Ice Age Floods Institute—Ellensburg Chapter

Ellensburg Area Field Trip

<u>Field Trip Leaders</u>:

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Saturday 15 September 2012

Itinerary & Overview

8:00am	Depart
8:30	Stop 1—Manastash Ridge I at I-82 Overlook
9:00	Depart
9:30	Stop 2—Yakima River Canyon at Umtanum Creek (+ Restrooms)
10:15	Depart
10:45	Stop 3—Manastash Ridge II on Umtanum Road
11:15	Depart
12:00	Stop 4—Thorp Grist Mill (Lunch & Restrooms)
1:00pm	Depart
1:15	Stop 5—Yakima River Overlook Northwest of Thorp
1:45	Depart
2:30	Stop 6—Ginkgo Petrified Forest State Park (+ Restrooms)
3:15	Depart
3:45	Stop 7—Frenchman Coulee
4:30	Depart
5:30	Arrive in Ellensburg

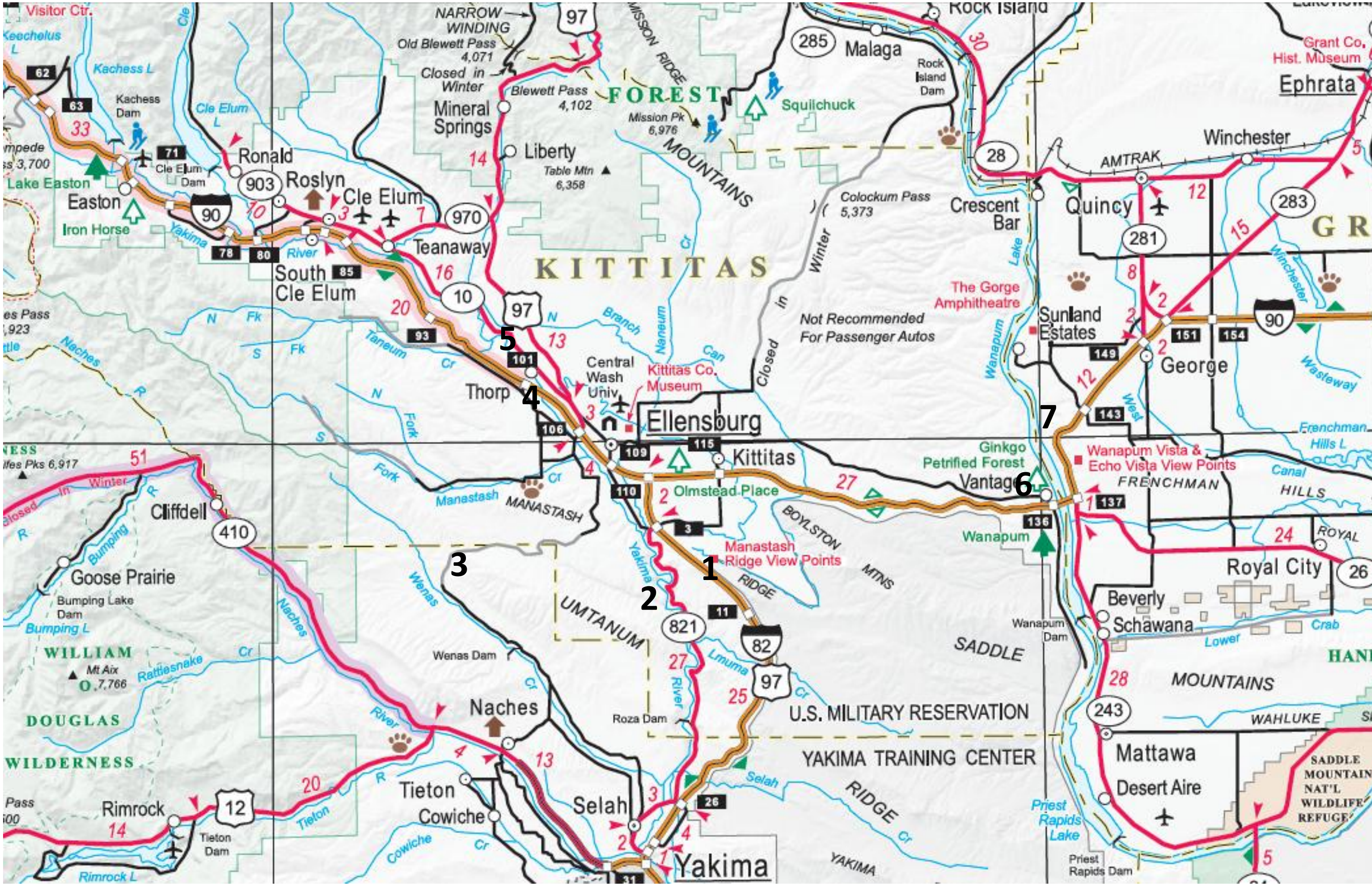


Figure 1. Map of field trip route. Stops are shown in bold numbers.

En route to Stop 1

- Major themes today:
  - Columbia River Basalts
  - Tectonics
  - Landslides
  - Glaciation
  - Stream Action
  - Missoula Floods
- Relative bearings (in direction bus is facing) (Figure 2)
- Our route:
  - University Way to University Way to I-90 eastbound to I-82. Proceed on I-82 south to the viewpoint at the top of Manastash Ridge
  - This segment of I-82 was constructed between 1969 and 1972 replacing US 97 (now state route 821) as the primary route between Ellensburg and Yakima
- Kittitas Basin as:
  - a central location in Washington
  - home of Central Washington University
  - significant in agriculture, especially timothy hay production
- Missoula Floods:
  - We are >400 feet above highest Missoula Flood deposits found in vicinity of Selah Gap near Selah to south
- Manastash Ridge geology as folded and faulted basalts and interbedded sedimentary rocks that was later shaped by landslides and streams

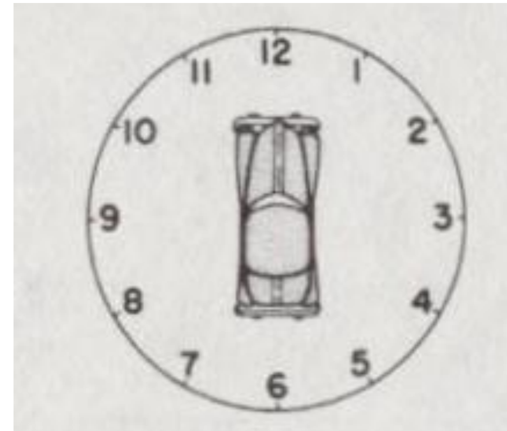


Figure 2. Relative bearings using a clock. Assume that the bus is always pointed to 12 o'clock. From Campbell (1975, p. 1)

