imagine – even the highest point on Gable Mountain (1,120 feet) was submerged under another 100 ft of floodwater during the largest Ice Age floods! Flood channels up to a mile wide and 140 feet deep were scoured out on either side of the ridge as the floods raced past (see Figures 16 and 24).

Figure 20. Eroded basalt ridge of Gable Mountain, a Yakima Fold within the central Pasco Basin. Ice Age floods, coming out of Sentinel Gap hit this ridge head on before splitting and carving flood channels on either side. The entire mountain was completely awash during the largest floods. Note the distinct northern tilt of the upfolded basalt flows along the ridge.

Priest Rapids Bar and Eddy Scars

"The bar farthest upstream … lies east of the Columbia, is about 12 miles long, 850 feet above tide and nearly 400 feet above the Columbia at its head. It lies on the inside of a broad curve in the valley, its base close to river."

Bretz (1928)

Priest Rapids Bar (Figures 16 and 18), also known as Wahluke bar, is up to 430 feet high, making it one of the tallest bars in the Mid-Columbia Basin. At its northwest end the bar is armored with basaltic boulders ripped out and transported from Sentinel Gap during flooding. Fields of giant current ripples are scattered across the top of the bar. In geologic terms, Priest Rapids Bar represents a combination expansion-crescent bar. It developed on the inside of a huge bend as floodwaters smashed up against Umtanum Ridge and deflected east into the Pasco Basin (Figure 16). Priest Rapids Bar, at 800-900 feet elevation, is the same height as Cold Creek Bar across the river, indicating these two bars developed simultaneously as floods raced into the western Pasco Basin.

As floodwaters expanded into the Pasco Basin, back eddies several miles in diameter formed as floodwaters swirled around the downstream end of Priest Rapids Bar (Figure 16). This is apparent from a couple of large, arc-shaped shallow escarpments (eddy scars) etched into the downstream end of the flood bar (Bjornstad 2006). The higher back eddy is the largest at five miles in diameter! Another eddy scar exists inside the larger one. It is smaller and lies at a lower elevation, suggesting it developed during a smaller flood or a later, lower stage of the same flood.

71 TURN RIGHT OFF SR 24 INTO THE HANFORD REACH NATIONAL MONUMENT (GRAVEL ROAD).

79 CONTINUE 8 MILES TO WHITE BLUFFS OVERLOOK. RETURN TO SR 24.

Stop 6. White Bluffs Overlook

The White Bluffs Overlook (Figure 21) is the premiere viewing site for the 196,000 acre Hanford Reach National Monument (Bjornstad 2006; Bjornstad et al. 2007). Also visible from the overlook are many Hanford operations including the Waste Treatment (i.e., Vitrification) Plant and extensive environmental cleanup projects (including multiple cocooned nuclear-reactor cores) along the Columbia River (Figure 22). The White Bluffs line the north and east sides of the Columbia River for about 30 miles through the central Pasco Basin (see Figure 2). The White Bluffs are composed of ancient river and lake deposits of the Ringold Formation (Lindsey 1996). The deposits accumulated in the Pasco Basin until about 3 million years ago. Since then, the Columbia River and Ice Age floods have cut back down into the Ringold Formation, removing up to 600 feet of deposits from the center of the basin leaving behind the present White Bluffs escarpment. During the largest Ice Age flood, floodwaters at the overlook would have been another 300 feet overhead!

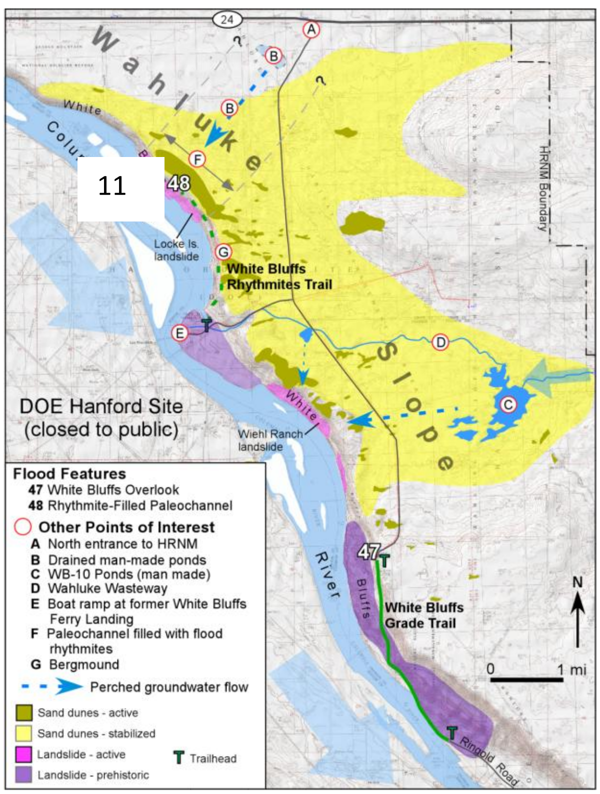


Figure 21. The White Bluffs Overlook (#47) is located within the Hanford Reach National Monument. Large blue arrows show movements of Ice Age floodwater. From Bjornstad (2006).

The White Bluffs also show lots of evidence for landsliding (Figure 21), some of which is associated with Ice Age flooding, but also from very recent slumping after the irrigation water was introduced behind the bluffs starting in the 1960's (Schuster et al. 1987; Bjornstad 2006; Bjornstad and Peterson 2009). Looking downslope from the overlook, immediately below the bluffs, is hummocky topography that is characteristic of a landslide (Figure 22). This landslide is much older and a different style than other, modern landslides occurring along the bluffs. This landslide likely occurred 14,000 years to 15,000 years ago, during or after one of the last Ice Age floods. Unlike modern local landslides, no water is seeping out along the slide, suggesting the water that created this prehistoric slide is no longer present. Also, judging by the rounded and weathered nature of the slump blocks a long time has elapsed since this slope failed.

