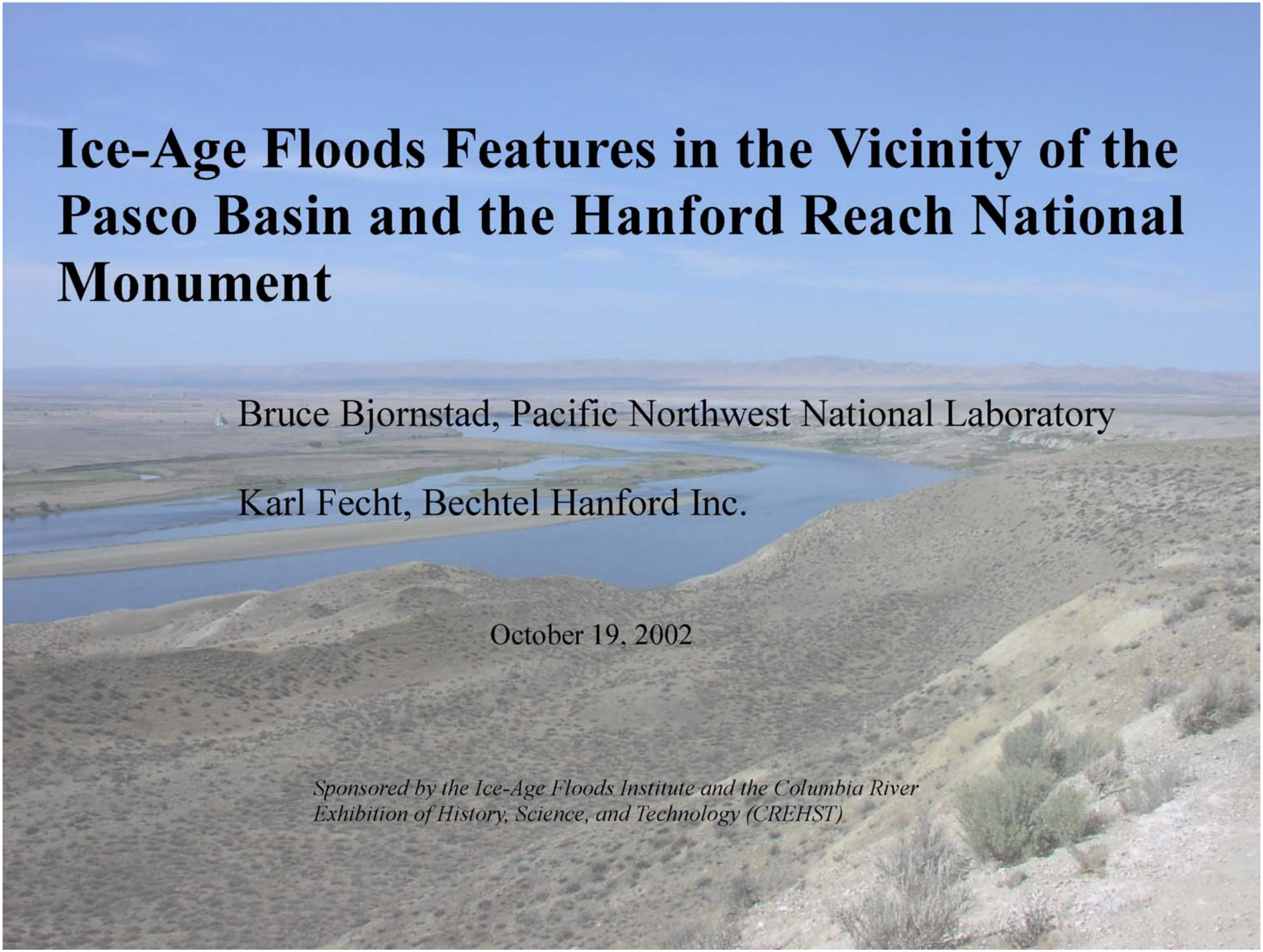

Ice-Age Floods Features in the Vicinity of the Pasco Basin and the Hanford Reach National Monument

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Preface

This field guide and roadlog provide an introduction to ice-age flood features that occur in the vicinity of the Pasco Basin and the Hanford Reach National Monument (HRNM). Portions of this field trip include restricted-access areas within the HRNM. Therefore, this field trip cannot be completed in its entirety by individuals without first obtaining permission from the Richland Office of the U.S. Fish and Wildlife Service. There are a total of 6 stops along the ~140-mile route (Figure 1). Features between stops are indicated with the letters A-P on Figure 1. Field trip leaders will point out and discuss these features as we drive past them.

Cumulative distances from the origin (CREHST parking lot) appear in the left column followed by the distance between roadlog entries. The entire field trip route, including stops and features along the way, is shown in Figure 1. Field trip stops are also indicated on a more regional-scale map of ice-age floods features (Figure 2). During this field trip we'll be circumventing the Department of Energy's Hanford Site. Because of heightened security after the events of September 11, 2001 we will not be able to enter the Hanford Site but will be able to view many of its outstanding flood features as we circle around. First use of geologic terms that may not be familiar to some are underlined in the text and defined in a glossary, located at the back of this field-trip guide. References cited in the text are also included in the back.

Acknowledgements

We would like to acknowledge A&B Asphalt and Larry Olsen for allowing us permission to access and examine flood features on their property. We also appreciate the cooperation of Jenna Gaston from the U.S. Fish and Wildlife Service, the agency responsible for management of the Hanford Reach National Monument. Appreciation is also extended to Gary Kleinknecht and his passion for ice-rafted erratics who has scoured the region and brought to our attention every erratic in existence, and even some that don't. Thanks also to George Last and Ivar Husa, who together performed the iceberg calculations for the erratic at Stop 2 and Chris Murray who provided the image displaying the clastic dike network in Figure 13. Finally, we would like to acknowledge the support of Gwen Leth and her staff at the CREHST museum. And of course this trip would not have been possible without constant encouragement and prodding from Dale Middleton.

Introduction to Ice-Age Floods Features Within the Pasco Basin

Repeated ice-age cataclysmic floods stripped away large volumes of Palouse loess, carved deep coulees into the underlying basalt bedrock, and created the Channeled Scabland of eastern Washington (Bretz et al. 1956; Baker and Nummedal 1978; Waitt 1985, 1994; Baker et al. 1991). The Cordilleran ice sheet, extending southward from Canada, created ice-dammed lakes, the largest of which was glacial Lake Missoula (Figure 2). However, some cataclysmic floods may have originated from sources other than Lake Missoula or augmented the outflow from Lake Missoula. These sources include a single flood from an overspill of Pleistocene Lake Bonneville at 14.5 ka (O'Connor 1993), floods from other ice-dammed lakes in the Columbia drainage (Baker and Bunker 1985), or outbursts from beneath the Cordilleran ice sheet itself (Shaw et al. 1999).

Ice-age floods converged onto the Pasco Basin, simultaneously, from three directions. (1) Floodwaters primarily entered from the north off the Channeled Scabland. However, some of the flow was diverted west down lower Crab Creek along the north side of the Saddle Mountains, eventually entering the Pasco Basin from the northwest via Sentinel Gap (Figure 1). (2) Floodwaters entered the basin from the east through Ringold, Koontz, and Esquatzel Coulees. (3) Floodwaters also entered from the east after overtopping several drainage divides into the Snake River. Floodwaters entered the Pasco Basin via these three different areas at a higher rate than could be discharged through a single narrow outlet at Wallula Gap. Because of the hydraulic constriction, floodwaters ponded temporarily, forming Lake Lewis (Allison 1933).

Each cataclysmic flood transported massive amounts of sediment, all within a period of a week or less (O'Connor and Baker 1992). Unlike many areas impacted by the ice-age floods, the Pasco Basin was an area of significant sediment accumulation because of the ponding of floodwaters that took place behind Wallula Gap. As a result, many of the flood features we'll be investigating are depositional features, some of which are unique to this area. Within this turbid column of floodwater was a stratified mixture of sediments being transported by the floods. The sediments deposited from ice-age flooding have a wide range in grain sizes from large boulders to very fine sand and silt. At the base of the flow, along the sediment-water interface, traction currents carried everything from gigantic boulders that bounced and rolled along the bottom, to finer-grained particles (gravel to clay) in suspension. Higher in the water column, floodwaters were limited to transporting sand, silt, and clay-sized particles. As a result, deposition of the coarsest flood material (cobbles and boulders), as well as entrained finer-grained sediment, was concentrated to lower elevations along the bases of flood channels towards the center of the basin. At higher elevations adjacent to the flood channels, floodwaters were starved of coarser material and, thus, yielded principally horizontally-laminated sands. Around the margins of the basin and in backflooded valleys often only rhythmically bedded slackwater sand and silt were deposited. Clay-sized particles are generally absent in ice-age flood deposits because of the extremely short duration of the floods; thus, the smallest particles remained suspended in the floodwater and were flushed out of the basin with the floodwater. Flood deposits in the Pasco Basin are informally called the Hanford formation.

The first Ice Age floods likely occurred during the early Pleistocene, around 1.5 to 2.5 million years ago (Bjornstad et al. 2001). At least two episodes of pre-Wisconsinan cataclysmic flooding, one middle Pleistocene (>130 ka) and one early Pleistocene (>780 ka), are identified from surface exposures based on radiometric age dates, as well as paleomagnetic and pedogenic evidence. Physical evidence for pre-Wisconsin cataclysmic floods is limited to small, isolated localities that are widely distributed across southeastern Washington. The evidence for older floods is commonly obscured by erosion or deposition by younger floods and an extensive blanket of Holocene eolian and fluvial deposits.

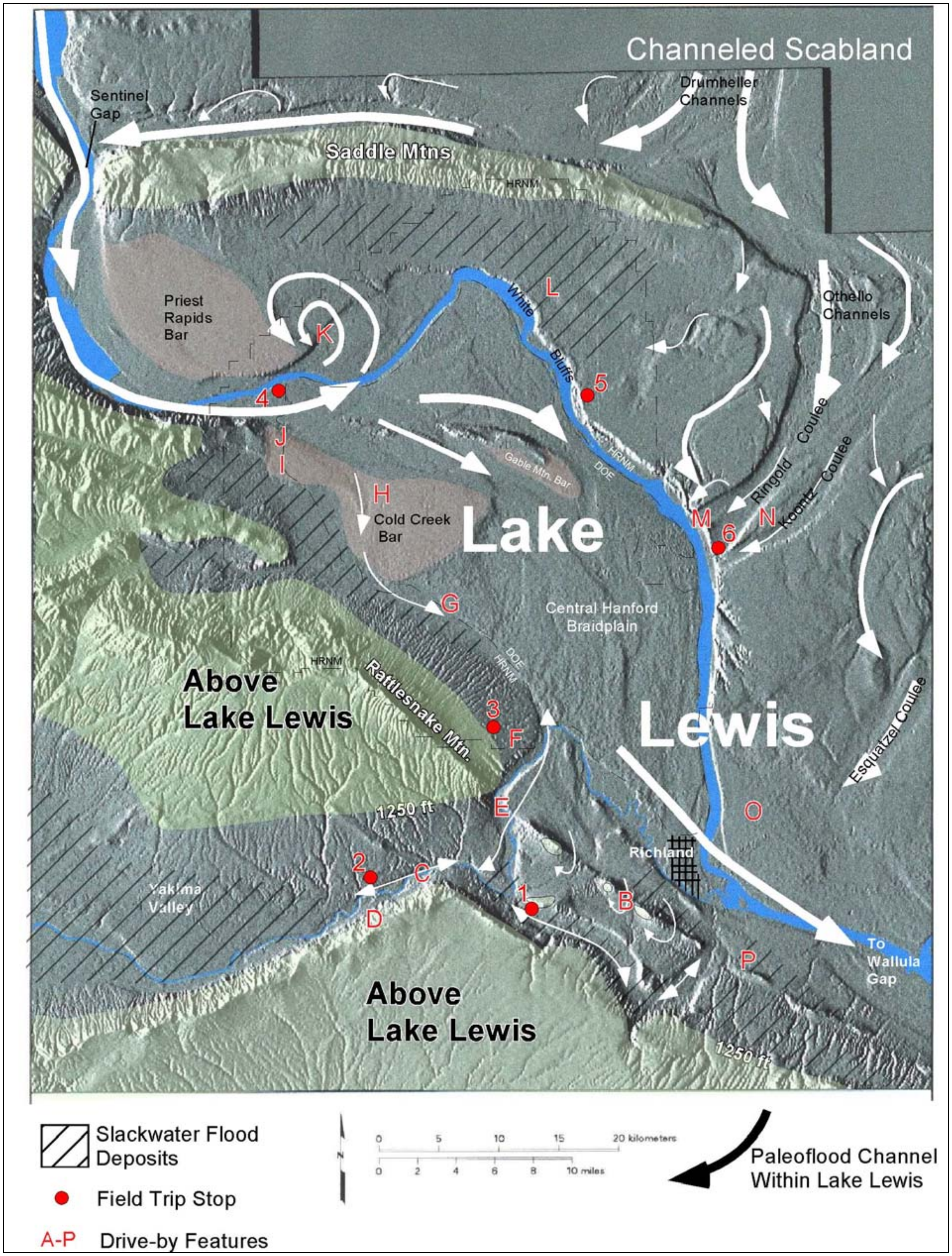

Figure 1. Flood features and field trip stops in the vicinity of the Pasco Basin.