Stop 1—Manastash Ridge I

- Columbia River Basalts & Ellensburg Formation
  - Wanapum Basalts (Frenchman Springs & Roza members)
  - Interbeds (Vantage and Squaw Creek members of Ellensburg Formation)
  - Our marginal location
- Yakima Fold Belt
  - Manastash Ridge as an asymmetrical anticline
  - Kittitas Basin as a syncline
  - Table Mountain as a monocline
  - Reflecting north-south compression
  - Active since ~10 Ma with deformation continuing through present (Tolan et al, 2009)
- Older rocks to north & west
  - Ingalls Tectonic Complex
  - Mt. Stuart Batholith
  - Swauk Formation
  - Teanaway Basalts
- Kittitas Basin as a late Tertiary“depocenter”
  - lahars
  - alluvial fans
  - glacial drift
  - loess
- Kittitas Basin Climate (Figure 8)
  - warm, dry summers and cool, moist winters
  - windy springs and summers

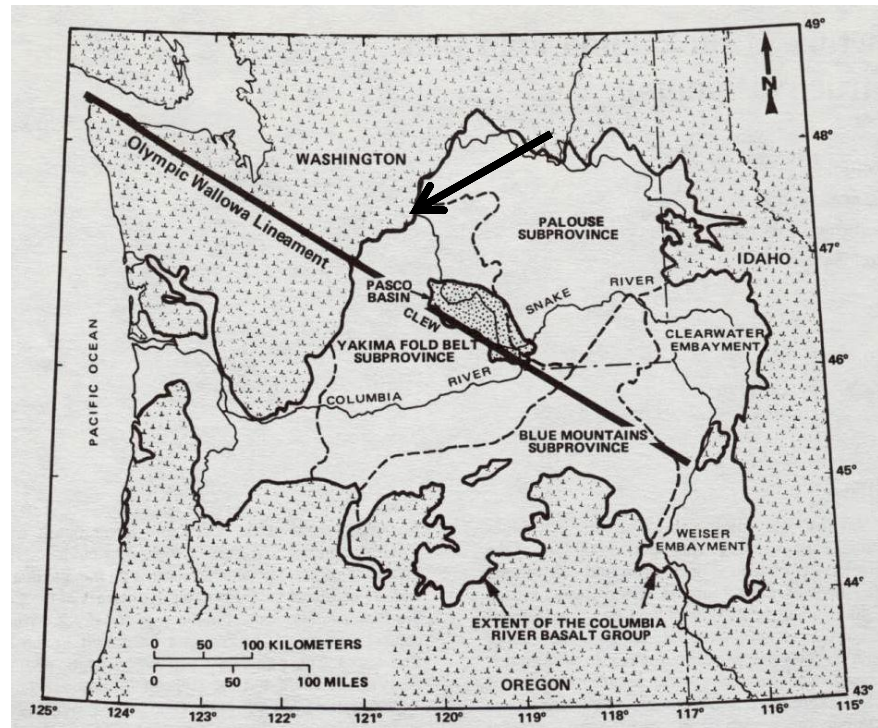


Figure 3. The Columbia River Basalt Group, the four major structural-tectonic subprovinces (the Yakima Fold Belt, Palouse, Blue Mountains, and Clearwater-Weiser embayments), the Pasco Basin, the Olympic-Wallowa lineament, and the CLEW, which is the central portion of the OWL that passes through the western part of the Columbia Plateau (Reidel & Campbell, 1989, p. 281). Bold arrow indicates our approximate location.

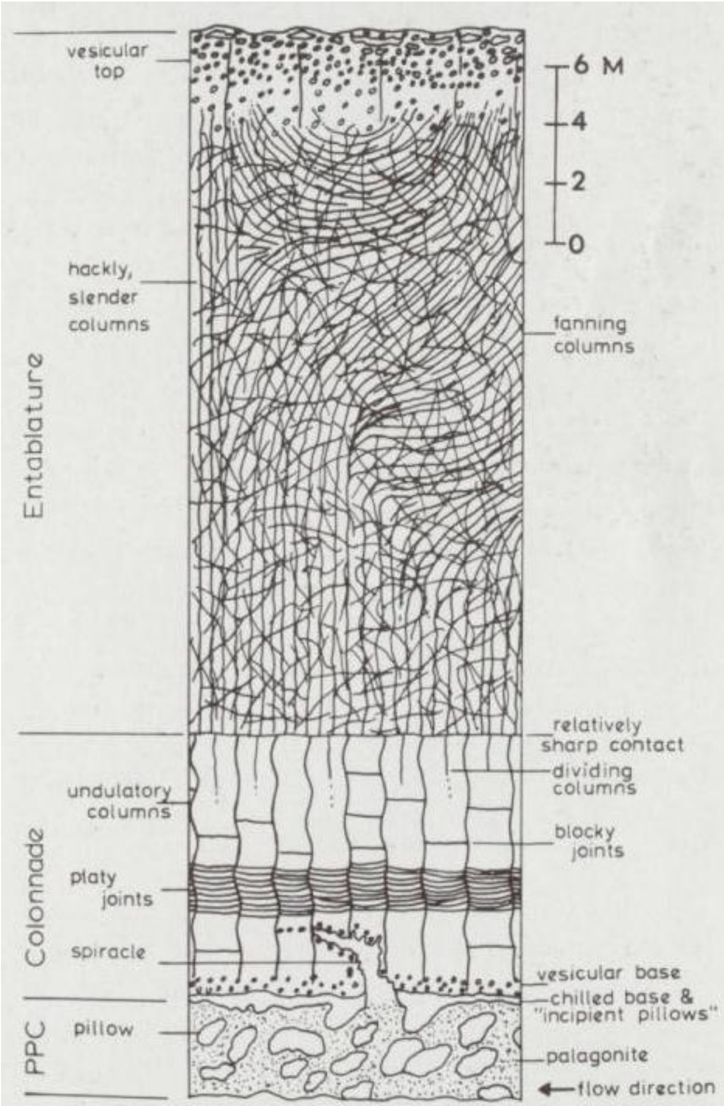


Figure 4. Cross-section of a typical flow in the Columbia River Basalt Group. From Swanson and Wright (1978, p. 51).