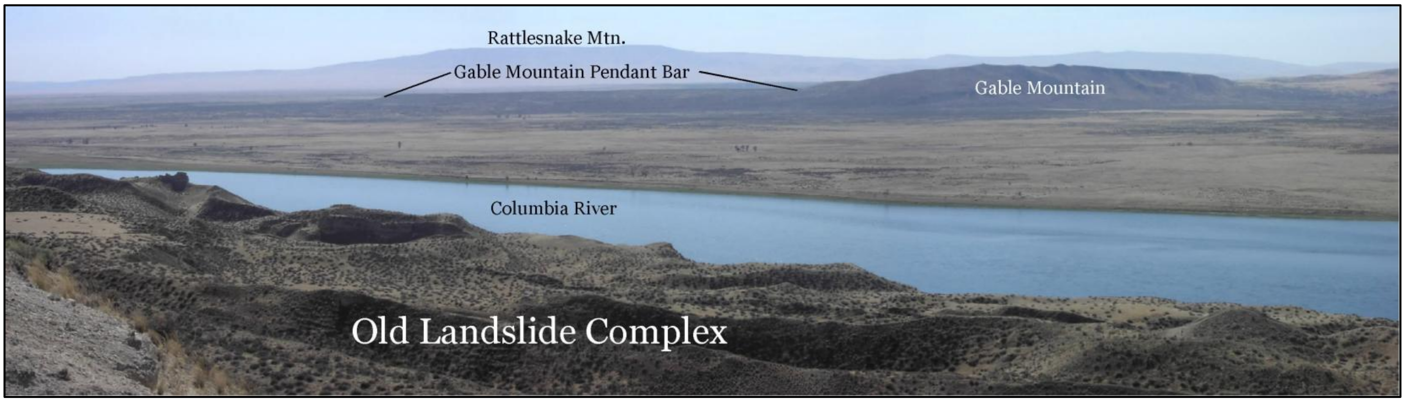


Figure 22. View looking southeast from White Bluffs Overlook onto the U.S. Department of Energy's Hanford Site.

Since the 1960's landsliding resumed when irrigation water was diverted to ponds behind the bluffs (Figure 21) in an effort to enhance wildlife. Since then, this water has migrated to the bluff face, which destabilizes the slopes and leads to slumping. The long string of active sand dunes immediately above the bluffs to the north has formed where winds blow some of the loosened landslide debris back up on top of the bluffs (see Figure 25, left).

Gable Mountain Bar

Also visible from the White Bluffs Overlook (Stop 6) is the 300-ft tall Gable Mountain flood bar located straight across the river on the Hanford Site (Figure 23). It represents one of the best examples of a pendant flood bar, which formed in a more-protected area just downstream (southeast) of Gable Mountain (Bjornstad 2006). Floodwaters deposited this pendant bar as they flowed around Gable Mountain and, at times, completely overtopped its summit.

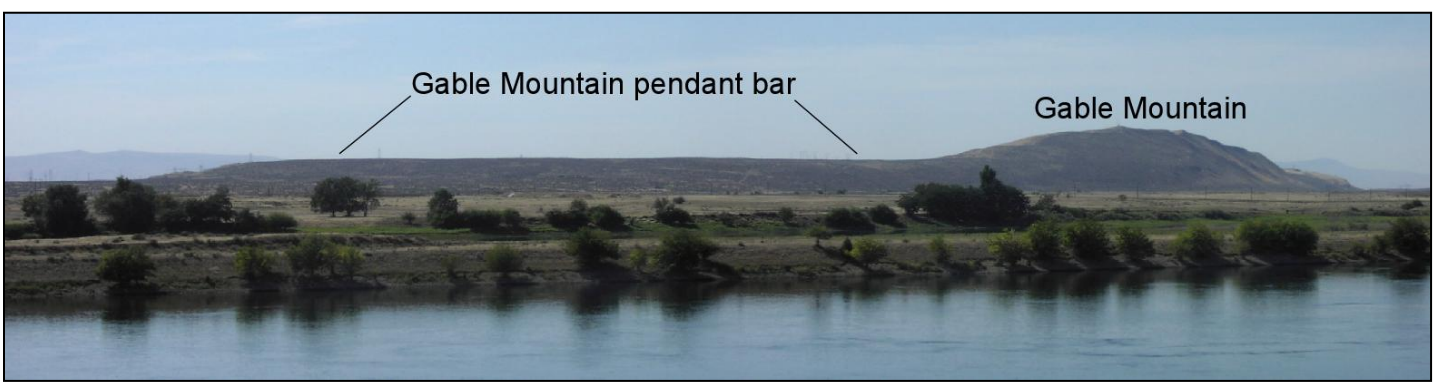


Figure 23. The flat-topped Gable Mountain pendant bar extends on the lee side Gable Mountain for over a mile. View looking southwest. Flow of floodwaters that created the bar was from right to left. The largest Ice Age floods once rose 100 feet over the top of Gable Mountain.

Central Hanford Braidplain

In the distance, to the southeast of the White Bluffs Overlook (Stop 6), is a more subtle flood feature – the Central Hanford Braidplain (Bjornstad 2006). It consists of a broad, complex network of interconnected flood channels beyond the Gable Mountain and Cold Creek flood bars. The dimensions of the braidplain are an incredible 20 miles long by 12 miles wide! The channel network is not visible here or anywhere from ground level, but strikingly apparent on digitally enhanced, shaded-relief image like that in Figure 24. The braidplain was probably formed from the last, successively smaller floods at the end of the last glacial cycle around 14,000 years to 15,000 years ago.