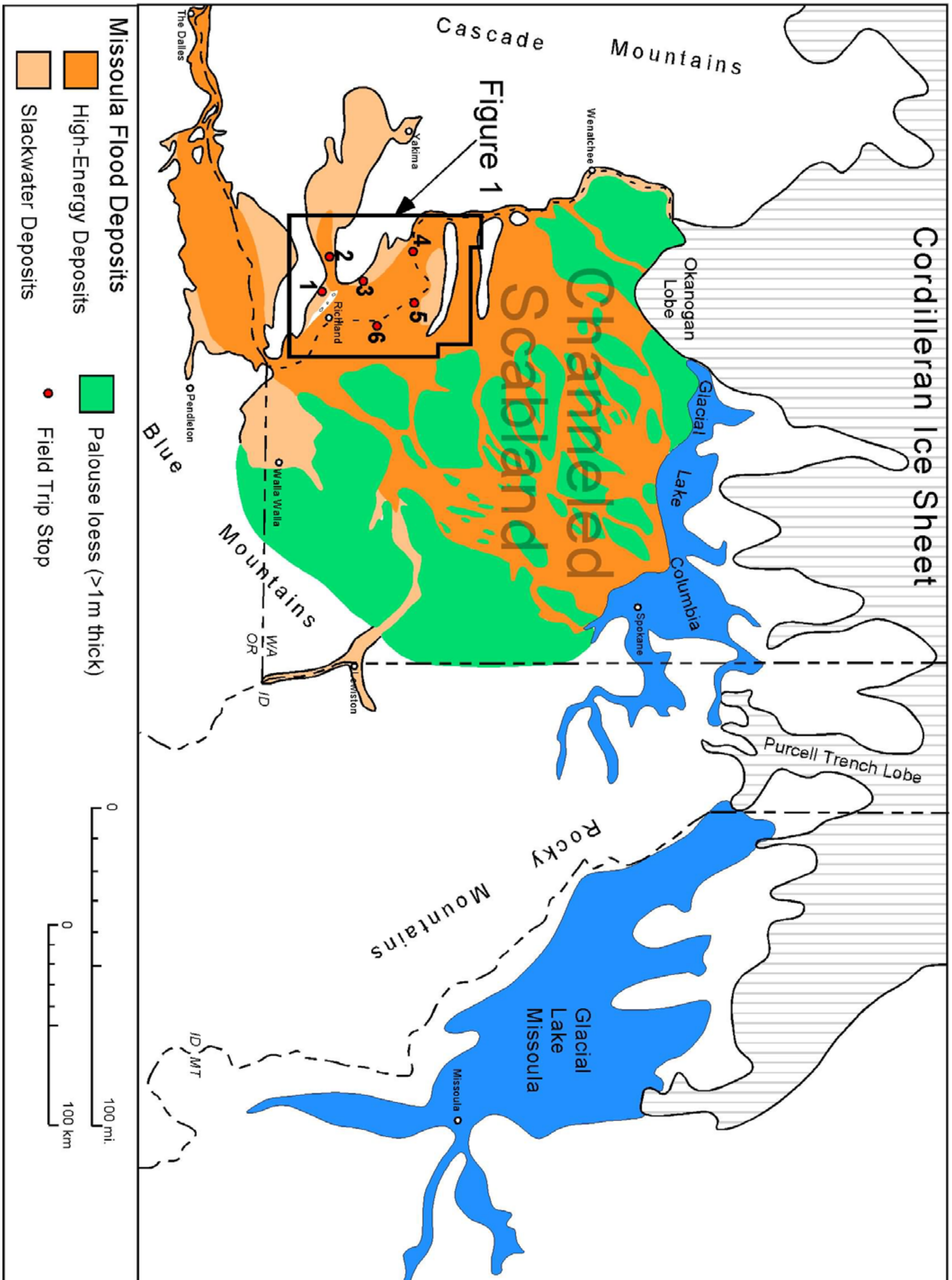

Figure 2. Regional aspects of ice-age flooding in the Pacific Northwest.

Roadlog

Total Miles | **Miles Between**

0.0 0.0 CREHST Parking Lot, Richland. Elev. = 380 ft.

0.1 0.1 *Turn left onto George Washington Way*

1.0 0.9 *Quickly bear right onto I-182 and then I-82 toward Yakima*

3.6 2.6 Feature A. Immersion

The last cataclysmic floods occurred about 15,000 years ago at the end of the last Ice Age. During the largest floods the Pasco Basin was flooded up to an elevation of 1250 ft (Baker et al. 1991) when floodwaters backed up behind a hydraulic constriction at Wallula Gap creating Lake Lewis. The lake was temporary, however, and only lasted up to five days (O'Connor and Baker 1992) before all the floodwater drained out through Wallula Gap.

5.1 1.5 Feature B. Lake Lewis Isles

At this saddle (elev. 900 ft) Badger Mountain rises up to the east and Candy Mountain to the west. During the largest ice-age floods these hills, along with nearby Red Mountain and Goose Hill, were islands completely surrounded by floodwater. Only the top 300 ft of Badger Mountain and uppermost 150 ft of Candy Mountain were exposed as islands within Lake Lewis (Figure 3). These mountains are part of "the Rattles", a string of hills that extend southeastward from Rattlesnake Mountain. Structurally, the Rattles represent uplifted <u>brachyanticlines</u> of Columbia River basalt, along a major structural feature referred to as the Olympic-Wallowa lineament (DOE 1988; Reidel et al. 1994). From this saddle the road descends toward Badger Coulee.

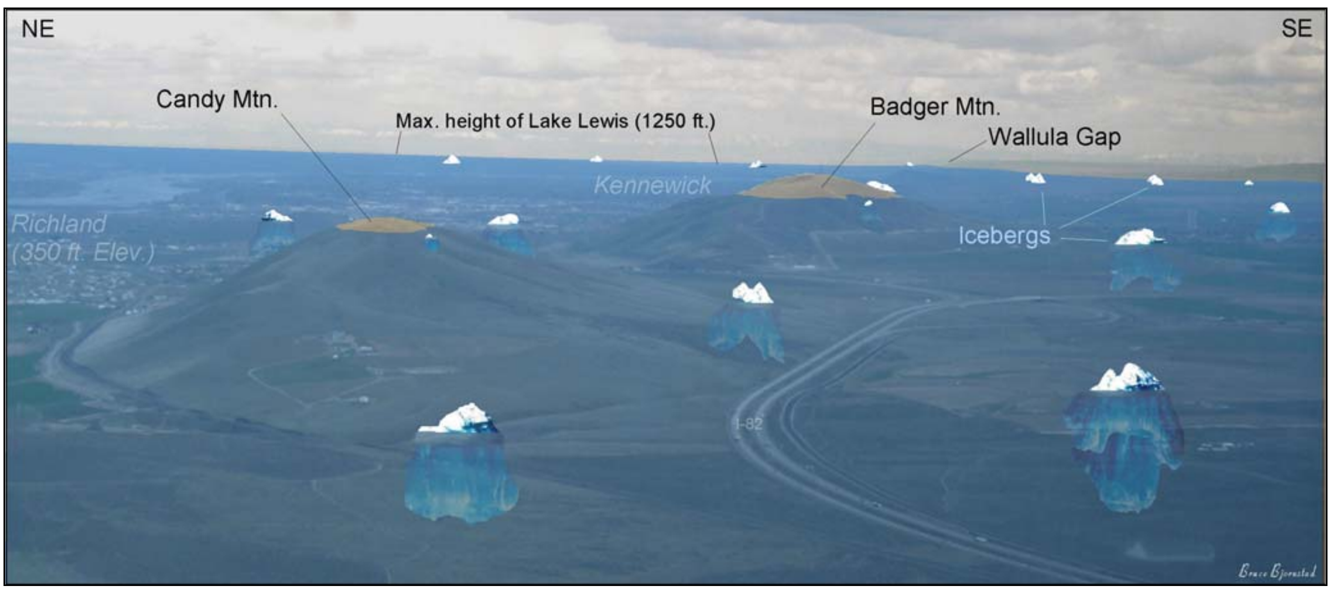

Figure 3. Lake Lewis as it might have appeared in the southern Pasco Basin at the highest flood stage. View is looking east. Candy and Badger Mountains were islands, temporarily, during the larger floods. The Columbia River and the Tri-Cities are in the distance on the left and Badger Coulee is to the right. Icebergs tended to congregate around the margins of the Pasco Basin where flood currents were not as strong and developed back eddies.

5.8 2.2 *Exit onto I-82 towards Yakima*

11.6 5.8 *Take Exit 96 at Benton City. Turn left under overpass and another left onto Jacobs Rd. At about ¼ mile turn right onto Field Rd and proceed to gated entrance to A&B Asphalt quarry.*

12.6 1.0 Stop 1. Old Floods and Diversion of the Yakima River

An exceptional exposure of flood deposits exists here at this site (elev. = 540 ft), referred to as Kiona Quarry (Figure 4), located at the west end of Badger Coulee (Figure 1). This site is an unusual exposure since flood deposits from both high-energy as well as low-energy flood events exist together. At least two gravel-dominated sequences lie at the base of this exposure, which overlies basalt bedrock at the east end. The two flood-gravel sequences are differentiated on the basis of a distinct color change; the lower sequence has a browner color compared to the grayer gravel-dominated sequence immediately above. Large-scale, <u>fore-set</u>

bedding within these gravels are a characteristic of gravel-dominated cataclysmic flood deposits within the Pasco Basin (DOE 2002). Fine-grained lenses sampled from the lower gravel-dominated sequence have reversed magnetically polarity (>780 ka), while the overlying gray-colored gravel sequence has a normal magnetic polarity (<780 ka). Overlying the gravel-dominated flood deposits is a thick calcic paleosol sequence. The results from two radiometric age dates (U/Th) obtained from this sequence were >210 and >400 ka (Bjornstad et al. 2001). Above the paleosol sequence lies several tens of feet of relatively unweathered, rhythmically bedded, slackwater flood deposits (i.e., Touchet Beds). About 20 slackwater rhythmites are represented. The texture and lithology of this slackwater flood sequence is similar to other late Pleistocene (Wisconsinan age) slackwater deposits in the area.