Stratigraphic Subdivision of Columbia River Basalt Group (CRBG)

SERIES		GROUP	SUB-GROUP	FORMATION (Age, Volume, % of CRBG)	MEMBER	MAG*
Miocene	Upper	Columbia River Basalt Group	Yakima Basalt SubGroup	Saddle Mountain Basalt (14-6 Ma, 2,400 km3 volume, 1.5% of CRBG)	Lower Monumental Member	N
					Ice Harbor Member	N,R
					Buford Member	R
	Middle				Elephant Mountain Member	R,T
					Pomona Member	R
					Esquatzel Member	N
					Weissenfels Ridge Member	N
					Asotin Member	N
					Wilbur Creek Member	N
					Umatilla Member	N
				Wanapum Basalt (15.5-14.5 Ma, 10,800 km3 volume, 6.0& of CRBG)	Priest Rapids Member	R3
					Roza Member	T,R
					Frenchman Springs Member	N2
					Eckler Mountain Member	N2
	Lower			Grande Ronde Basalt (17-15.5 Ma, 151,700 km3, 87%)		N2
						R2
				Picture Gorge Basalt		N1
						R1
				Imnaha Basalt (17.5-17 Ma, 9,500 km3 volume, 5.5% of CRBG)		R1
						T
						N0
						R0

* Magnetic Polarity:
N, normal; R, reversed; T, transitional; subscripts denote magnetostratigraphic units

USGS *Topinka, USGS/CVO, 1997, Modified from: Swanson, et.al., 1989, AGU Field Trip Guidebook T106*

Figure 5. Columbia River Basalt Group stratigraphy. From http://vulcan.wr.usgs.gov/Volcanoes/PacificNW/AGU-T106/columbia_river_basalt_group.html

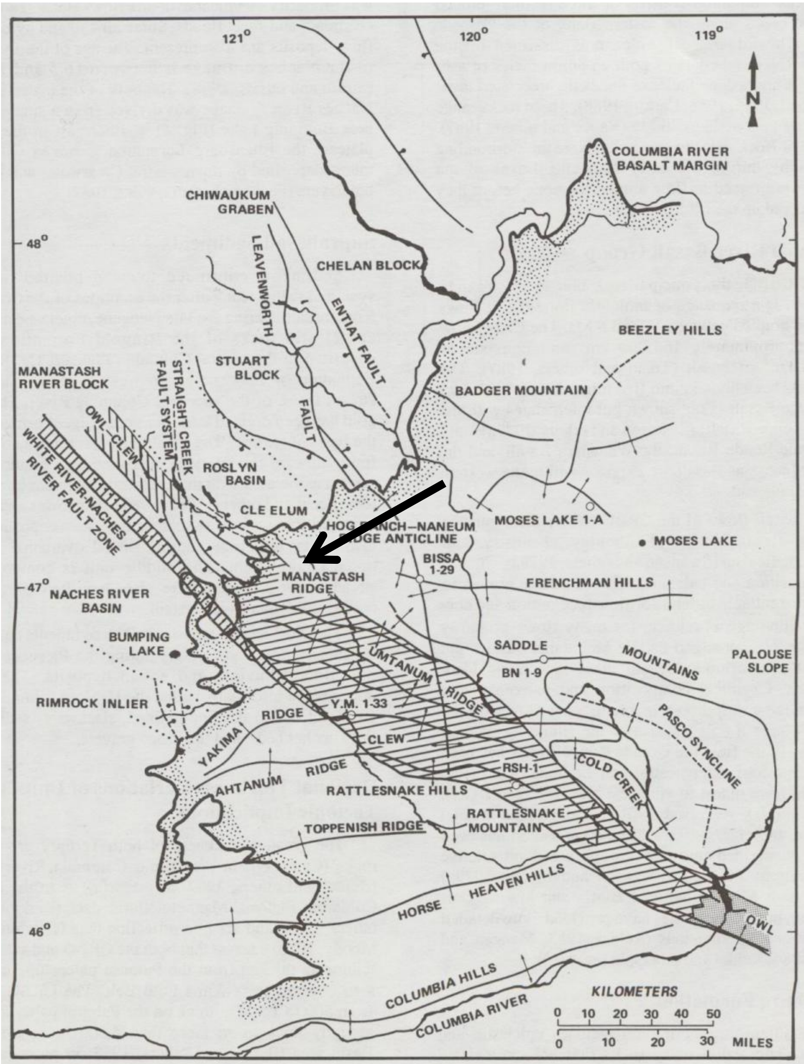


Figure 6. Generalized map of major faults and folds along the western margin of the Columbia Plateau and Yakima Fold Belt (from Reidel & Campbell, 1989, p. 281). Bold arrow indicates our approximate location.

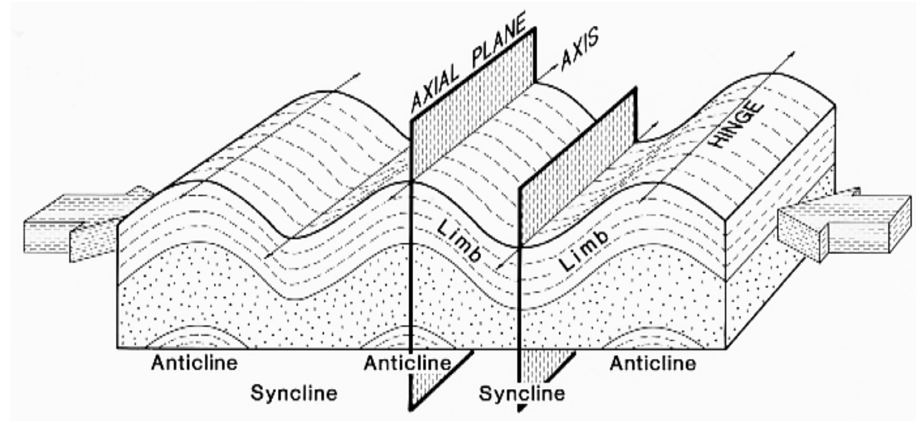


Figure 7. Model of compressive stress, and resulting anticlines and synclines in a fold belt. Image from http://www.maine.gov/doc/nrimc/mgs/explore/bedrock/2-lights/images/figure-5.htm