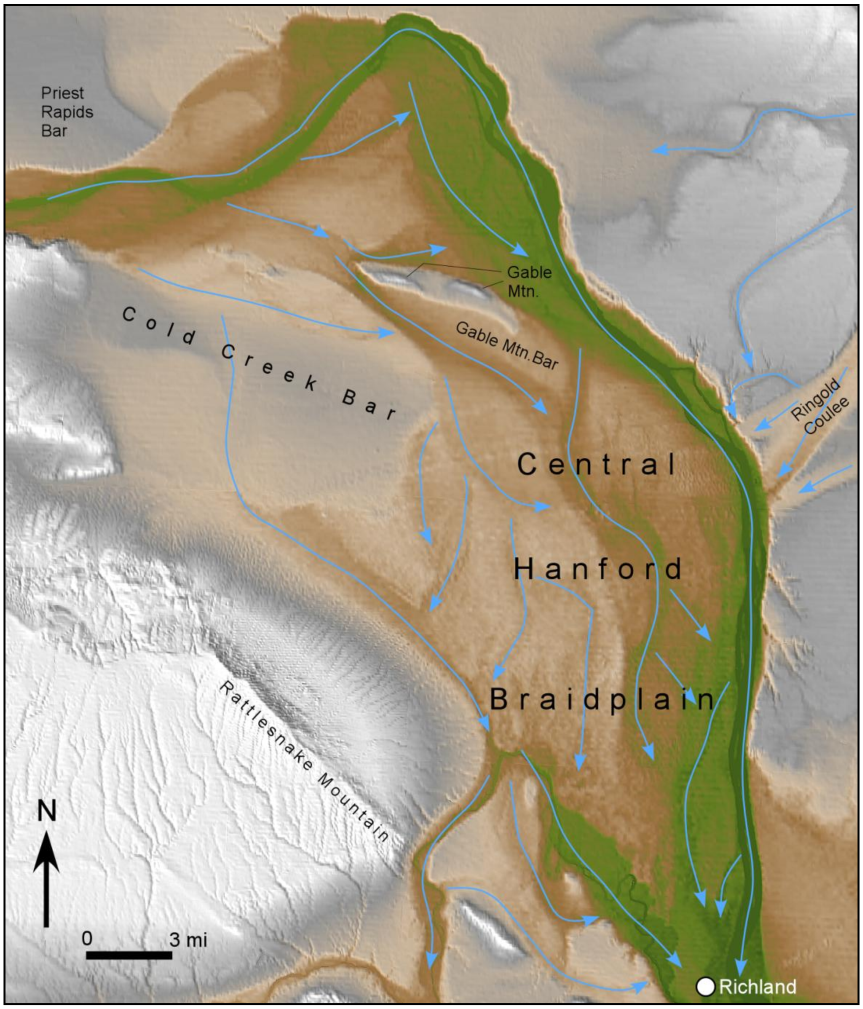


Figure 24. A complex network of interconnected Ice Age flood channels (blue arrows) makes up the Central Hanford Braidplain. The braidplain appears to be soley the result of a flood (or floods) entering the basin from the northwest via Sentinel Gap. From Bjornstad (2006).

White Bluffs Rhythmites

A few miles north of Stop 6 is an unusual paleochannel filled with up to 120 ft of rhythmically bedded slackwater flood deposits (Figures 21 and 25). The origin of the paleochannel is open to debate, but it may belong to the ancestral Crab Creek or another tributary of the Columbia River. In any case, the paleochannel predates the Ice Age floods. The base of the exposed paleochannel today hangs 200 feet above the Columbia River (#48 in Figure 21). Sometime after the channel was abandoned by the stream that cut it, repeated Ice Age floods slowly backfilled the channel with rhythmically bedded slackwater deposits. Since the last floods, tens of feet of wind-blown sand have been deposited over the rhythmite sequence by the predominantly strong southwest winds that have reworked Ringold and flood deposits exposed along the bluffs.

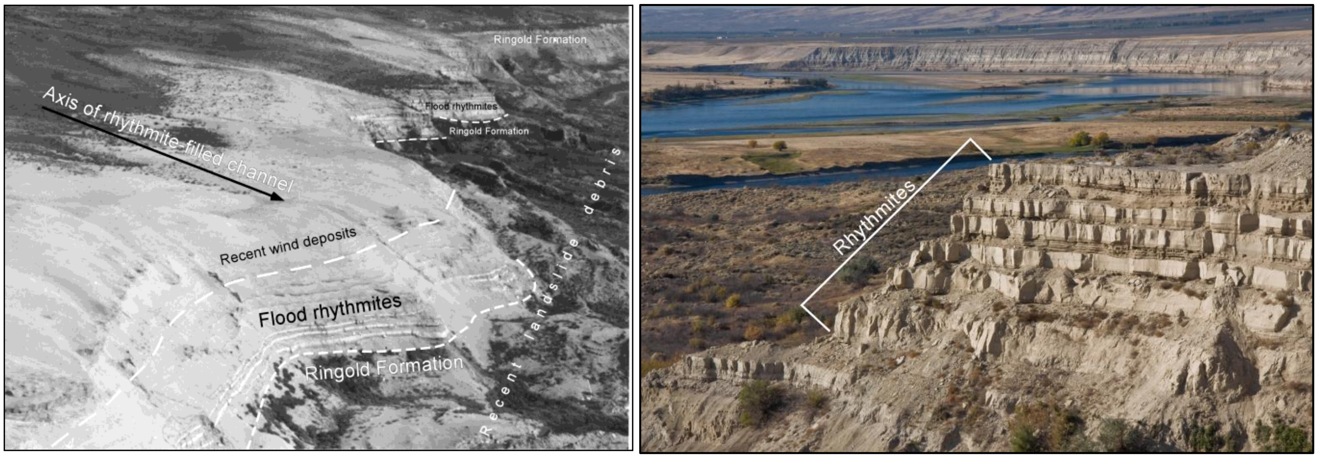


Figure 25. Paleochannel filled with distinctly banded, slackwater flood rhythmites along the northern White Bluffs. Left: The base of the paleochannel is indicated with the short dashed line, while the top of the flood deposits is indicated with the long dashed line. Notice that no flood deposits (or landsliding) are present beyond the margin of the paleochannel in the upper right. Right: closer view of White Bluffs graded rhythmites, each of which likely represents deposition during a separate Ice Age flood event.