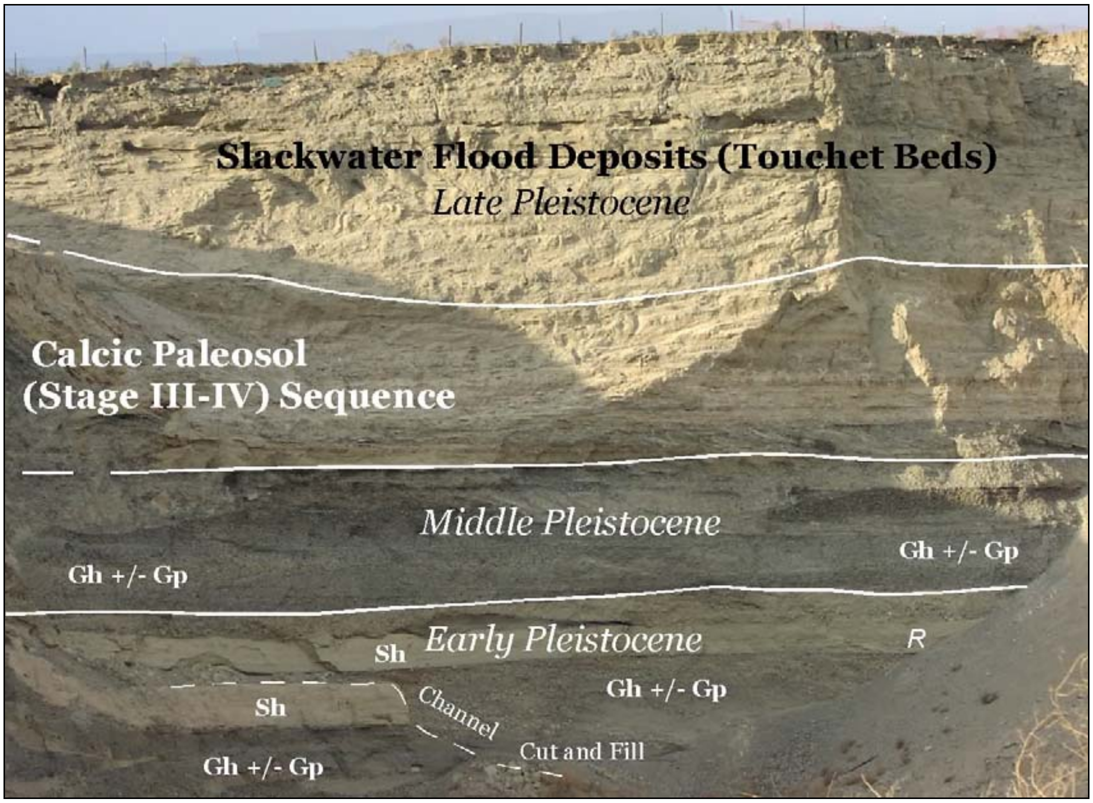

Figure 4. West end of Kiona Quarry exposure. Notice the high-relief, channel-fill structure that truncates the lowermost Sh bed. Sh = horizontally-laminated sand, Gh = horizontally bedded gravel and sand, Gp = planar-cross bedded gravel and sand. R = location of reversed magnetic-polarity samples.

A relatively old age for the lowermost gravel sequence is corroborated by a reversed paleomagnetic polarity in the Sh beds at base of exposure, suggesting these layers were laid down during an early Pleistocene flood prior to 780,000 years ago. Top of the flood sequence here and elsewhere within Badger Coulee consists of rhythmically bedded slackwater deposits (Touchet Beds). In between is a thick calcic paleosol sequence which probably developed during the last interglacial period (Sangamon = 80-130ka). Why the sudden and drastic change in type of deposition before and after formation of the calcic paleosol?

Prior to ice-age flooding the Yakima River flowed through Badger Coulee (Fecht et al. 1987) to join the Columbia River not far from where it does today (Figure 5). Gravel-dominated deposits in the lower half of the sequence were probably laid down when floodwater moved freely down Badger Coulee, prior to later blockage. It appears the first ice-age floods apparently flowed unobstructed through the lower Yakima River valley via Badger Coulee, indicated by the presence of the magnetically reversed, coarse-grained flood deposits at Kiona Quarry. At least through the early Pleistocene and into the middle Pleistocene the Yakima River, as well as the ice-age floods, were able to maintain a channel through Badger Coulee, also indicated by the presence of normal polarity flood gravels at Kiona Quarry. However, by the middle Pleistocene it appears Badger Coulee finally became choked off with flood deposits. This might be expected for Badger Coulee, a location that was peripheral to the main flow of the floods. Apparently, when flood deposits in Badger Coulee accumulated to a critical height of about 700 ft, the Yakima River found a new route into the Pasco Basin through a saddle between Rattlesnake and Red Mountain (Figure 5). The point of diversion for the river was at Kiona-Benton City. Since then Badger Coulee became an area of strictly slackwater deposition during flooding, which would account for the extensive slackwater flood deposits that blanket Badger Coulee (Bunker 1980, 1982).

Figure 5. Path of the pre-Middle Pleistocene Yakima River through Badger Coulee. Oblique view looking north. **Stop 1** is Kiona Quarry; "B" and "E" are other features discussed in text.

Other points of interest at Kiona Quarry are high-relief channeling (see Figure 4) and transport of large, friable, rip-up clasts during flood events. Clastic dikes are common within flood deposits, particularly within slackwater beds. Clastic dikes appear as vertical to subvertical structures that cross-cut normal sedimentary layering (Fecht et al. 1999). While some dikes appear to have been hydraulically injected from below, others suggest infilling from above. Clastic dikes are generally believed to be a type of soft-sediment deformation that occurred during, or soon after, cataclysmic flooding, perhaps induced by seismicity.

Another point of interest is a low-angle reverse fault, which displaces older flood deposits at the west end of Kiona Quarry. The faulting is associated with tectonic movement along anticlinal ridges of the Yakima Folds within the basin (DOE 1988; Reidel et al. 1994). The middle-Pleistocene-age calcic paleosol is displaced by the fault, but the late-Pleistocene slackwater sequence is not, indicating fault displacement probably occurred sometime in the last 100,000 years.

15.6 3.0 *Drive through Benton City via Rt. 225 N*

16.0 0.4 *Left onto OIE (Old Inland Empire) Rd.* At 16.8 miles notice slackwater flood deposits containing late Pleistocene (15,000 yrs B.P.) Mount St Helens "set S" tephra in roadcuts on the right. This tephra layer is commonly observed in late-Pleistocene slackwater flood deposits in and around the Pasco Basin. These slackwater deposits probably correlate with the uppermost deposits at Kiona Quarry at Stop 1 (Figure 4).

20.6 4.6 Feature C. Funneled Flow Through Chandler Narrows

Floodwaters moved UP into the Yakima Valley from the Pasco Basin via Chandler Narrows (Figures 1, 6, and 7). At Chandler Narrows there is a constriction in the valley where a short section of scabland-like features are present, referred to as "The Badlands". These consist of eroded high-relief mesas, buttes, and benches eroded into basalt bedrock. Erosion dominated here since the velocity of the floodwaters increased temporarily due to narrowing (i.e., venturi effect). West of Chandler Narrows the valley widens, scabland-like features disappear, and deposition of flood deposits again becomes the norm.

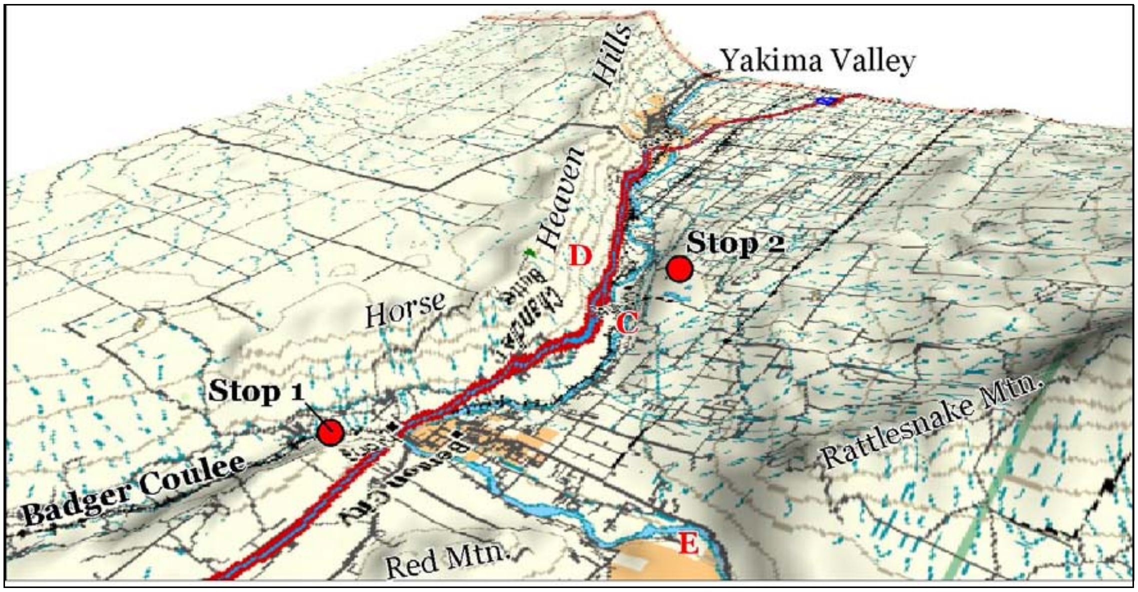

Figure 6. Oblique view looking southwest up the Yakima Valley.


Figure 7. Chandler Narrows (Feature C) at “The Badlands” looking east.

21.6 1.0 **Feature D. Chandler Butte Landslide Complex**

A large landslide complex exists across the valley along the north side of the Horse Heaven Hills. This landslide, and many others like it, occur along steep northern flanks of east-west trending anticlinal folds of the Yakima Fold Belt (Reidel and Fecht 1994a, 1994b). Many of these landslides may have occurred at the end of, or immediately following, large ice-age flood events. The combination of rapid hydraulic loading and saturation, followed by rapid fall of hydraulic head reduced the pore pressure and overstressed the soil and rock layers to the point of failure. Seismicity, which may have also lead to development of clastic dikes (discussed at **Stop 1**), may have triggered landslide movement.

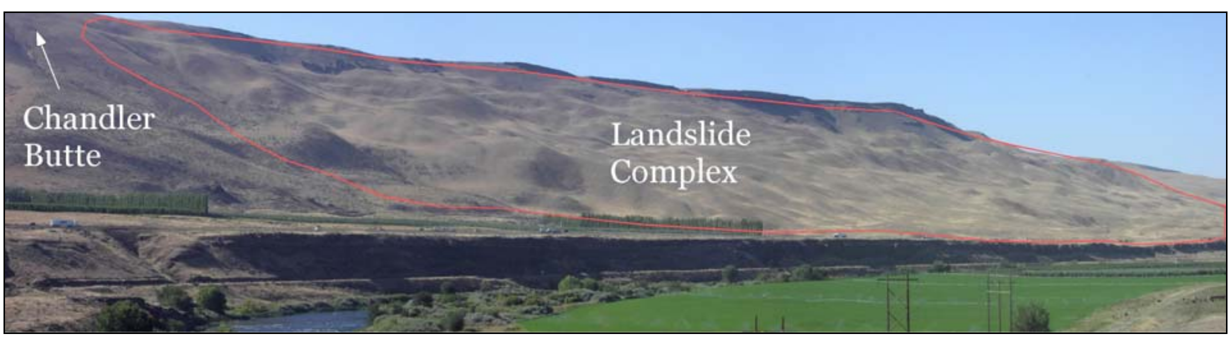

Figure 8. Chandler Butte Landslide Complex (Feature D) looking southwest. Yakima River in foreground.

23.1 1.5 *Turn right up District Line Rd.*

23.5 0.4 Sequence of ice-age flood gravels along roadcut. Characteristics identifying these as flood gravels include their composition of mostly angular basalt clasts in a poorly sorted matrix of silt and sand, in addition to the large-scale, fore-set bedding indicating current flow that deposited these gravels was to the west (i.e., upvalley). These gravels lie on the lee side of a basalt knoll and survived because of the protected position behind the basalt outcrop.

24.0 0.5 Stop 2. Giant Ice-Rafted Erratic

Icebergs, derived mostly from the breakup of the ice dam that created glacial Lake Missoula, floated in Lake Lewis. Most of these icebergs found their way up backflooded valleys and along the margins of the basin in slackwater eddies where the currents were not as strong. As Lake Lewis drained, many icebergs became grounded. Today we can recognize where these icebergs came to rest by the presence of large erratics, which are rocks that are totally foreign to this area (mostly granitic and metamorphic types). This is the second largest ice-rafted erratic discovered so far in the vicinity of the Pasco Basin (the largest lies at the same elevation [850 ft] in Badger Coulee but is not as accessible as this one).

Figure 9. Ice-rafted erratics. Left: Artist Stev Ominski's conceptualization of what an erratic looked like soon after coming to rest in Oregon's Willamette Valley. Right: Isolated erratic (granodiorite) boulder featured in Stop 2.

Based on the measured dimensions of the erratic and the specific gravity of granite [2.63 g/cm^3 (Dietrich et al. 1965)], the mass of the erratic is estimated at 120-155 tons (Table 1). The exact dimensions of the iceberg are unknown but using Archimedes Principle, the minimum mass and volume of the iceberg can be calculated. Because floodwaters were extremely turbid and the density of the floodwater was greater than 1.0 g/cm^3, the actual size of the iceberg is probably greater than that calculated in Table 1. Minimum calculations for the iceberg suggest a mass ~10 times and a volume ~25 times that of the erratic itself.