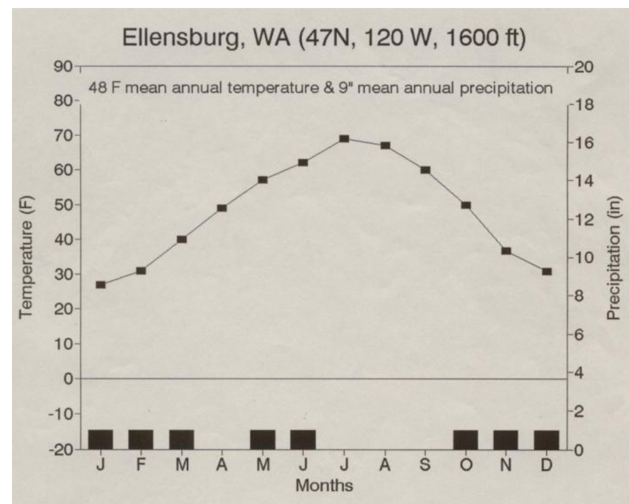


Figure 8. Climograph for Ellensburg, Washington based on 1961-1990 climate normal.

Figure 9. Kittitas Basin from I-82 Overlook. View to northwest.

En route to Stop 2

- We follow I-82 for several miles to Exit 11.
  - En route, we pass through Vanderbilt Gap:
    - Was this gap in Manastash Ridge a former route of the Yakima River?
    - Now it is only occupied by wind and vehicles, and is best thought of as a “wind gap”
    - Note the near vertical interbeds and CRB’s in Vanderbilt Gap indicating the impacts of tectonic activity in the formation of the ridge
  - Note the shrub-steppe vegetation reflecting our semi-arid climate
- At Exit 11, where we will turn around and retrace our steps into the Kittitas Basin
  - Landslides of I-82 (from Washburn, 1989):
    - Heading north on I-82 on the south and north sides of Manastash Ridge, large hummocks below scalloped slopes indicate previous landslides
    - Numerous past slides because of:
      - Dipping beds
      - Silt- or clay-rich interbeds
    - During construction, six landslides occurred in new roadcuts between north base of Manastash Ridge and ridge crest:
      - 3 of 6 occurred in “ancient” landslides
      - All likely triggered by construction
      - All stabilized by lowering angle of roadcuts, removing mass from head of slide, terracing, or adding rock buttressing
- At Exit 3, we take State Route (SR) 821 west where it joins Canyon Road. We bend south to enter the Yakima River Canyon. We will follow SR 821 several miles to the Umtanum Recreation Area.
  - Note the windy road that follows the meanders of the Yakima River

Stop 2—Yakima River Canyon

- The Yakima River:
  - as an “exotic river” originating in the humid Cascade Range and flowing through semiarid Central Washington
  - as a highly managed system with three large reservoirs upstream storing water for diversion to farms
  - as important to salmonids and recreation
- The Yakima River and the Yakima Fold Belt:
  - created the “entrenched meanders” of the Yakima River Canyon—tremendous incision & lateral erosion (Figures 9 and 10)!
  - Yakima River as a “structure-transverse” drainage
  - Structure-transverse drainage typically forms in one of four ways (Baker et al, 1987):
    - *Superposition—river incised through a debris cover exposing underlying structures*
    - *Headward erosion into weaker strata that is exposed by folding and faulting to form a subsequent stream*
    - *Antecedence*—river was here before structures and subsequent incision kept up with uplift
    - Streams travel in structural lows (e.g., synclines) therefore are *consequent streams*
      - According to Schmincke (1964), the Yakima River course follows a cross structural sag at the ends of plunging anticlines
      - Incision began later than 10.5 Ma, but how much later?

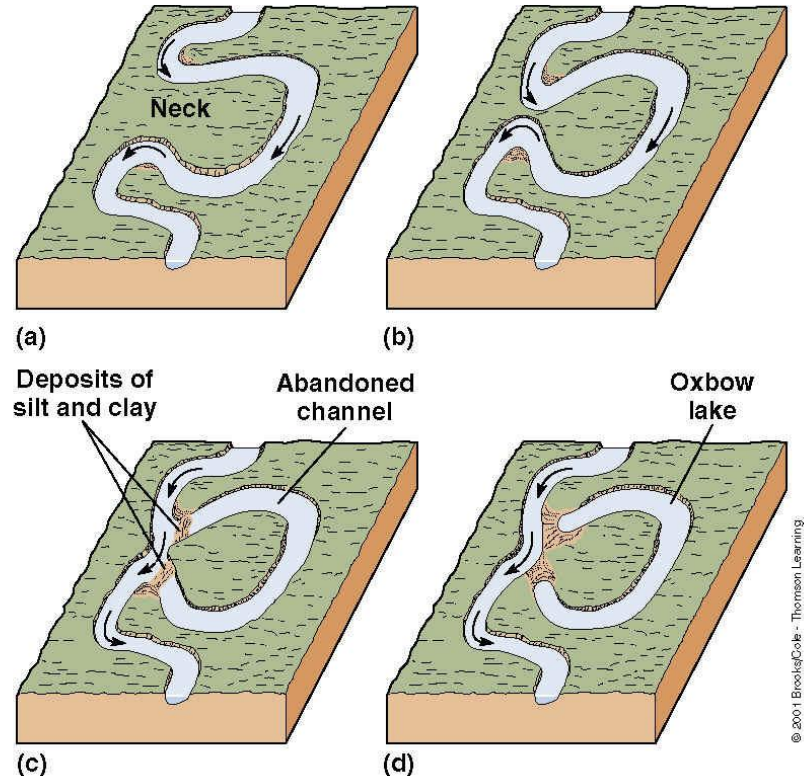


Figure 10. Lateral migration of meanders and resulting cutoffs and oxbows. From http://sinuosity.posterous.com/a-house-built-on-sand-literally .