Up to about a dozen rhythmites, composed mostly of sand, occur within the channel fill (Bjornstad 2006; Keszthelyi et al. 2009). Rhythmites are thicker (up to 5 feet or more) in the middle of the channel and thin toward the edges and display all the characteristic features of slackwater rhythmites, including graded bedding and climbing ripple-drift cross lamination.

Landslides also occur in this area because of the underground flow of water that seeped between the more-permeable flood sands and the top of the relatively impermeable, clay-rich sediments of the Ringold Formation underneath. The source of the water for these landslide complexes, came from irrigation-wastewater ponds created since the 1960s to enhance wildlife. In some cases these ponds were located 1 to 2 miles to the northeast (see Figure 21). When the ground became saturated, the wet, soft sediment of the Ringold Formation lost much of its strength, leading the soil to slump (Bjornstad and Peterson 2009). This began in the late 1970s and continues today, even though some of the ponds have been drained in an effort to stop the sliding.

87 Turn right (east) onto SR 24 towards Othello.

96 Drop off north side of Saddle Mountains into the Othello Basin.

98 Turn right (south) at intersection with Sagehill Road. Road climbs back up the side of the Saddle Mountains.

99 Radar Hill Overlook Stop. Pull off at the ridge crest near the radar station. Continue south on Sagehill Road.

Stop 7. Radar Hill Overlook

The overlook from the top of Radar Hill provides an excellent view of several flood features, including the Drumheller Channels and head of Othello Channels (Figure 26). A major divergence in the floodwaters, referred to here as “Parting of the Waters,” occurred near Othello toward the eastern end of the Saddle Mountains (Bjornstad 2006). Here, floodwaters rushing down from Drumheller Channels smashed head on into the Saddle Mountains. The ridge was too high for floodwaters to flow over, so they were forced to flow in opposite directions along the north side of the impasse. Some floodwaters poured west down lower Crab Creek Coulee toward an opening in the Saddle Mountains at Sentinel Gap (see Figure 16). The remainder rushed east around the nose of the Saddle Mountains where the ridge finally lowered enough for floodwater to spill over at Othello Channels.

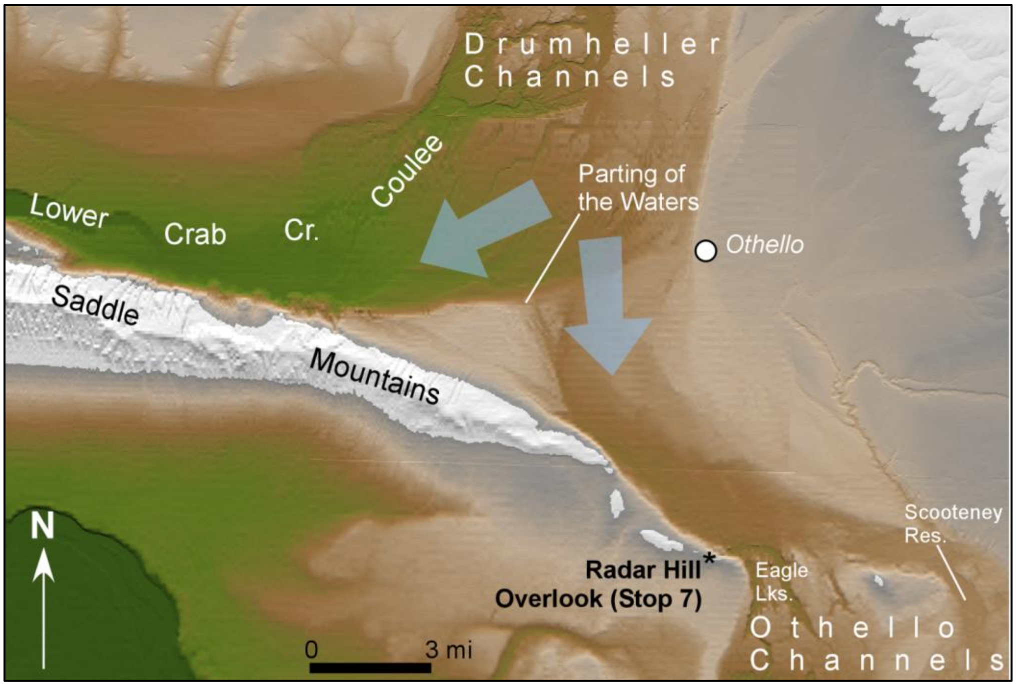


Figure 26. Shaded-relief map of the southeastern Othello Basin. Areas in white were above maximum flood level. After scouring out the Drumheller Channels Ice Age floods plowed into the Saddle Mountains obstruction, forcing floodwaters to diverge east and west. From Bjornstad (2006).

The point of flow divergence is represented by the apex of a triangle-shaped, raised point of land that juts northward from the Saddle Mountains (Figure 26). This wedge of land that parted the floodwaters is almost flat on top and lies 300 feet above lower Crab Creek Valley. The wedge represents an erosional remnant of the Ringold Formation, which once partly filled the Othello Basin. Ringold Formation sediments were preserved because floodwaters temporarily moved slightly slower here. On either side of the wedge, erosive floodwaters completely stripped away the Ringold sediments. Huge rounded basalt boulders up to 4 feet in diameter, ripped out of Drumheller Channels, litter the upper surface of the wedge.