A spectacular image of an iceberg circulated around on the internet (and used in Figure 3) shows the height-to-width ratio of ~1.25 with only about 20% of the iceberg extending above the waterline. Using this information and back calculating from the volume estimate in Table 1, an estimated minimum size for the iceberg represented at **Stop 2** might have been about 40ft X 30ft X 30 ft; the longest dimension being its height. Subtracting that which extends above the water, the base of the iceberg may have extended down to about 30 ft below water level. Using these estimates it's possible the iceberg here may have become grounded once Lake Lewis drained down to an elevation of ~880 ft above sea level.

	Erratic	**Iceberg**
Length [ft (m)]	17.4 (5.3)	??
Width [ft (m)]	15.1 (4.6)	??
Height [ft (m)]	5.6-6.9 (1.7-2.1)	??
Mass [tons (metric tons)]	*120-155 (110-140)*	*1015-1325 (920-1200)*
Volume [cubic ft (cubic m)]	*1450-1835 (41-52)*	*34,960-45,910 (990-1300)*

Table1. Measured and calculated values for the determination of mass and volume of erratic and iceberg. Calculated values are in italics.

Return to Benton City via the Old Inland Empire highway.

32.6 8.6 *Left onto Rt. 225 N.*

33.6 1.0 Feature E. New Route of Flood-Defeated Yakima River

We are approaching the saddle where the present Yakima River passes between Red Mountain to the east and Rattlesnake Mountain to the west (Figures 5 and 6). The basalt bench above the river lies at 700 ft, which is the elevation Badger Coulee must have been choked with flood deposits in order for the river to find a new route at this next lowest point in the Yakima basin. Since its diversion, the Yakima River has incised it's channel ~300 ft downward into this saddle. As discussed in **Stop 1** this diversion probably occurred sometime during the middle Pleistocene (~200-700 ka).

36.6 3.0 Roadcuts expose slackwater flood deposits left behind by the last ice-age flood(s).

39.8 3.2 *Turn left into entrance to Fitzner/Eberhardt Arid Lands Ecology Reserve (now part of the HRNM).* Because it is an ecology reserve, this area is secured with a locked gate and access is presently closed to the general public. Elev. = 520 ft.

40.3 0.5 Feature F. Erratic Behavior on Laliik

Laliik is the name given Rattlesnake Mountain by the local Native Americans. There is a possibility that people were present to witness at least one ice-age flood. Native Americans most likely lived along the Columbia River, which served as a source for food and water. It's been estimated that a person might have had only a half-hour warning between the first rumbles and inundation. Native Americans would have had to move very quickly to elevations above 1250 ft to escape the floodwaters. Laliik would have been one of the few places in the Pasco Basin where people could have waited out a flood and survived, but their places of habitation lay 10-20 miles east and north of Laliik. Because of the long distance to safety, probably not many living in the Pasco Basin survived a single flood, not mention multiple floods, which may have occurred at intervals of every several dozen years during the late Pleistocene (Waitt 1985). The few fortunate souls that survived a flood, if any, probably quickly learned to seek other, more-hospitable environments (e.g., west towards the Cascades) or faced extermination.

Located at the southern margin of the Pasco Basin, the northern flank of Rattlesnake Mountain was a slackwater area during ice-age flooding. Icebergs floating in Lake Lewis tended to migrate to and concentrate in slackwater areas and evidence for this is well represented on Rattlesnake Mountain. Evidence for these floating icebergs consists of erratics and bergmounds, which consist of rocks foreign to this area. Erratics appear as isolated gravel clasts ranging up to large boulders in size. Erratics are mostly composed of granodiorite, quartzite, basalt, argillite, gneiss, or schist. Among boulder-sized erratics, light-colored granodiorite (Figure 10) is the most common rock type. Isolated erratics have been reported up to an elevation of 1250 ft (Baker et al. 1991), although here on Rattlesnake Mountain we do not see any erratics above 1200 ft elevation. Not coincidentally, the maximum elevation for ice-rafted erratics here is the same as the maximum elevation for scouring by the floods along Wallula Gap. Together, these two independent lines of evidence firmly establish the maximum elevation for the Ice Age floods at 1200-1250 ft within the Pasco Basin.

Figure 10. Granodiorite erratics on north side of Rattlesnake Mountain. Left: small erratic cluster; right : isolated erratic. These erratics lie near the upper limit (1200 ft elevation) for floodwaters in the Pasco Basin and probably melted out of smaller icebergs that were able to nudge up closer to the high-water mark along Rattlesnake Mountain (in background). The light-color of these granitic erratics stood out in stark contrast to the burnt and barren landscape immediately following the wildfire of 2000.

Bergmounds consist of a large cluster of erratics composed of a single lithology or multiple lithologies (Fecht and Tallman 1978, Chamness 1993). Unlike individual erratics or small erratic clusters, bergmounds contain more erratic debris and usually display some topographic relief (Figure 11). The topographic relief may not completely represent a buildup of erratic debris however. It may just be the result of preferential erosion around the flanks of the bergmound, which did not contain a protective covering of erratics.

Figure 11. Bergmounds on Rattlesnake Mountain north of Iowa Flats at 900 ft elevation. Left: notice broad, low-relief shape of bergmounds. Right: Angular, mostly granitic ice-rafted debris observed at the top of a bergmound.

41.1 0.8 At 800 ft elevation we begin to see broad, low-relief mounds covered with ice-rafted debris (bergmounds). Bergmounds disappear up the road at about 1000 ft elevation. Because bergmounds contain more ice-rafted debris it follows that they melted out of larger icebergs compared to isolated erratics or small erratic clusters. Although it is possible that some erratics could have dropped out of large icebergs before they became grounded.

Unlike isolated erratics, bergmounds are generally restricted to elevations between 600-1000 ft in the Pasco Basin. One explanation for why bergmounds aren't observed above ~1000 ft elevation is illustrated in Figure 12. If bergmounds developed from the grounding and subsequent melting of larger icebergs, then it follows that they could not have migrated as close to the edge of Lake Lewis. Because of their size, they would have become grounded at lower elevations compared to smaller icebergs, which may have only carried one or a few ice-rafted erratics. These smaller icebergs, containing less material, would naturally migrate closer to the edge of the lake, where the lake bottom rose to at a higher elevation.

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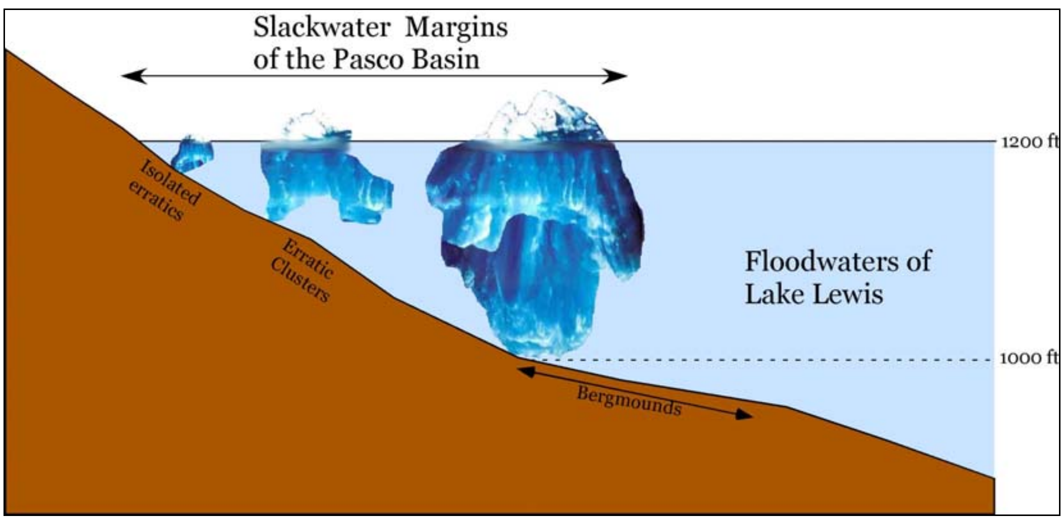

Figure 12. Diagram showing how icebergs of different sizes might account for the distribution of bergmounds, erratic clusters, and isolated erratics observed on Rattlesnake Mountain.

41.6 0.5 From here two ancient landslides are clearly visible on Rattlesnake Mountain. However, these landslides lie above the maximum level of the ice-age floods and therefore are probably not the direct result of the floods.

43.3 1.7 *Bear right along road that contours to west along flank of Rattlesnake Mountain.* This large gently sloping landscape is called Iowa Flats.

44.0 0.7 Abundant isolated scattered erratics occur along the road here at 1150 ft. Most appear to have been exhumed during road construction. Apparently more erratics exist than can be observed at the surface. Many lie buried in a matrix of fine-grained slackwater flood deposits, slopewash, and <u>eolian</u> loess, which together form a thin veneer of sediment over basalt bedrock.

45.0 1.0 **Stop 3. Lakefront Property (Elev. 1250 ft)**

Here at Battelle's old and abandoned Ecology Reserve Headquarters we are close to or at the highest level of the ice-age floods, for no ice-rafted erratics occur above this elevation. Looking out into the Pasco Basin imagine what it was like to have everything below us underwater!   In the center of the basin Lake Lewis was up to 900 ft deep.

50.2 5.2 *Left onto Rt. 225 N*

51.7 1.5 *Left onto Rt 240. Drive west up Cold Creek Valley.*

60.6 8.9 Feature G. Unusual Patterned Ground

An unusual type of patterned ground is associated with clastic dikes along the Cold Creek valley (Figure 13) and few other places within the Pasco Basin. Vertical to sub-vertical clastic dikes are a common feature of slackwater (i.e., sand- to silt-dominated) flood deposits in the Pasco Basin, and believed to be a type of soft-sediment deformation that occurred during, or soon after, cataclysmic flooding, perhaps induced by seismicity (Fecht et al. 1999). Where clastic dikes intersect the ground surface and aren't buried by younger sediments they may form interconnected, polygonal, dike networks (Fecht et al. 1999). Individual dikes may penetrate downward several tens or even a hundred feet or more.

To the right is an expansive interconnected network of clastic dikes (Figure 13). Networks of clastic-dike polygons are difficult to see from the ground but are clearly visible on aerial photographs since they contain more fine-grained material than the material between dikes. Dikes stand out in relief and retain more moisture, and therefore attract different assemblage of plants. It is this contrast in vegetation, which causes the dikes to stand out on aerial photographs.

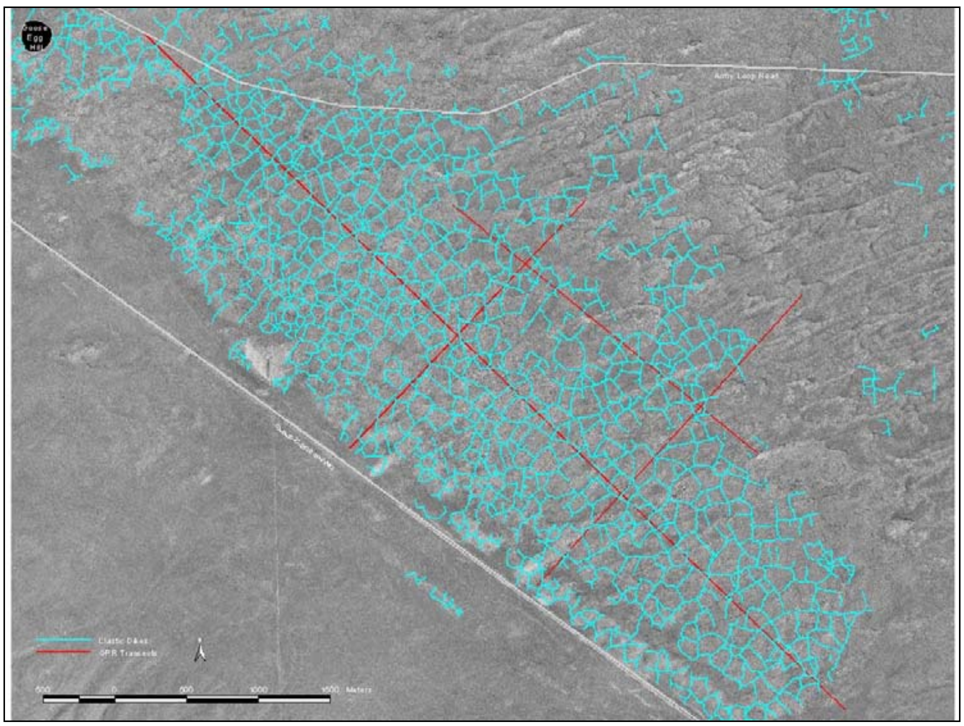

Figure 13. Tracings (blue lines) of interconnected network of clastic dikes (Feature G) just north of Hwy 240. Clastic-dike polygons disappear under a cover of post-flood sand dunes to the northeast. Red lines are locations of ground-penetrating-radar surveys used to evaluate dike behavior in the subsurface.