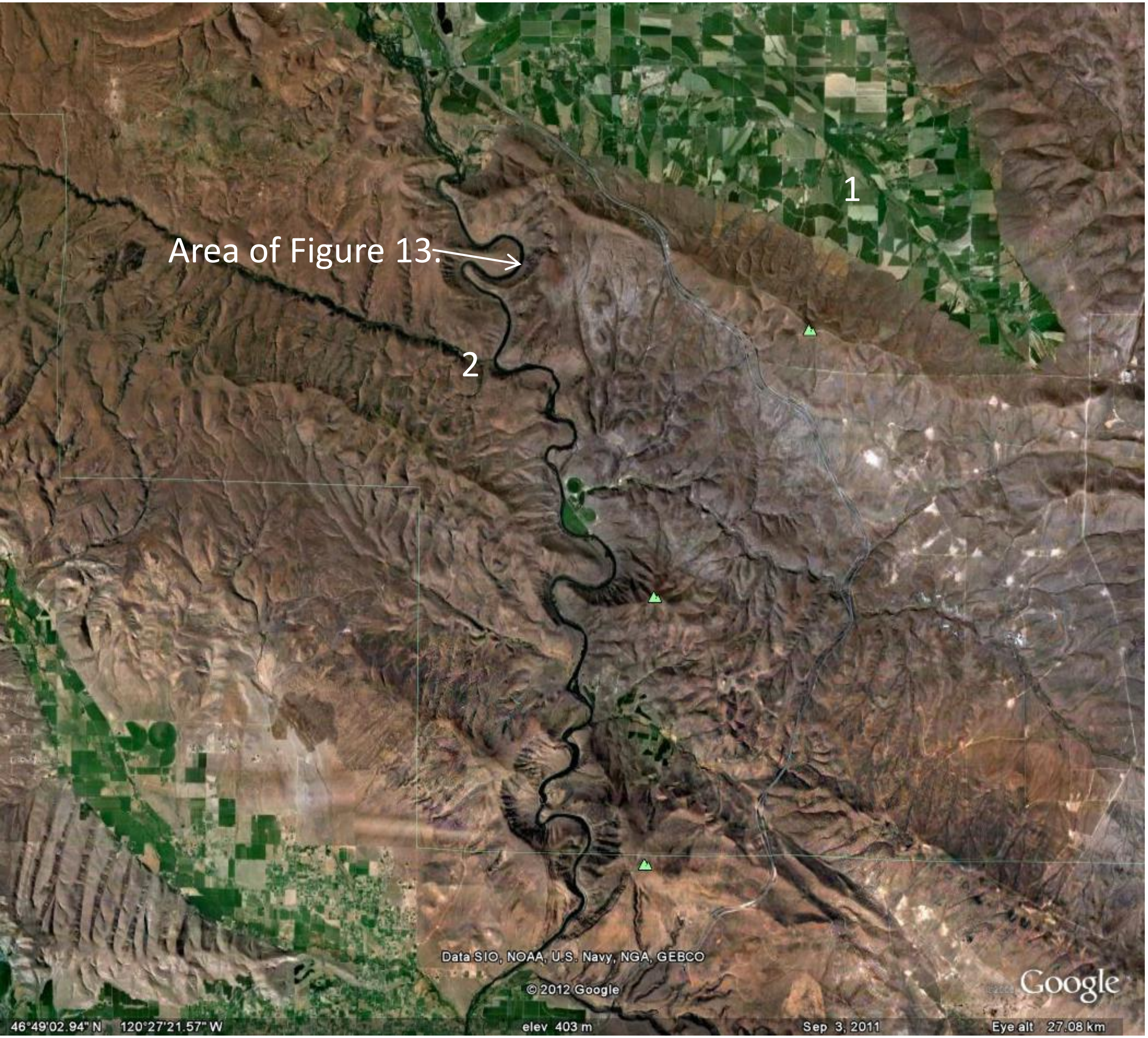


Figure 11. Yakima River Canyon. Location of Stop 2 indicated by "2".

- Yakima River Canyon Mass wasting:
  - Yakima River incision and resulting steep slopes (aided by highway and railroad)
  - steep slopes + precipitation = “mass wasting”(Figure 12)
  - Evidence of prehistoric, historic, and contemporary mass wasting here in variety of types (Figures 13, 14 & 15)
  - Nearly 250 mass wasting features cover 22% of the Yakima River Canyon
  - The most common mass wasting here are shallow, rapid events including debris and earth flows, rockfall, and translational slides
  - Less common but larger in size are deep seated rotational slides and complex slide- flows
  - Most mass wasting (~70%) features are active or recently active

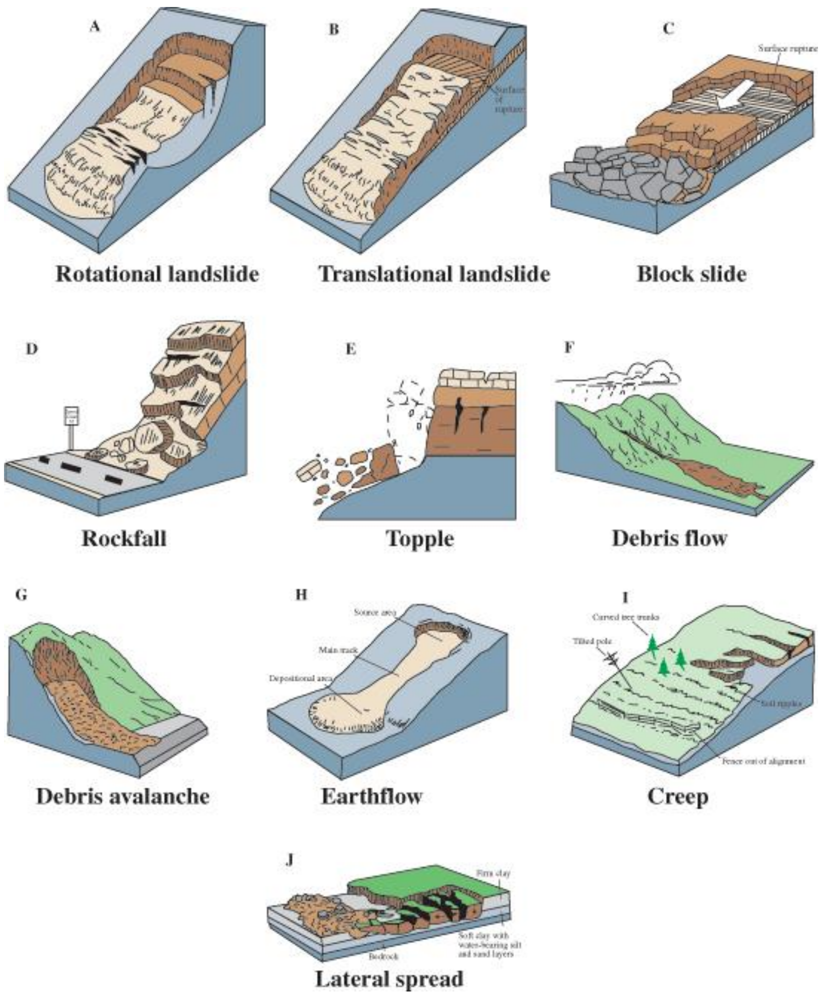


Figure 12. Type of mass wasting. From http://pubs.usgs.gov/fs/2004/3072/fs-2004-3072.html

Figure 13. Debris fans of 3 July 1998 debris flows, Yakima River Canyon. Arrows indicate debris flows that reached State Route 821 or Burlington Northern Santa Fe railroad. Washington Dept. of Transportation photo.