106 Begin descent into Ringold coulee.

108 At the bottom of the grade continue straight onto Road 170, which runs down the coulee.

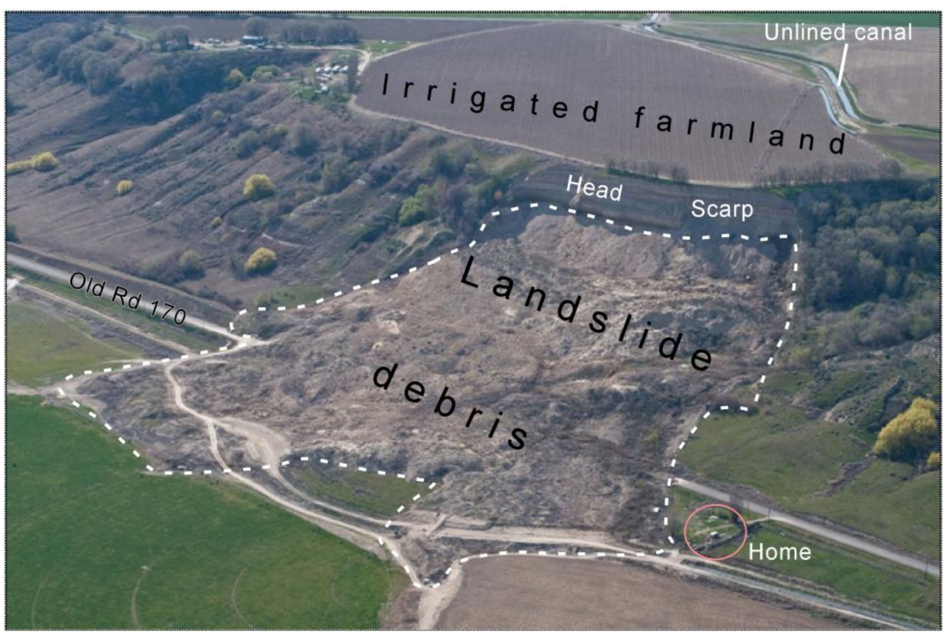


Figure 27. Basin Hill landslide of May 13, 2006 along the west side of Ringold Coulee (see Figure 28). Slides like this one have been occurring all along the White Bluffs ever since the addition of irrigation water began in the 1960's (Schuster et al. 1987). Adding water causes steeper bluffs of Ringold Formation sediment to lose strength and become extremely unstable (Bjornstad and Peterson 2009). County road 170 has since been diverted around the slide.

Ringold Coulee

A major conduit for floodwaters entering the Pasco Basin from the northeast is Ringold Coulee (Bjornstad 2006; Bjornstad et al. 2007). Ringold Coulee, along with Koontz Coulee, are a pair of parallel, 12-mile-long channels that carried floodwaters coming from the Othello Channels (Figure 28). These two coulees are different from most other coulees in that they are shallow and created when floodwaters only eroded into the "soft" sediments of the Ringold Formation. Furthermore, since these coulees emptied into the backwaters of Lake Lewis, the energy of the floods was dampened and erosion reduced. In contrast, most scabland coulees were created by floodwaters that scoured deeper into hard, basalt bedrock itself.

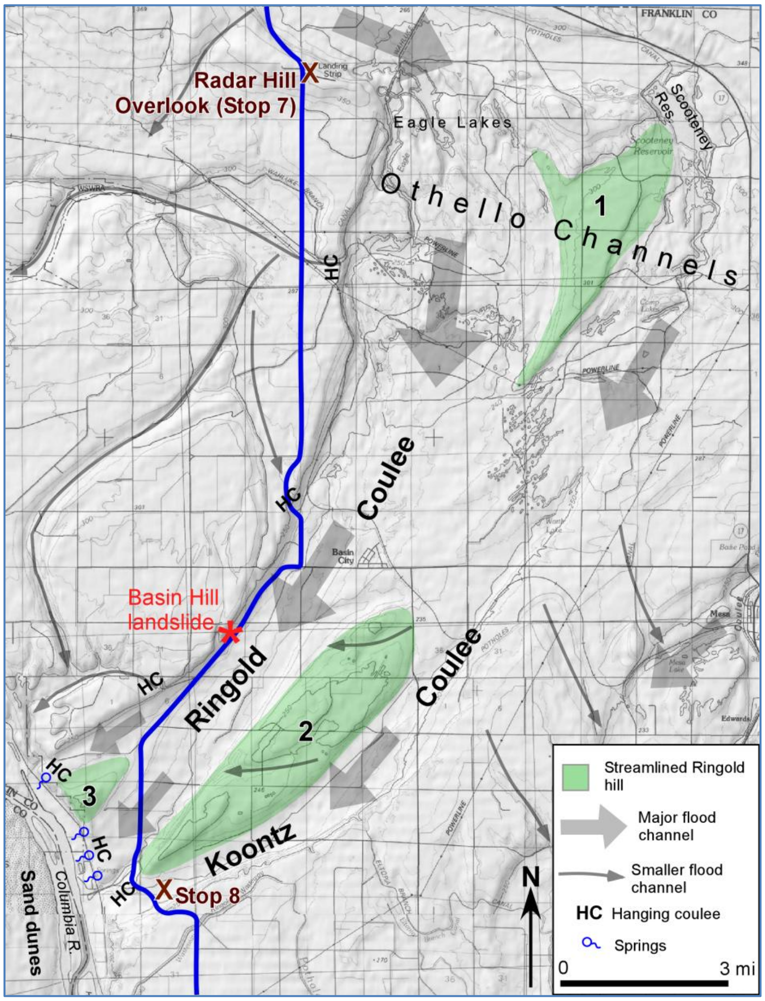


Figure 28. Flood features associated with Ringold and Koontz coulees - an extension of the Othello Channels. See Figure 27 for an aerial view of the Basin Hill Landslide.

Ringold Coulee is about 300 feet deep and narrows from about 6 miles wide near Othello Channels to only 3.5 miles wide at its mouth where it hangs about 200 feet directly above the Columbia River (Figure 28). Ringold Coulee is part of a continuous channel that begins at Eagle Lakes (west side of Othello Channels). At the mouth of Ringold Coulee the floodwaters split to flow around an eroded knob of Ringold Formation, which floodwaters washed over and streamlined (No. 3 in Figure 28). To the northwest, several abandoned spillways, partially filled with flood debris, exit and rejoin Ringold Coulee via hanging coulees (HC).