Goose Egg Hill, an unusual conical-shaped mound, occurs at the northwest end of the dike network in Figure 13. In the past Goose Egg Hill was believed to be a bergmound, however, it does not contain exotic ice-rafted debris as do other bergmounds. It may represent an erosional remnant of the dissected flood bar in the background.

63.6 3.0 Enter into hummocky surface topography, which are Holocene sand dunes derived from the reworking of flood deposits by the strong southwest to northeast winds in this area.

66.6 3.0 Feature H. Giant, 12-Mile Long Flood Bar

The long, low, flat-topped feature to the north is Cold Creek flood bar, composed of flood-deposited coarse sand and gravel. This 12-mile long bar formed by floodwaters that expanded and deposited their load as they moved south and east beyond Umtanum Ridge (Figures 1 and 14). Flood deposits reach their maximum thickness (300 ft = 100 m) within the Pasco Basin at the eastern end of Cold Creek bar (Figure 15). This bar, first recognized as a giant flood bar by Bretz et al. (1956), represents a compound bar that accumulated incrementally over time after many episodes of ice-age flooding. The flood deposits within Cold Creek bar are significant and are being studied in detail because most of Hanford's high-level radioactive and hazardous wastes are stored within the bar. Understanding the strata and mechanisms behind the ice-age floods is imperative to understanding the potential migration of contaminants from the Hanford Site.

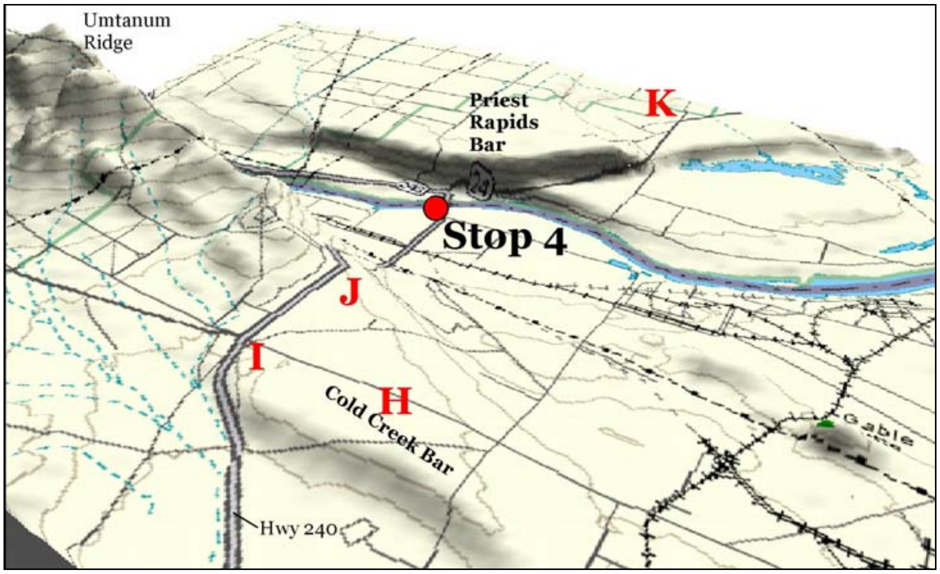

Figure 14. Oblique view looking northwest across Cold Creek and Priest Rapids flood bars. Floodwaters, which created the bars, came from the upper left in the direction of Sentinel Gap (see Figure 1).

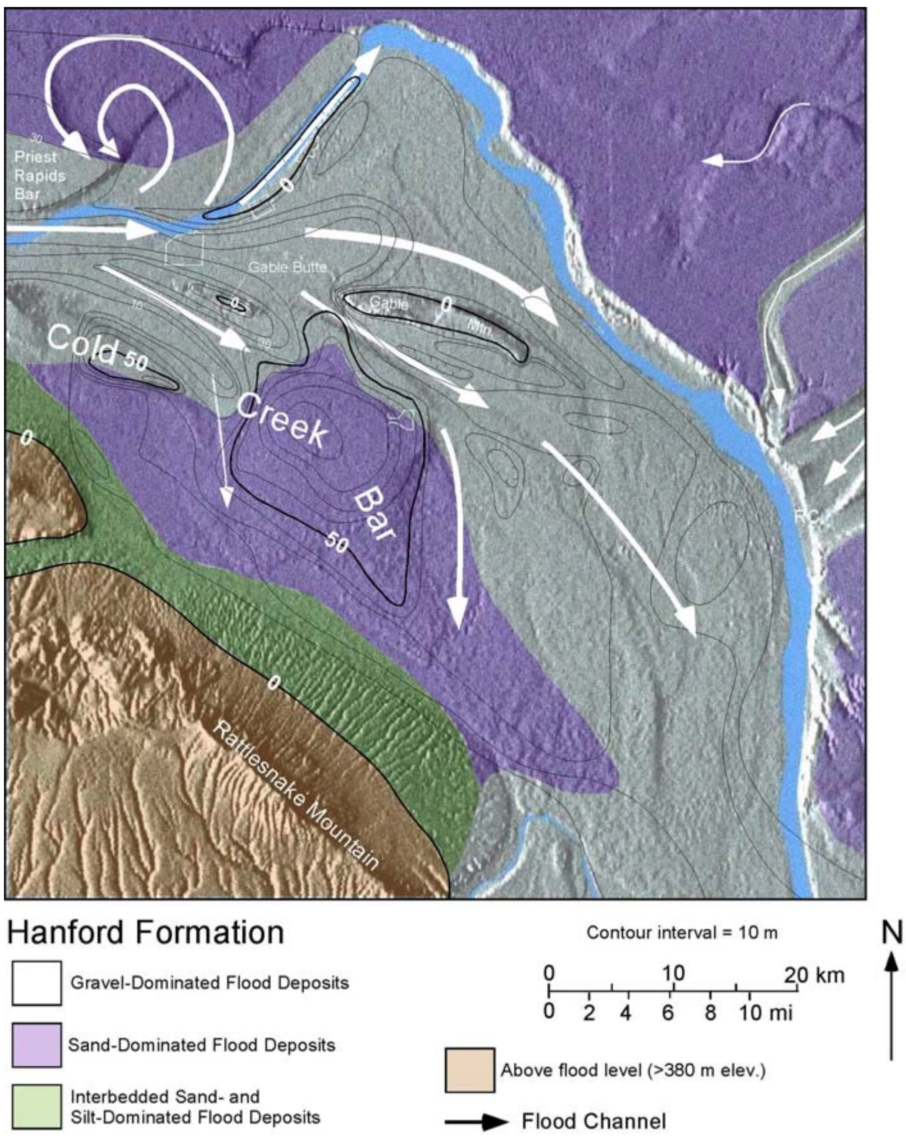

Figure 15. Thickness and distribution of flood deposits (i.e., Hanford formation) in the west-central Pasco Basin.

72.1 5.5 **Feature I. More Bergmounds Atop Cold Creek Bar (Elev. 900 ft)**

Bergmounds, similar to those on Rattlesnake Mountain (Feature F), also formed at the west end of Cold Creek bar (Fecht and Tallman 1978, Chamness 1993). Several of these broad, low-relief mounds can be observed as we drive by the turnoff to Yakima (Figure 16). Individual bergmounds can be up to 150 ft in diameter and 12 ft high. The surface of Cold Creek bar here is almost 600 ft above the present level of the Columbia River, several miles to the north. This elevation is within the range (600-1000 ft) for bergmounds previously discussed along the northern flank of Rattlesnake Mountain. Bergmounds gathered here, and up the Cold Creek valley to the southwest, due to eddying flood currents that swirled around the east end of Umtanum Ridge. These bergmounds became grounded atop the bar as floodwaters of Lake Lewis receded from the Pasco Basin. Much of the relief of bergmounds may be due to the protection of the mantling gravel, which armored the bergmound and protected any underlying slackwater flood deposits from being eroded by the last of the floodwaters as they drained out of the basin and from erosion associated with runoff of ephemeral streams that drain the upper Cold Creek valley. *Continue north on Hwy 240.*

Figure 16. Bergmound at west end of Cold Creek flood bar near Yakima Barricade. View is looking south with Rattlesnake Ridge in the background.

73.8 1.7 **Feature J. Missoula-Floods Landfill**

Pull off onto widened shoulder just before dropping down off north side of Cold Creek bar.
Flood bars southeast of Sentinel Gap (Figure 1) represent the final resting place for much of the debris scoured and eroded off the Channeled Scabland by the Missoula floods. As floodwaters raced through the constriction at Sentinel Gap two mechanisms were at work, which lead to sediment deposition and the development of these gigantic flood bars. First was the sudden change from constricted flow to more open flow. Second, was the slowing effect Lake Lewis had on current velocity during the later stages of flooding. As mentioned previously, the combination of these two mechanisms resulted in an accumulation of up to 300 ft of flood deposits southeast of here, along the eastern end of Cold Creek bar (Figure 15).

Notice the relatively even upper surface of Priest Rapids bar across the river at the same elevation (900 ft) as the top of Cold Creek bar. Priest Rapids bar formed along the inside of a giant, 10-mile-wide point bar after floodwaters passed through Sentinel Gap (Figure 1). At Vernita Bridge an impressive 300 ft of relief exists between the top of the bar and the river below (Figure 14). Both Priest Rapids and Cold Creek bars may be classified as expansion bars (Waitt 1994), which form below flow constrictions where competence of the flow is reduced, resulting in sediment deposition.

74.2 0.4 A highway cut to the right (east) exposes a sequence of old flood gravels from an early Pleistocene cataclysmic flood(s) emanating through Sentinel Gap.

77.1 2.9 **Stop 4. Lunch 800 Feet Downunder.**

Here at the Vernita Rest Area (Elev. 445 ft) floodwaters coming down from Sentinel Gap and ponding in Lake Lewis were up to 800 ft deep. Floods were vigorous enough here to maintain a channel between Priest Rapids bar to the north and Cold Creek bar to the south (Bretz et al. 1956). From Vernita, floodwaters fanned out across the Hanford Site and central Pasco Basin (see Figure 1) locally scouring out and backfilling the central portion of the basin with coarse sand and gravel deposits. At the same time finer grained sand and silt were deposited around the margins of the basin and in adjacent backflooded valleys (Figures 1 and 15).
Continue north on Hwy 240.

77.3 0.2 If the Columbia River is low one can observe large boulders along the lower river banks. These large boulders are remnants left over from ice-age floods that the Columbia River has been unable to transport downstream as the river has incised into the river channel during the Holocene. The course of the Columbia River has undergone a number of changes within the Pasco Basin due to fluctuations in river flow due to deglaciation and changes in climate since the Pleistocene.

78.1 0.8 *Turn right onto Hwy 24 toward Othello.* Drive along base of Priest Rapids bar. Gable Butte and Gable Mountain across the river on the right were completely submerged during the largest cataclysmic floods.

82.1 4.0 Feature K. Giant Eddy Currents

As floodwaters expanded into the basin. backeddies, up to several miles in diameter, formed as floodwaters swirled northward around the east end of Priest Rapids bar. This is apparent from the large arc-shaped scours and stepped terraces observed in Figure 1. The highest back eddy also has the largest diameter (~5 miles). Another eddy inside the larger one has a smaller diameter but lies at a lower elevation, suggesting it developed during: 1) a smaller flood or 2) during a later, lower stage of the same flood.

88.6 6.5 Drive along the expansive Wahluke Slope at 800 ft elevation. This even, gently sloping feature represents the undissected upper surface of the Pliocene Ringold Formation pretty much as its remained for about the last three million years. While this area lay underwater during the larger ice-age floods, little or no erosion took place apparently because of the protection provided from floods by the Saddle Mountains to the north (see Figure 1). Only a thin layer of slackwater flood deposits overlies the older deposits.

97.3 8.7 *Turn right into the Wahluke Wildlife Area* (now part of the HRNM).