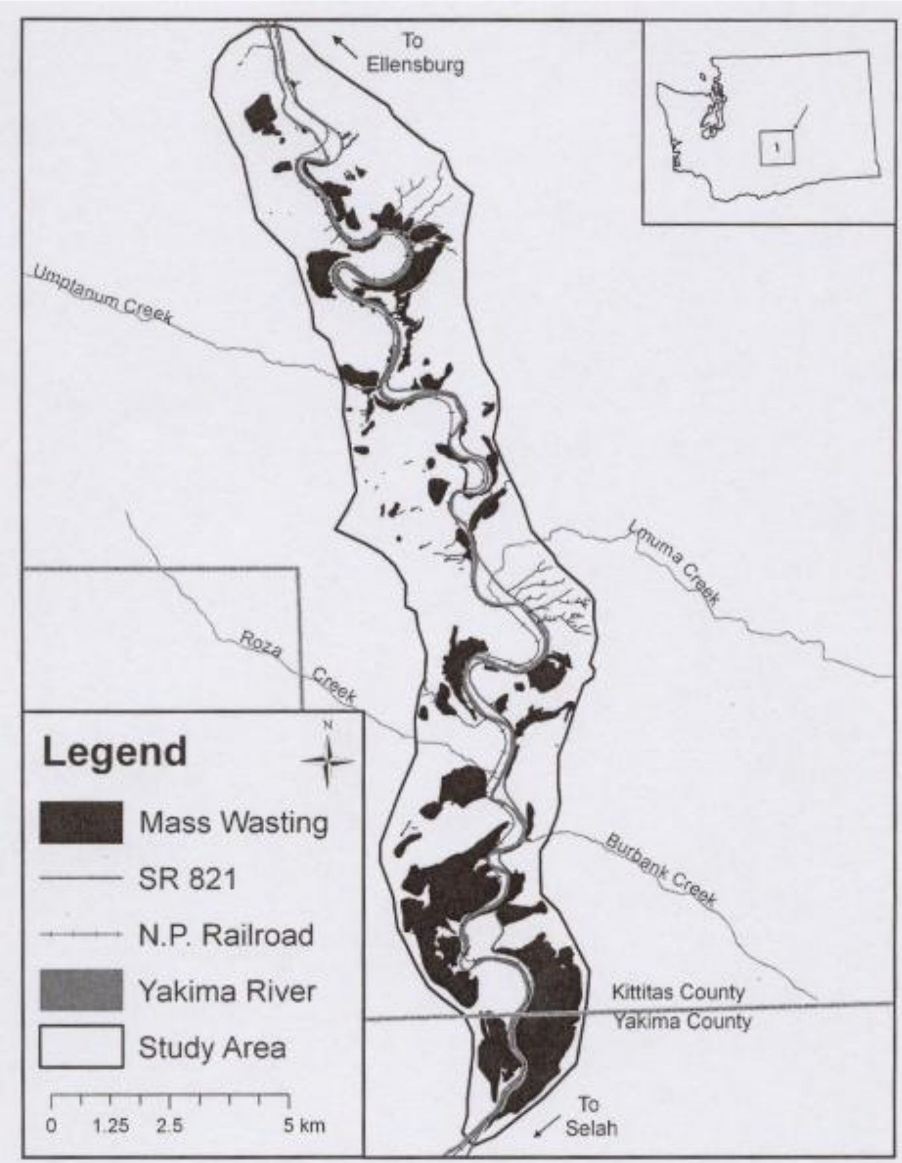


Figure 14. Overall mass wasting in the Yakima River Canyon. From Winter (2012, p. 60).