At the mouth of Ringold Coulee are many springs surrounded by lush vegetation. The origin of the springs is from excess irrigation water from farmlands within Ringold Coulee. Up to several tens of feet of basalt-rich, coarse flood sediment fill the bottoms of these coulees. Irrigation water quickly infiltrates the coarse flood deposits until it hits the underlying impermeable Ringold Formation. Upon reaching the top of the Ringold groundwater moves laterally towards the

Columbia River. The springs at the mouth of Ringold Coulee gush out along the contact between the Ringold Formation and the flood deposits several tens of feet about the level of the Columbia River. These springs sap out along the east bank of the river (see lower left corner in Figure 28).

116 CONTINUE SOUTH AND EAST ON RINGOLD RD INTO KOONTZ COULEE.

Stop 8. Koontz Coulee

"Most of Othello's discharge went southwest across a plain determined by the flat-lying Ringold superbasalt sedimentary formation in the Pasco basin. The several distributary channels (Koontz Channels) all hang at varying altitudes above the present Columbia."

Bretz (1969)

Koontz Coulee is part of a continuous channel that extends northeast to the Othello Channel that contains Scooteney Reservoir (Figure 28). This coulee transported floodwaters coming down the east side of Othello Channels. Koontz Coulee joins and hangs 100 ft above Ringold Coulee near its mouth, just before dropping into the Columbia River. Floodwaters spilled over between these two parallel coulees. As floodwaters waned and during smaller floods, most or all the flow was confined to Ringold Coulee, which is lower.

At the mouth of Koontz Coulee, it's flat-bottom hangs above Ringold Coulee where the two coulees intersect (Figure 28). The larger, earlier Scabland floods associated with the last glacial cycle probably occupied both Ringold and Koontz coulees and the Columbia River, all at the same time. As later floods became progressively smaller, they probably bypassed higher elevation channels and coulees, like Koontz Coulee.

Other flood features located along Ringold and Koontz coulees are streamlined sedimentary hills (No. 1 through 3, Figure 28). These hills were created when floodwaters eroded and sculptured the fine sand, silt and clay of the Ringold Formation. One streamlined sedimentary hill (No. 1) lies in a more-protected area between the two primary Othello Channels. Visible at Stop 8 is another streamlined hill that separates Ringold from Koontz Coulee (No. 2).

Driving out of Koontz Coulee, notice the extensive field of active sand dunes behind and across the river (Figure 29). The dunes are much younger than the floods but an indirect result nevertheless. Winds that have reworked flood sediments since the last Ice Age flood, about 13,000 to 14,000 years ago, formed these dunes. The dune field is exactly in line with Ringold and Koontz Coulees, which aligns with the predominant strong wind direction (southwest to northeast) for winds that blow through the Pasco Basin. The coulees therefore represent a natural wind tunnel that focus the wind and provide an easy exit for airflow out of the basin.

Figure 29. Active sand dunes along the Columbia River from above Ringold Coulee looking into the predominant wind direction (arrow). The dunes have formed since the last Ice Age floods due to reworking of flood deposits by strong southwesterly winds (Bjornstad 2006). The dunes have been shown to migrate from 8 to 15 feet per year.

119 TURN RIGHT (SOUTH) AT INTERSECTION WITH TAYLOR FLATS ROAD.

A few miles head and to the left (north) is the lower part of Esquatzel Coulee, which brought floodwaters off the Channeled Scabland from the northeast (see Figure 2). Esquatzel Coulee is a subdued, low-relief feature here because of the dampening effect Lake Lewis had on the movement of floodwaters through the central Pasco Basin. Esquatzel Coulee gradually gets deeper and more pronounced northward away from the influence of Lake Lewis.

132 TAYLOR FLATS ROAD MERGES WITH ROAD 68. CONTINUE ON ROAD 68.

135 INTERSECTION WITH I-182 IN PASCO. TURN RIGHT ONTO I-182 WEST TOWARDS RICHLAND.

139 TURN ONTO SR 240 TOWARD KENNEWICK.

140 EXIT SR 240 AT COLUMBIA PARK TRAIL. CONTINUE ON STEPTOE ST.

143 CROSS CLEARWATER AVE. AND CONTINUE STRAIGHT ON CLODFELTER RD.

147 TURN LEFT INTO THE COYOTE CANYON MAMMOTH DIG SITE.

Stop 9. Coyote Canyon Mammoth Site (CCMS)

The Coyote Canyon mammoth was discovered in November 1999 while excavating and hauling fine-grained soil for use as topsoil (Last et al. 2013). In late 2007, the land went up for sale, and the presence of the mammoth was disclosed. In the spring of 2008, a pedestrian survey and test excavation confirmed the location of the mammoth site uncovering a number of mammoth-size bones, including a humerus and scapula in near articulated position. Excitement grew that this site might offer a unique opportunity for students, teachers, and researchers to investigate mammoth remains in the context of Ice Age flood deposits, and a non-profit organization, the Mid-Columbia Basin Old Natural Education Sciences (MCBONES) Research Center Foundation was established to oversee environmental, paleontological, and geological research and education at the site. A survey of all mammoth finds discovered to date indicates most lie within the upper limit (1,200 ft elevation) of Ice Age flooding and therefore may be associated with Pleistocene outburst floods (Last and Bjornstad 2009).

Formal excavation of the site began on September 25, 2010, and has continued two weekends a month from March through October. Soil/sediment is excavated in 10 cm layers using standard archeological techniques. All sediment is wet screened (washed) to remove the fines, making it easier to pick out micro-flora and -fauna specimens (such as rodent bones) for paleoecological analysis. Over forty-five mammoth-size bones or bone fragments have been documented, including many ribs, vertebrae, and foot bones, as well as the left scapula and humerus and one other yet to be identified long-bone. Figure 30 illustrates the in-situ arrangement of bones and ice-rafted erratic clasts as interpreted at the end of the 2013 dig season.