97.6 0.3 Feature L. Good Idea Goes Bad

The large area of trees and shrubs on the right was an artificial wetland, created in the late 1960's or early 1970's using excess irrigation water, to create more habitat for wildlife (DOI 1999). Unbeknownst to the biologists, planners, etc., a preferential pathway existed for the percolation water along a buried paleochannel, which connects the artificial wetlands with the White Bluffs escarpment near Locke Island only 3 miles to the southwest (Figure 17). Water percolating from artificial wetlands moves quickly down through highly transmissive flood deposits. Upon encountering the low-permeability Ringold Formation, the water is forced to move laterally along the contact until it saps out in springs along the White Bluffs. The soft rocks of the Ringold Formation are relatively strong when dry, but lose much of their strength when wetted (Schuster 1989). Where wet the unstable, Ringold Formation sediments have slumped and slid along the steep White Bluffs escarpment. Landslide activity reached its peak by the early 1980's and in 1996(?) water to the pond was cut off and the wetlands have since disappeared. However, water continues to seep out along the bluffs apparently due to a large volume of water stored in the underlying sediments over years of infiltration. In 1998 an estimated 30 million cubic yards of sediment had been displaced within the Locke Island landslide complex alone (DOI 1999). It is unknown how long the landsliding will continue.

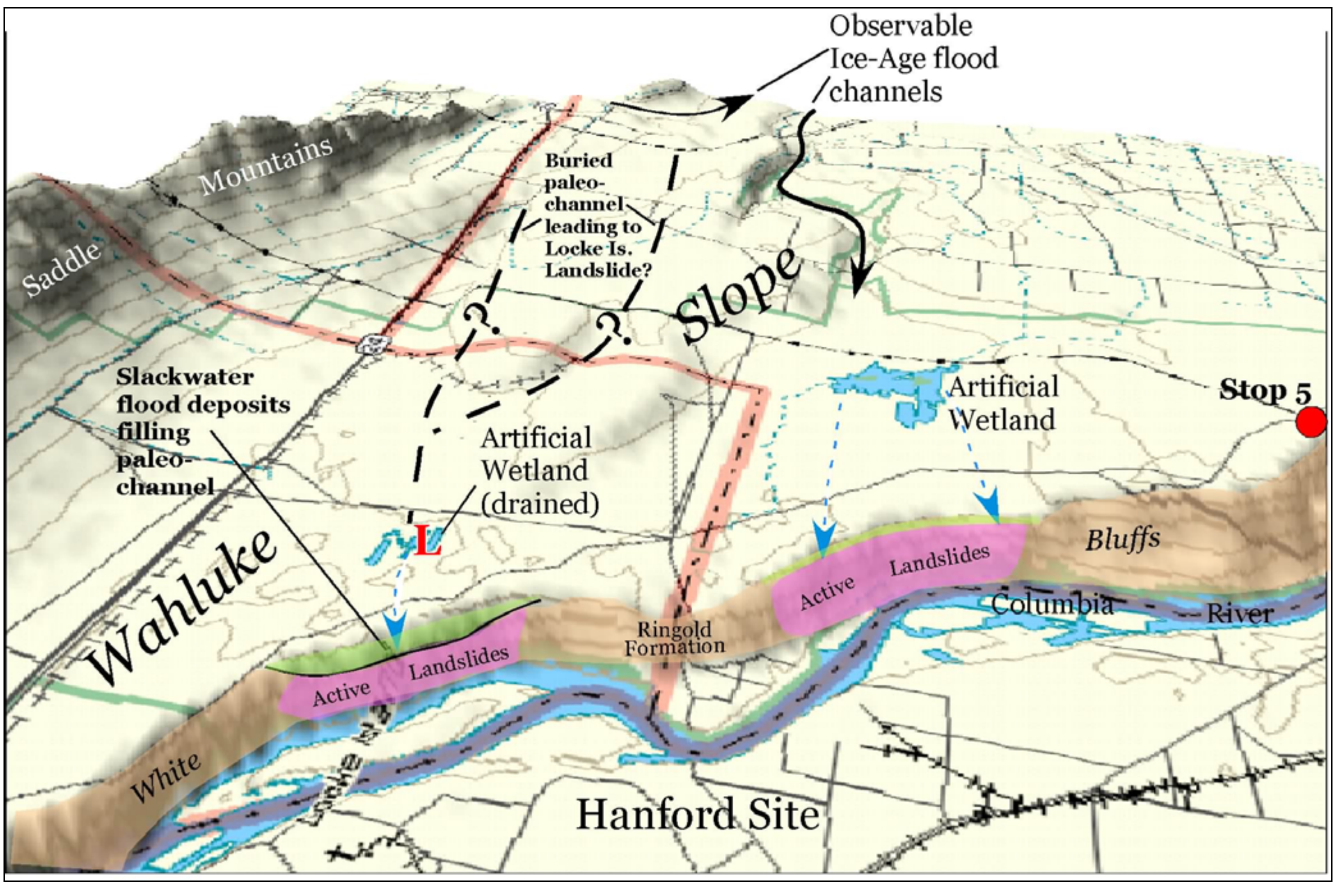

Figure 17. Artificial wetlands lead to active landsliding along the White Bluffs. 8X vertical exaggeration. Oblique view looking northeast.

Despite the good intentions of those wanting to enhance wildlife habitat, the repercussions have resulted in significant environmental degradation. Negative impacts include a significant loss of land to landslides as well as threatening the cultural and biological resources along the river. Landsliding has (and still is) displacing the river away from the bluffs, resulting in constriction the river channel and erosion along the northern bank of Locke Island, once the site of Native American villages (Nickens et al. 1998). Significant amounts of sediment are being remobilized as the river erodes Locke Island, as well as along the toe of the landslide complex. This sediment is being redeposited along bars just downstream in the vicinity of some of the most prolific salmon-spawning habitat along the Columbia River (Figure 18).

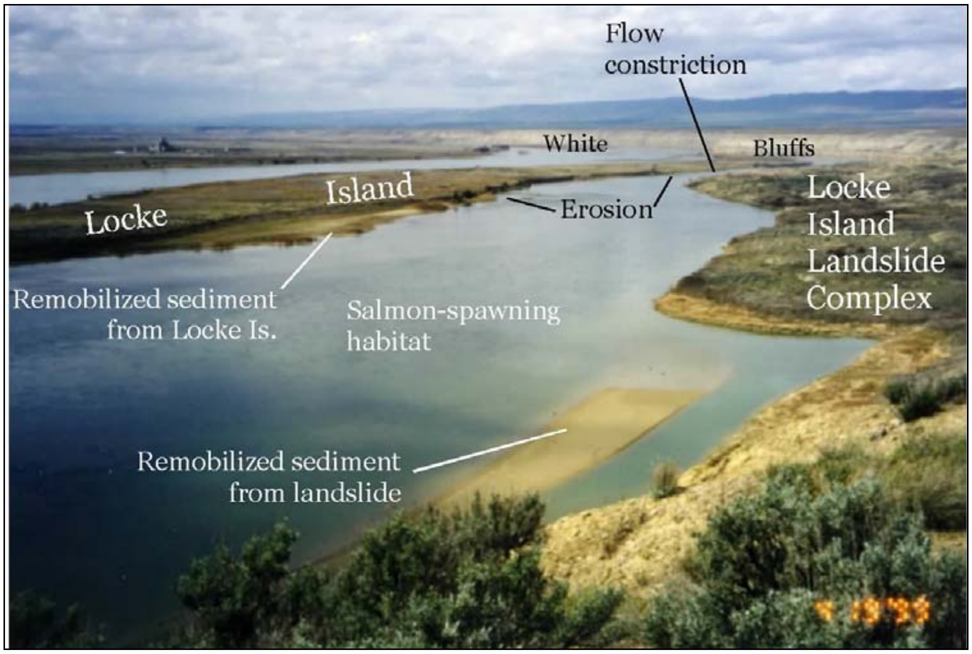

Figure 18. Erosion and redeposition of sediment in the vicinity of Locke Island. View looking west.

Landsliding occurs near Locke Island for a good reason. Here, a well-exposed sequence of sand-dominated flood deposits fills a 1.5-2.0 mile wide and 60-ft deep paleochannel incised into the Ringold Formation along the White Bluffs adjacent to Locke Island. The center of the buried channel lies at about 590 ft elevation, 200 feet above the level of the Columbia River below. Not surprisingly, the width of the landslide conforms almost exactly to width of the paleochannel (Figure 17). The origin of the buried paleochannel is uncertain at this time. It may represent a backfilled flood channel or perhaps the old channel of the Palouse River, which may have passed through this area prior to the initiation of ice-age flooding.

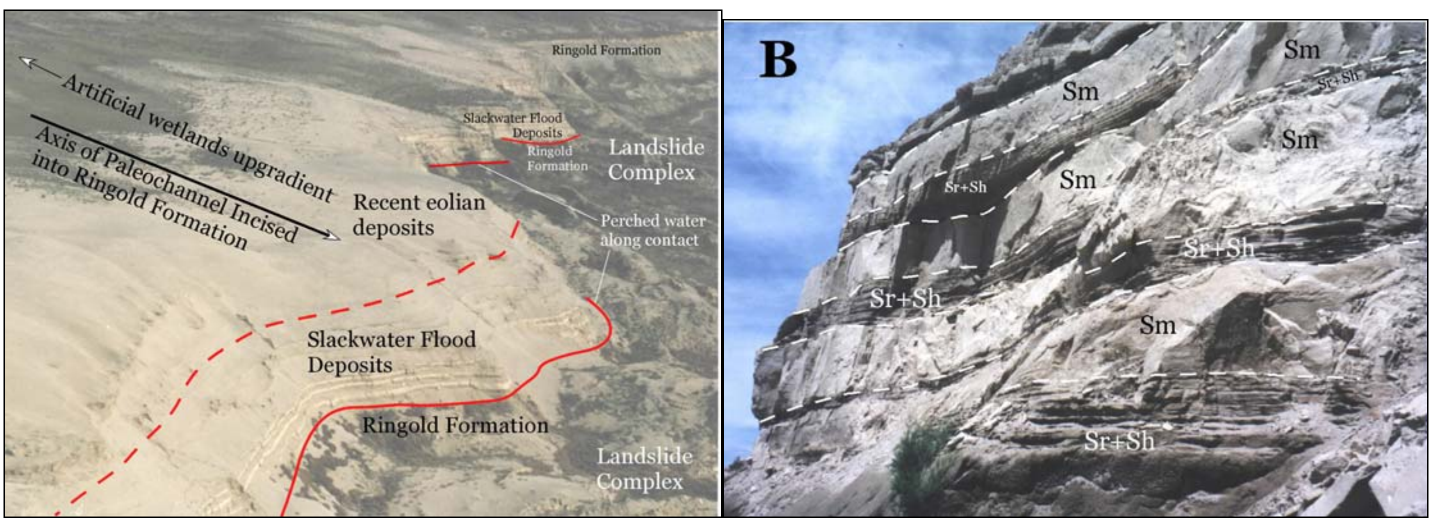

Figure 19. Slackwater flood deposits filling paleochannel incised into the Ringold Formtion along the White Bluffs. Left: aerial view looking southeast. The base of the paleochannel is indicated with a solid line, while the top of the flood deposits, which partially fill the channel, is indicated with a dashed line. Notice that no flood deposits are present beyond the margin of the paleochannel in the distance. Right: closeup of rhythmically bedded flood deposits composed of mostly sand, which fill the paleochannel. Sm = massive (eolian) sand, Sr = rippled sand, Sh = horizontally laminated sand.

Within this fill, are preserved as many as 9 relatively thick (up to 5 ft) “rhythmites” grading from horizontally laminated coarse- to fine-grained sand (Sh) and rippled fine sands (Sr) at the base to mostly massive, fine- to coarse-grained sand (Sm) at the tops of individual beds. The Sh/Sr beds, which display soft-sediment deformation and rip-up clasts, represent flood-laid beds. The intervening light-colored, poorly sorted Sm beds, which show signs of bioturbation, are interpreted as eolian deposits that developed via the reworking by wind of the underlying Ringold Formation; a similar process appears to be continuing today (Figure 19). The flood sequence in Figure 19 demonstrates that slackwater rhythmite formation is not limited to finer-grained flood deposits along valley margins of the Pasco Basin or its backflooded tributary valleys. Under the right conditions, slackwater deposits may also exist toward the interior of the basin.