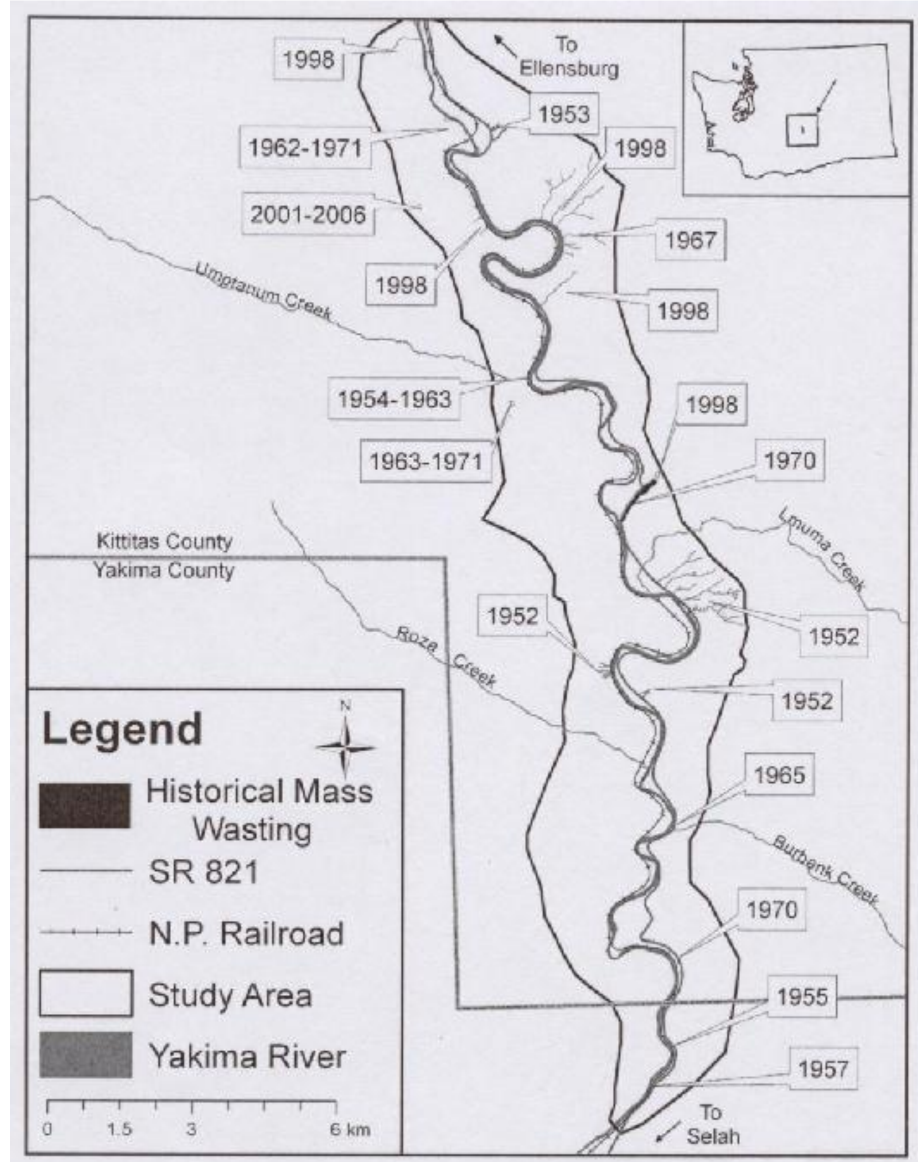


Figure 15. Mass wasting events occurring between 1942 and 2006 in the Yakima River Canyon as identified from airphotos and newspaper accounts. From Winter (2012, p. 74).

En route to Stop 3

- As we drive north on SR 821 and again note the small terraces on the steep hillsides. These are "terracettes".
  - Terracettes result from:
    - Creep
    - Animals traversing hillsides
- We follow SR 821 and Canyon Road into Ellensburg where we turn left at the second light north of I-90 onto Umtanum Road. We follow Umtanum Road south to climb again onto Manastash Ridge. En route we ascend the steep alluvial fan of Shushuskin Canyon.
  - *Alluvial fans* are common features in the area, forming at the mouths of canyons emptying into Kittitas Basin. They often have their origins in intense runoff events, ranging in size from tens of feet in diameter (think recent Yakima River Canyon debris flows) to miles in diameter (the Manastash Fan which we cross between the Yakima River and Manastash Ridge on this leg of the trip.
- Once atop Manastash Ridge, Umtanum Road turns into gravel and we follow this for just over three miles to Stop 3. Stop 3 is located at the top of the hill before the road descends to Umtanum Creek.
- Note Umtanum Ridge to our south. This is another anticline in the Yakima Fold Belt.

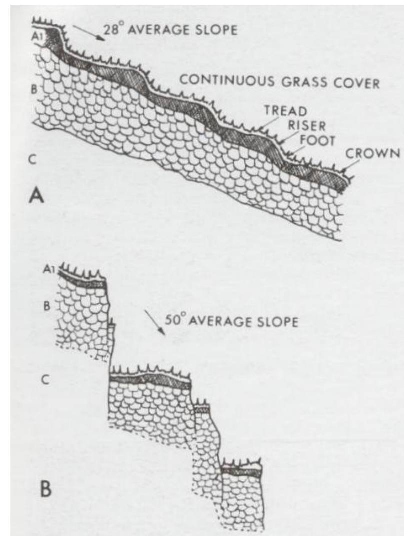


Figure 16. Cross section of terracettes. From p. 258 in Selby, M.J. 1993. *Hillslope Materials and Processes* (2nd edition). Oxford, Oxford University Press.

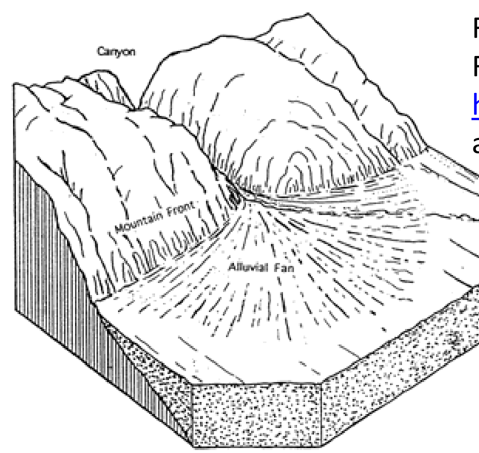


Figure 17. Alluvial fan model. From http://www.uni.edu/~andersow/ alluvialdeposits.html

Stop 3—Manastash Ridge II

Figure 18. Overhead view of "Manastash Mound" patterned ground along Umtanum Road, southwest of Ellensburg. Stop 3 location indicated with "3".

- We are standing within an area curious soil mounds known locally as "Manastash Mounds"
- One could consider these as a form of "patterned ground", a ubiquitous phenomena in western landscapes
- "Patterned ground" as:
  - circles
  - polygons
  - nets
  - stripes
  - Steps
- Possible origins:
  - Wind deposition (e.g., Freeman, 1926)
  - Wind erosion (e.g., Olmsted, 1963)
  - Water deposition
  - Water erosion (e.g., Waters & Flagler, 1929)
  - Columnar jointing & erosion (Knechtel, 1952)
  - Thermal cracking & erosion (Kaatz, 1959)
  - Burrowing rodents (e.g, Cox & Allen, 1987)
  - Seismic activity (e.g, Berg, 1990)
  - "Equifinality" & multiple origins?
- Possible ages:
  - Relicts from late Pleistocene (Kaatz, 1959; Fryxell, 1964)
  - Relicts from Holocene (Bandow, 2001)
    - Manastash Ridge—base of soil mound 7,800 +/- 700 years
    - Thorp Prairie—base of soil mound 5,600 +/- 500 years
  - Forming at present (Don and Diana Johnson, personal communication)

Figure 19. Patterned ground on Manastash Ridge.

Figure 20. Burrowing rodent hypothesis for patterned ground. From Porter (1965, p. 64).