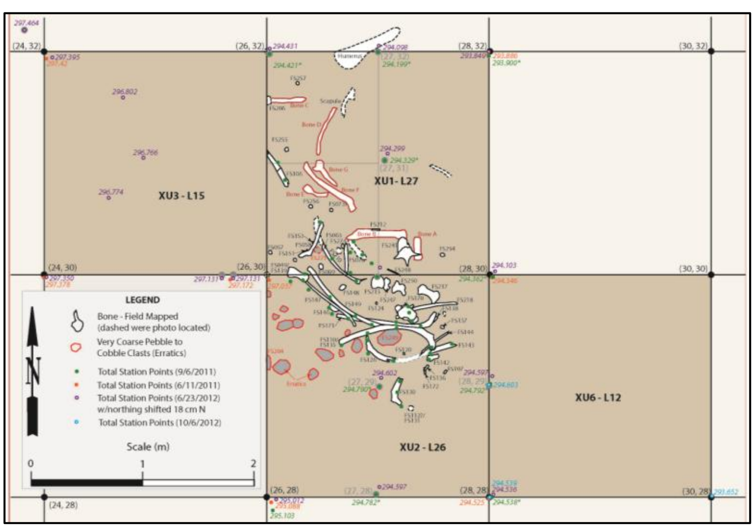


Figure 30. Plan view showing the state of the excavation work at the end of the 2013 dig season.

The left humerus and scapula have since been uncovered and found to be in near articulated position, suggesting that soft tissue must have held them in the correct anatomical positions during burial (Figure 31).

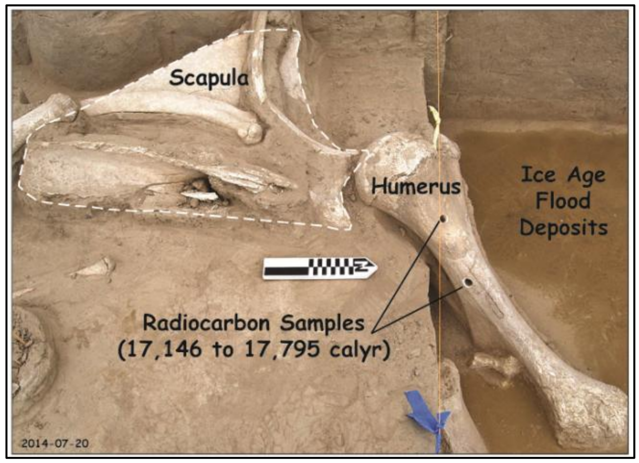


Figure 31. Left scapula and humerus in near articulated position, showing the location of radiocarbon samples (after Last and Barton, 2014).

Geologic investigations have confirmed that the mammoth bones are located within slackwater Ice Age flood deposits. Radiocarbon dating of the humerus has yielded a mean calibrated age for the mammoth's death of 17,449 years ago (14,295 14C yr B.P.) (Barton et al. 2012). This, together with the partially articulated position of the bones, places the mammoth's death coincident with one of the larger Ice Age floods near the middle of the flooding sequence from the last glacial cycle. Subsequent excavation suggests that at least two additional flood events then covered the mammoth bones which are spread over a vertical interval of at least 50 cm (Figure 32). Last and Krogstad (2014) demonstrated that the youngest of the Ice Age flood deposits extends to about 15 cm overlying the upper most mammoth bones.

A number of the mammoth bones show signs of animal gnaw marks. Wahl and Barton (2013) suggest that these were produced by at least two rodents and at most two lagomorph species (i.e. rabbits, hares, and pikas), which typically utilize such bones for nutrition and to sharpen and erode their ever-developing incisor teeth. This suggests that some period of subaerial exposure occurred after the mammoth carcass was initially deposited, and prior to subsequent floods that then more fully buried the mammoth remains.

Figure 32. Stratigraphy showing the location of mammoth bones (at base) within slackwater Ice Age flood deposits (after Last and Barton, 2014).

The top of the Ice Age flood deposits has been locally covered with windblown loess deposits and pedogenically (soil development) altered, leaving an overprint of calcium carbonate (Figure 32). This surface appears to have been reworked by bioturbation (e.g. disruption and mixing by worms, burrowing animals, etc.) processes leaving an irregular surface. This is overlain by a sequence of loess deposits that is then locally overlain by a sequence of slopewash (material transported downslope by non-channelized water, sheet erosion).

Excavation and research is expected to continue at the CCMS for a number of years, with teams of students, teachers, volunteers, and professional scientists working together on a variety of small integrated studies. These efforts will undoubtedly discover new mammoth bones, and paleoecologic and geologic findings to improve our understanding of the site. To follow our progress and/or get additional information go to: www.mcbones.org or www.coyotecanyonmammothsite.org and/or our facebook page at https://www.facebook.com/McbonesResearchCenterFoundation.

154 RETRACE ROUTE TO SR 240, TURNING TOWARD RICHLAND.

157 ARRIVE AT SHILO INN. END OF ROAD TOUR.

Cited References

Baker, V.R., Bjornstad, B.N., Busacca, A.J., Fecht, K.R., Kiver, E.P., Moody, U.L., Rigby, J.G., Stradling, D.F., and Tallman, A.M., 1991, "Quaternary Geology of the Columbia Plateau", *in* Morrison, R.B., ed., Quaternary Nonglacial Geology; Conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. K-2.

Barton, B.R., G.V. Last, and G.C. Kleinknecht, 2012, "Initial radiocarbon dating of the Coyote Canyon mammoth, Benton County, Washington State," AMQUA Abstracts with Programs, 22nd Biennial Meeting of the American Quaternary Association, Duluth, Minnesota, p. 44.