98.5 0.9 *Merge left onto paved road.*

99.1 0.6 An active field of sand dunes on the right are from post-flood wind erosion of the White Bluffs escarpment, which lies immediately beyond the dunes. The bluffs are repeatedly windblasted by strong southwesterly winds, which carry loosened sedimentary particles up and over the top of the bluffs (see Figure 19).

101.2 2.1 *Intersection with White Bluffs boat landing. Continue straight (south).*

105.4 4.2 Stop 5. Slip Slidin' Away

Here at the top of the White Bluffs (Elev. 960 ft) floodwaters were still almost 300 ft deep during the largest flood. The White Bluffs are an erosional remnant of the fluvial-lacustrine Ringold Formation, which until about 3 million years ago filled the basin up to this level (DOE 1988; Reidel et al. 1991, 1992; Lindsey 1995). Since that time, the Columbia River and the ice-age floods have eroded back down into the Ringold Formation removing up to 600 ft of the Ringold Formation from the center of the basin.

Landslides of two distinct ages, described by USGS investigators (Schuster and Hays 1984; Hays and Schuster 1987; Schuster et al. 1987), can be observed from this point. Recent landslides resulting from water seeping out of man-made wetlands up to several miles behind the bluffs can be seen off to the right (northwest). This area of sliding is shown in Figure 17 (also on cover of this field guide). The hummocky topography below the bluffs between here and the river is from a much older episode of landsliding (Figure 20). Notice there is no water seepage along this slide like there is for modern landslides, suggesting a different mechanism was responsible for this older slide. Also, judging by the rounded and weathered nature of the landslide blocks, considerable time has elapsed. This information seems to suggest this slide occurred a long time ago, perhaps soon after one of the last Pleistocene ice-age floods about 15,000 years ago.

Another major flood bar from the ice-age floods in the Pasco Basin is Gable Mountain bar, located across the river on the Hanford Site south of here (Figures 1 and 20). It represents a five-mile long pendant bar, composed of loose sand and gravel, which formed in a more-protected area just downstream of Gable Mountain, a flood-scoured ridge of basalt (Fecht 1978). The upper surface of the bar is about 700 ft in elevation, or about 200 ft lower than Cold Creek bar located upstream. The summit of Gable Mountain (1085 ft) was completely submerged under almost 200 ft of water during the largest ice-age flood!

Figure 20. View looking south from the top of the White Bluffs at **Stop 5**.

105.6 0.2 *Continue through locked gate.* Descend along road, which is cut into ancient lake deposits of the Pliocene Ringold Formation. A well-developed paleosol sequence is exposed at mile 105.9, which represents a temporary draining of the Ringold lake that existed here about 4 million years ago.

106.7 0.9 Tilted and fragmented blocks of Ringold Formation are exposed in the roadcuts here. This represents the southern extension of the ancient landslide complex discussed at **Stop 5**.

107.9 1.2 The old Hanford townsite, abandoned in the 1940's at the beginning of the Manhattan Project, can be seen across the river. The large structure left standing is the remains of the high school.

108.5 0.6 *Pass through the second and last locked gate.*

111.0 2.5 Here is close-up view of recent landsliding on the White Bluffs as a direct result of man (Figure 21). Agricultural activity is occurring right up to the edge of the bluffs, as indicated by the windbreak (row of poplar trees) used to protect crops and reduce evapotranspiration. The wetted soils are those that support greenish vegetation in Figure 21 and a sign that fields above are being over irrigated. Excess irrigation water moves a considerable distance laterally along some of the more impermeable beds of the Ringold Formation, as well as percolating downward. The water increases the pore pressure between sediment grains, which causes a reduction in material strength. With the steep bluff face the loss of material strength results in slope failure and formation of landslides.

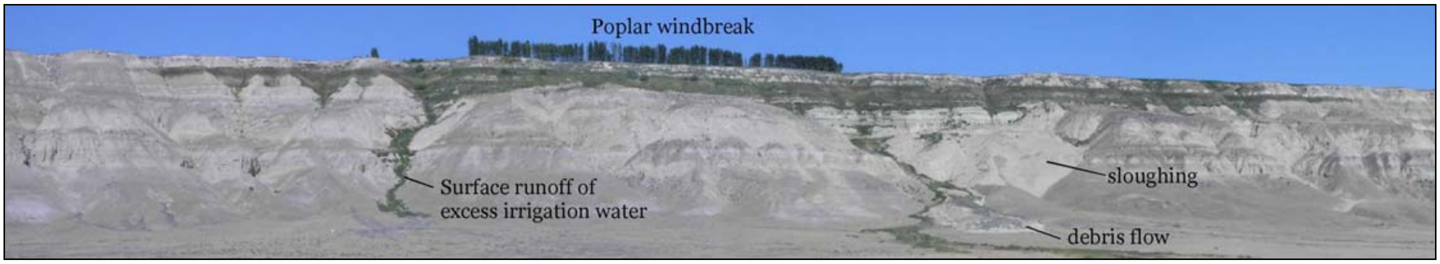

Figure 21. Modern landslide due to agricultural activity behind the White Bluffs. Notice significant lateral spreading of irrigation water away from the area of application.

114.4 3.4 Another thick paleosol sequence of the Ringold Formation exposed in long roadcut.

115.0 0.8 Feature M. Ringold Springs Oasis

Lush vegetation and springs suddenly appear like an oasis in this desert environment. Here, along the northwestern margin of Ringold Coulee, spring sapping occurs where excess water from intense agriculture and irrigation upstream moves preferentially down the axis of this major ice-age flood channel. Ringold Coulee represents a <u>hanging valley</u>, the floor of which lies ≥100 ft above the level of the river below. Coarse-grained flood deposits blanket the floors of Ringold and Koontz Coulees shown in Figure 22. Excess irrigation water moves laterally in the subsurface along the top of the relatively impermeable Ringold Formation, and gushing out in springs where the contact between flood gravels and Ringold Formation lies above the level of the road (Reidel et al. 1991).

Hanging valleys at the mouth of Ringold Coulee (Figure 22) suggests that the river has continued to incise since the last ice-age floods, perhaps during a period of either deglaciation or Holocene downcutting.

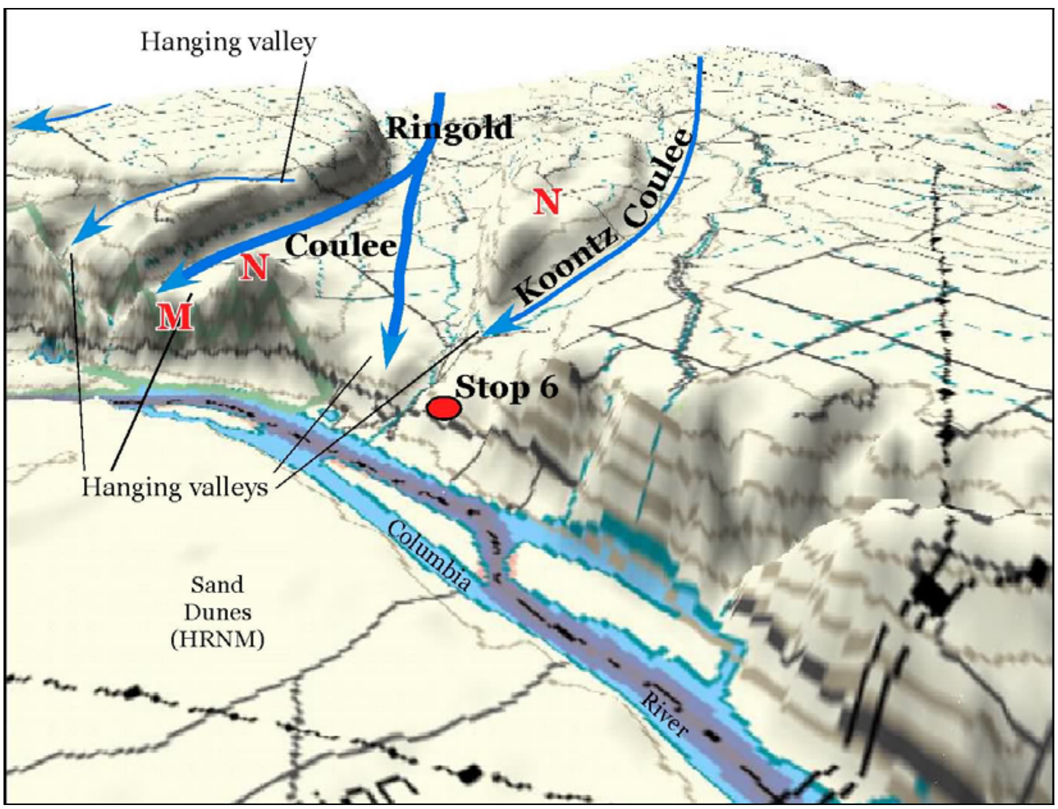

Figure 22. Flood features near the mouth of Ringold and Koontz Coulees. Blue arrows are flood-scoured channels, along which excess irrigation water tends to flow today. View looking northeast. 8X vertical exaggeration.

116.2 1.0 A large dune field exists across the river, which is now part of the HRNM. The dunes formed as a result of strong southwesterly winds, which blow across the Hanford Site. Ringold Coulee is in line with this wind direction and thus acts as a natural "wind tunnel" for the movement of these winds out of the basin (Reidel et al. 1992). The source material for the sand dunes are the flood deposits that have been reworked by the wind since the last ice-age floods about 15,000 years ago.

117.4 1.2 *Pass Ringold Fish Hatchery and park at intersection of Ringold and Ringold River Road.* Hike short distance up to borrow pit.

Stop 6. Flood Deposits at Mouth of Ringold Coulee (Elev. 460 ft)

Here, at a borrow pit located at the mouth of RingoldCoulee, are exposed sequences of both gravel- and sand-dominated flood deposits. The present exposure is not as good as a few years ago (Figure 23), when there was evidence for at least two erosional unconformities, probably formed during separate ice-age floods. The base of the sequence is dominantly gravel while the overlying younger deposits are dominantly sand.

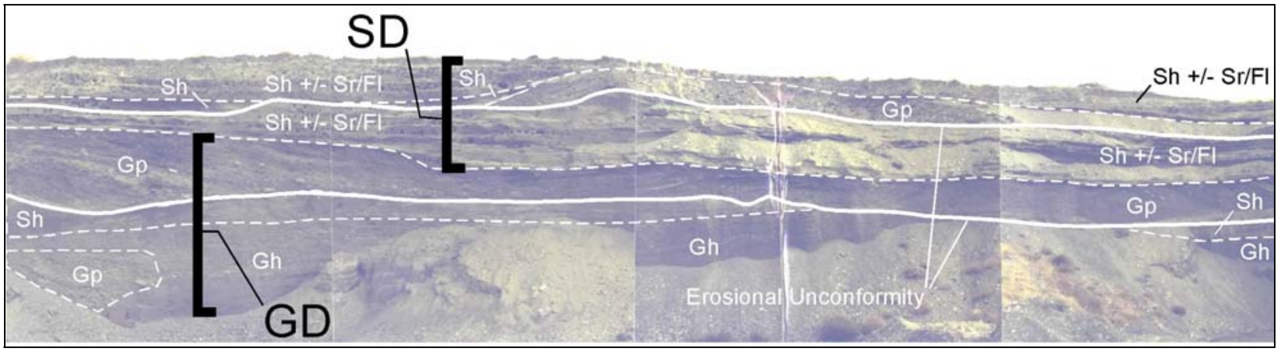

Figure 23. Flood deposits exposed at mouth of Ringold Coulee at Stop 6. Gh = horizontally bedded gravel, Gp= planar-cross bedded gravel, Sh = horizontally laminated coarse sand, Sr = ripple-laminated fine sand, and Fl = horizontally laminated fine sand to silt. SD = sand-dominated and GD = gravel-dominated flood sequences.

118.0 0.6 Notice a large horseshoe-shaped escarpment just north of the road, which developed as a result of a spring sapping out along the contact between Ringold Formation and flood deposits. A thick sequence of gravel-dominated flood deposits, which display large-scale fore-set beds dipping to the southwest, suggest transport down Ringold Coulee. These flood deposits are mantled by a thick layer of eolian sand, deposited by strong winds that have moved through Ringold Coulee since the last ice-age floods.

118.6 0.6 Feature N. Streamlined, Flood-Scoured "Ringold Islands"

Ringold and Koontz Coulees are a pair of ice-age flood channels that delivered floodwater coming around the east end of the Saddle Mountains via the Othello Channels (Figure 1). These coulees display less relief than coulees on the Channeled Scabland because they are carved into Miocene-to-Pliocene-age Ringold Formation sediments, which are more easily eroded than basalt. Streamlined islands of Ringold Formation sediments, similar to islands of eroded loess in the Palouse region (Baker and Nummedal 1978), is present near the mouth of Ringold Coulee (Figure 22). One of these islands occurs right at the mouth of Ringold Coulee and another divides Ringold and Koontz Coulee. The streamlined island within Ringold Coulee is truncated at its southwest end, probably beveled off by a more recent flood coming down the Columbia Valley from the northwest. These streamlined landforms are an erosional feature left behind as the floods scoured away and sculpted the weakly consolidated Ringold Formation within these flood channels. Note also the several hanging valleys along and at the mouths of these coulees, including where Koontz Coulee joins Ringold Coulee (Figure 22).
Turn right onto Ringold Rd.

119.1 0.5 Cross bottom of Koontz Coulee. The floor of Koontz Coulee lies ~200 ft higher than the bottom of Ringold Coulee. This suggests Koontz Coulee was occupied during an earlier stage of flooding or an earlier larger flood(s) coming off the Channeled Scabland from the northeast.

121.6 2.5 *Turn right onto Taylor Flats Road.* Drive for several miles along the flat, even, upper paleosurface of the Ringold Formation with a thin veneer of scattered slackwater flood deposits at ~1050 ft elevation. While this area was just underwater during the largest floods it escaped dissection and erosion by the floods, which was concentrated to areas north and east of here (Figure 1).

127.6 6.0 Feature O. Flood Bar

Drop down onto a low-elevation flood bar across the river from Richland (Figure 1). This area represents a large point bar for floods coming down the Columbia, and is composed of predominantly basaltic sand with occasional gravel. Current indicators within the bar indicate multiple flood directions, including from the northeast via Esquatzel Coulee as well as from the northwest via the Columbia River.

135.1 7.5 *Bear left onto Road 68.*

137.4 2.3 *Turn right onto I-182 towards Richland.*

141.4 4.0 *Take exit 5B onto George Washington Way.*

Feature P. Flood Terraces

Elevated terraces to the south along the foothills of the Rattles in South Richland and Kennewick represent terrace deposits of old ice-age floods.

143.2 1.8 *Return to CREHST Museum, Richland.*
End of Field Trip

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Glossary of Terms
(underlined in text)

anticlinal: pertaining to an anticline or upwarped portion of a fold in the earth's crust.

basalt: a dark igneous volcanic rock composed of primarily two minerals: plagioclase and pyroxene. Over a period of 11 million years (6 to 17 million yrs B.P.) hundreds of flows of Columbia River basalt were extruded from long, linear joints in southeastern Washington, northeastern Oregon and west-central Idaho and traveled for hundreds of miles before cooling and solidifying to form the Columbia Plateau.

bedrock: a general term for the rock (i.e., basalt) that underlies the soil or other unconsolidated, surficial material.

bioturbation: the burrowing, churning, and stirring of sediment by organisms.

brachyanticline: a doubly plunging, short, broad uplift in the earths crust.

butte: a conspicuous, isolated, generally flat-topped hill with relatively steep side slopes, often capped by a more resistant layer of rock and bordered by talus. Often represents an erosional remnant carved from flat-lying rocks and smaller in extent than that of a mesa.

calcic: a diagnostic subsurface soil horizon characterized by the enrichment of secondary pedogenic calcium carbonate. Thick calcic horizons signify a long period of soil development in an arid to semiarid environment.

Channeled Scabland: an eroded, interconnected network of streamlined loess islands and flood channels, coulees, cataracts, and plunge pools scoured into basalt by cataclysmic floods in eastern Washington, unique to any other place on Earth. Similar to channel networks observed on Mars.

clast: an individual particle or fragment of a sediment or rock produced by the mechanical weathering of a larger rock mass.

clastic dike: a feature that cuts across bedding structures and is composed of the sedimentary material it transects. Believed to be the result of fracturing and sediment movement due to earthquake shaking during or soon after cataclysmic flooding.

clay: extremely small sedimentary particles that are less than 0.004 mm in diameter.

coarse-grained: pertains to sedimentary material composed of relatively large particles of sand and/or gravel.

coulee: a long, dry, steep-walled, trench-like gorge or valley representing an abandoned river channel. In south central Washington the term coulee is mostly used for an abandoned ice-age flood channel.

eolian: pertaining to the wind. Includes deposits of loess and dune sand.

erratic: a rock fragment carried by floating ice, deposited at some distance from the outcrop from which it was derived and generally composed of a different type of rock than the local bedrock.

expansion bar: a type of flood bar that forms where flood channels suddenly widen or expand in size. Channel expansion causes the current to decrease, which in turn causes sediment to settle out of suspension, forming a bar.

fine-grained: pertains to sedimentary material composed of relatively small particles of clay and/or silt.

flood bar: an accumulation of sediment, most often composed of sand and/or gravel, that occurs along flood routes where the currents move slower for various reasons. Different types of flood bars include eddy bars, expansion bars, shoulder bars, and pendant bars.

fluvial-lacustrine: pertains to sedimentary deposits laid down in ancient river (fluvial) and lake (lacustrine) environments.

fore-set bedding: primary sedimentary structure in flood gravels where a pronounced dip occurs in bedding planes in the direction of sediment transport.

glacial Lake Missoula: the source for most or all of the floodwater that created the Channeled Scabland. The lake formed behind an ice dam in the Idaho Panhandle, which periodically failed sending torrents of water downstream. At its maximum Lake Missoula contained 600 mi3 of water, was 2000 ft deep, 200 miles long, and covered an area 3000 mi2. It took up to 125 years to fill but only 2 to 3 days to completely empty.

granitic: a general term for any light-colored igneous rock that formed deep underground within a cooling body of liquid magma. The nearest granitic rocks occur in northern Washington

granodiorite: a type of granitic rock consisting of mostly crystalline quartz and plagioclase feldspar.

gravel: large sedimentary particles that are greater than 2 mm in diameter. Gravel clasts include, in increasing size, granules, pebbles, cobbles, and boulders.

HRNM: Acronym for the 195,000 acre Hanford Reach National Monument, which was created by presidential proclamation on June 9, 2000. The monument is presently managed by the U.S. Fish and Wildlife Service. It includes a horseshoe-shaped area within the Pasco Basin, which lies north, west, and south of the U.S. Department of Energy’s Hanford Site, as well as the 51-mile long Hanford Reach of the Columbia River. The HRNM is subdivided into six distinct management units based on location, natural resources, and administration. A comprehensive conservation plan is presently being developed for the monument.

hanging valley: a tributary valley whose floor is notably higher than the valley it joins. Characteristic of flood coulees, where flat valley floors suddenly drop off into nothingness at one or both ends where they join adjacent coulees.

Holocene Epoch: the period of geologic time since the last Ice Age (10,000 yrs ago to the present).

hydraulic constriction: where a large volume of water is confined to a narrow opening. If more water enters the opening than can drain through, then the constriction will cause water to back up, creating a type of hydraulic dam.

hydraulic head: the difference in water level at a point upstream from a given point downstream. A larger difference in head will result in more erosion and downcutting by floodwaters.

igneous: rock that solidified from molten or partly molten material (i.e., magma). One of the three principal rock types, along with sedimentary and metamorphic.

ka: thousands of years before present.

Lake Bonneville: an Ice-Age lake that formed in central Utah from melting mountain glaciers. The Great Salt Lake today is a much smaller remnant of Lake Bonneville. The lake drained catastrophically, only once, toward the end of the Ice Age about 15,000 years ago when the lake overtopped a drainage divide and partially drained northward into the Snake River.

Lake Lewis: a temporary lake that formed behind the hydraulic constriction at Wallula Gap. Within 5 days or less the lake grew to an elevation of 1250 ft above sea level before completely draining through the gap.

lithology: physical character of a rock, including its color, mineralogic composition, and grain size.

loess: windblown silt and fine sand that collects on lee sides of ridges at higher elevations within the Pasco Basin.

Ma: millions of years before present.

magnetic polarity: refers to flips in the Earth's magnetic field that have occurred periodically through geologic time. The last magnetic-polarity shift, which caused a reversal in the magnetic field, occurred 780,000 years ago.

mesa: an isolated, nearly level land mass standing distinctly above the surrounding country, bounded by abrupt steep-sided slopes on all sides and capped by layers of more-resistant rock.

metamorphic: any rock derived from pre-existing rocks by mineralogical, chemical, and/or structural changes. One of the three principal rock types, along with sedimentary and igneous.

Miocene Epoch: the period of geologic time between 5 and 24 million years before present when Columbia River basalt was extruded into the Pasco Basin.

paleomagnetic: pertains to the natural remanent magnetization of rock and sediment in order to determine the intensity and direction of the Earth's magnetic field in the geologic past.

paleosol: a buried soil horizon of the geologic past.

patterned ground: well-defined, more or less symmetrical forms, such as circles, polygons, nets, steps, and stripes, that are characteristic of, but not necessarily confined to, surficial material subject to intense frost action, especially in polar, subpolar and arctic regions. Patterned ground in the Pasco Basin, on the other hand, appears to be related to seismicity that occurred during or soon after cataclysmic flooding.

pedogenic: pertaining to soil formation.

pendant bar: a type of flood bar that forms immediately downstream of an obstruction in the flow of the flood current.

Pleistocene Epoch: the period of geologic time between 10,000 yrs and 2.5 million years before present. The Pleistocene essentially spans the same period of time known as the Ice Age.

Pliocene Epoch: an epoch of the Tertiary period, after the Miocene and before the Pleistocene.

point bar: an arcuate ridge of sand and gravel developed on the inside of a growing meander, which accompanies migration of a channel toward the outer bank.

radiometric: an age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products.

reverse fault: a fault, usually with a dip >45 degrees, where the hanging wall has moved up relative to the footwall of the fault.

reverse grading: refers to sedimentary beds that show an increase in particle size upward within the bed, as opposed to normal grading which shows a decrease upward. Most flood rhythmites display normal grading.

rhythmite: a graded sedimentary layer, several inches to several feet thick, deposited under slackwater conditions, especially in backflooded valleys during cataclysmic floods. Some believe that each rhythmite represents a separate cataclysmic flood from glacial Lake Missoula.

Ringold Formation: Sediments stratigraphically overlying Columbia River basalt and underlying cataclysmic flood deposits in southeastern Washington. Mostly derived from ancient river and lake deposits that accumulated within the ancestral Columbia River basin between about 3.4-8.0 million years ago.

rip-up clast: sedimentary material that has been eroded and transported only a short distance in a semi-consolidated (e.g., frozen) state.

Sangamon Interglacial: the period time, between glacial stages about 80,000 – 130,000 years ago, when climatic conditions were similar to those of today.

sand: sedimentary particles that are between 0.06 to 2.0 mm in diameter.

sedimentary: composed of sediment. One of the three principal rock types, along with igneous and metamorphic.

seismicity: Earth vibrations and shaking due to earthquake activity, as well as those artificially induced.

silt: small sedimentary particles that are between 0.06 to 0.004 mm in diameter.

slackwater: refers to areas with slower moving flood waters associated with cataclysmic flooding (i.e., backflooded valleys and valley margins) where fine-grained sediment (mostly sand and silt) was deposited.

soft-sediment deformation: deformation that occurs during or soon after sediment deposition while sediment is still partially or fully saturated with water. Examples of soft-sediment deformation include flame structures, load structures, and clastic dikes.

tectonic: pertains to forces within the earth's crust that give rise to earthquakes, folds, faults, and joints observed at or near the surface.

tephra: airfall deposit from a volcanic eruption. Usually consists of distinctive, light-colored, well-sorted, gritty particles of ash.

venturi effect: the principle that fluid moving through a smaller area will move at a higher velocity than the same amount of water moving through a larger area. As an example, floodwater moving through a narrow opening such as Wallula Gap was moving much faster, with significantly more erosive power, than the water that entered or exited the gap.

Wallula Gap: the narrow constriction, only a few miles wide, through which all floodwaters from glacial Lake Missoula passed on their way to the Pacific Ocean. During the largest floods, the water within Wallula Gap was over 1000 ft deep.

Wisconsinan: Pertaining to the classical fourth and last glacial stage of the Pleistocene Epoch in North America, following the Sangamon interglacial and preceding the Holocene Epoch. The late Pleistocene Wisconsinan glacial stage occurred between about 15,000-80,000 years before present.