Benito, G. and J.E. O'Connor, 2003, "Number and size of last-glacial Missoula floods in the Columbia River valley between Pasco Basin, Washington and Portland, Oregon," *Geological Society of America Bulletin*, v. 115, p. 624-638.

Bjornstad, B.N., 2014, "Ice-Rafted Erratics and Bergmounds from Pleistocene Outburst Floods, Rattlesnake Mountain, Washington, USA", *E&G Quaternary Science Journal*, v. 63, p. 44–59. DOI: 10.3285/eg.63.1.03.

Bjornstad, B.N., and E.P. Kiver, 2012, On the Trail of the Ice-Age Floods: The Northern Reaches, Keokee Company Publishing, Inc., Sandpoint, Idaho, 432 p.

Bjornstad, B.N., and R.E. Peterson, 2009, "Hydrogeologic Controls and Impacts of Quaternary Landslides Along the White Bluffs of the Columbia River, South-Central Washington", *7th Washington Hydrogeology Symposium Abstracts with Program, Tacoma, Washington, p. 36.*

Bjornstad, B.N., R.S. Babcock, and G.V. Last, 2007, "Flood basalts and Ice Age floods: Repeated late Cenozoic cataclysms of southeastern Washington", *in* Stelling, P. and D.S. Tucker, eds., Floods, Faults and Fire, Field Guide 9, Geological Society of America, Boulder, Colorado, p. 209-255.

Bjornstad, B.N., 2006, On the Trail of the Ice-Age Floods: A geological field guide to the Mid-Columbia Basin, Keokee Company Publishing, Inc., Sandpoint, Idaho, 307 p.

Bjornstad, B.N., K.R. Fecht, and C.J. Pluhar, 2001, "Long history of Pre-Wisconsin, Ice Age cataclysmic floods: evidence from southeastern Washington State", *Journal of Geology*, v. 109, p. 695-713.

Bretz, J H., 1928, "Bars of Channeled Scabland," *Geological Society of America Bulletin*, v. 39, p. 643-702.

Bretz, J H., 1969, "The Lake Missoula Floods and the Channeled Scabland," *Journal of Geology*, v. 77, p. 505-543.

Bretz, J H., H.T.U. Smith and G.E. Neff, 1956, "Channeled Scabland of Washington: New Data and Interpretations," *Geological Society of America Bulletin*, v. 67, p. 957-1049.

Denlinger, R.P., and D.R.H. O'Connell, 2010, "Simulations of cataclysmic outburst floods from Pleistocene Glacial Lake Missoula", *Geological Society of America Bulletin*, v. 122, p. 678-689, doi: 10.1130/B26454.1.

Fecht, K.R. and A.M. Tallman, 1978, "Bergmounds along the western margin of the Channeled Scablands, south-central Washington," RHO-BWI-SA-11, Rockwell Hanford Operations, Richland, Washington, 31 p.

Last, G.V. and E.J. Krogstad, 2014, "The use of X-ray fluorescence spectroscropy to refine stratigraphic interpretation of the Coyote Canyon Mammoth site," 85th Annual Meeting of the Northwest Scientific Association, Program and Abstracts, March 26-29, 2014, Missoula, MT., p. 73.

Last, G.V. and B.R. Barton, 2014, "*Mammuthus* Finds in Former Lake Lewis of Southeastern Washington," AMQUA 2014, American Quaternary Association, Abstracts with Program, 23rd Biennial Meeting, August 7-10, 20014, Seattle, Washington.

Last, G.V., B.R. Barton, and G.C. Kleinknecht, 2013, "Preliminary Paleontology and Geology of the Coyote Canyon Mammoth Site, Benton County, Washington," In *The Pleistocene Post*, Newsletter of the Ice Age Floods Institute, Spring 2013.

Last, G.V. and Bjornstad, B.N., 2009, "Distribution of *Mammuthus* and erratic finds relative to the size of Ice Age floods in southeast Washington," Geological Society of America, Abstracts with Programs, v. 41, p. 16.

Lewis, R.E., B.N. Bjornstad, and S.S. Teel, 1993, "Buried megaripples at the Hanford Site, Benton County, Washington", Geological Society of America, Abstracts with Programs, v. 25, no. 6, p A-67.

Lindsey, K.A., 1996, "The Miocene to Pliocene Ringold Formation and Associated Deposits of the Ancestral Columbia River System, South-Central Washington and North-Central Oregon," Open File Report 96-8, Washington State Department of Natural Resources, Olympia, Washington.

Keszthelyi, L.P., V.R. Baker, W.L. Jaeger, D.R. Gaylord, B.N. Bjornstad, N. Greenbaum, S. Self, T. Thordarson, N. Porat, and M.G. Zreda, 2009, "Floods of water and lava in the Columbia River Basin: Analogs for Mars", *in* O'Connor, J.E., R.J. Dorsey, and I.P. Madin, eds., Volcanoes to Vineyards: Geologic Field Trips through the Dynamic Landscape of the Pacific Northwest: Geological Society of America Field Guide 15, p. 845-874, doi: 10.1130/2009.fld015(34).

Pluhar, C.J., B.N. Bjornstad, S.P. Reidel, R.S. Coe, and P.B. Nelson, 2006, "Magnetostratigraphic evidence from the Cold Creek bar for onset of ice-age cataclysmic floods in eastern Washington during the Early Pleistocene", *Quaternary Research*, v. 65, pp. 123-135.

Schuster, R.L., A.F. Chleborad and W. H. Hays, 1987, "Irrigation-induced landslides in fluvial-lacustrine sediments, south-central Washington State," in 5th International Conference and Field Workshop on Landslides, Christchurch, New Zealand, p. 147-156.

Wahl, S.A. and B.R. Barton, 2013, "Preliminary analysis of rodent and lagomorph gnaw marks on mammoth ribs from the Coyote Canyon Mammoth site, Benton County, Washington", Northwest Scientific Association Annual Meeting, March 20-23, Portland, Oregon.