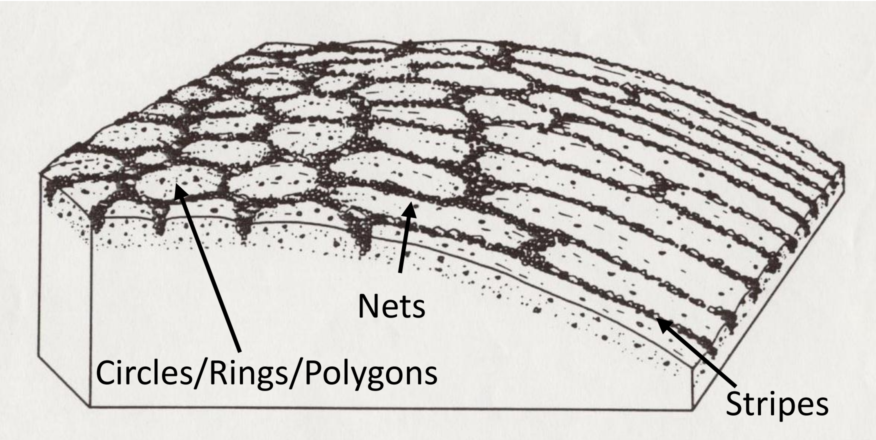


Figure 21. Oblique view of circles/rings/polygons, nets, and strips. From Sharpe (1938, p. ??).

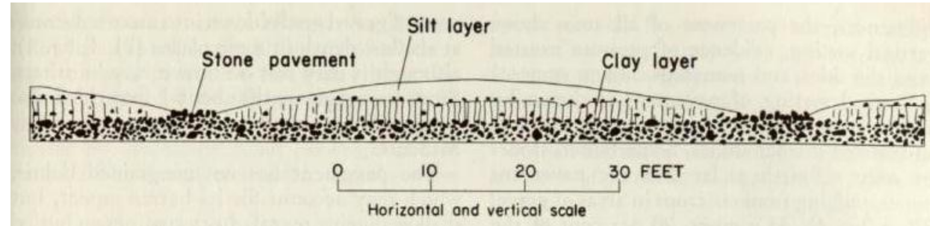
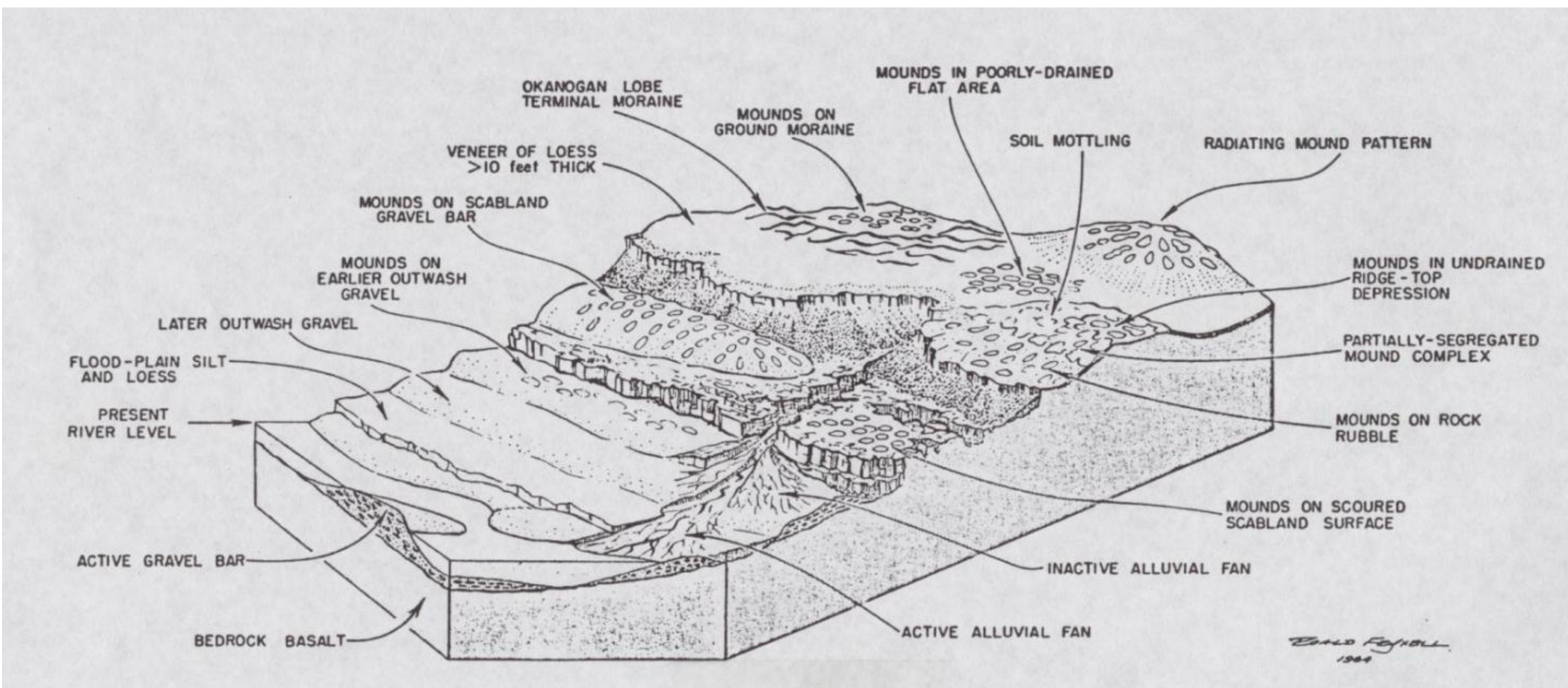


Figure 22. Cross section of circles and polygons. From Malde (1964, p. 197).

Figure 23. Spatial patterns of patterned ground on the Columbia Plateau. From Fryxell (1964).



En route to Stop 4 (& Lunch)

- After descending Umtanum Road back into the Kittitas Basin, we turn left onto Brown Road just before descending to the Yakima River. We will follow Brown Road along the distal edge of the Manastash Fan to Hanson Road.
- At Hanson Road, we will turn right, and almost immediately left onto South Thorp Highway. We will follow South Thorp Highway along the distal edge of the Manastash and Robinson fans nearly to I-90.
- En route to Cove Road and I-90, we parallel a scarp above the road created by Yakima River erosion into the Manastash and Robinson fans. We also parallel a riser below the road of an outwash "terrace" created by the Yakima River
  - *Terraces* are bench-like features that parallel rivers and valley walls.
  - Consist of treads & risers (like terracettes). Risers slope gently downvalley and represent former floodplains.
  - Result from:
    - Aggradation & subsequent incision
  - What causes aggradation?
    - Increased sediment load in rivers
    - Decreased discharge
    - Rise in base level (and resulting decrease in channel slope)
  - Common to have alternating periods of aggradation & incision over time tied to climate, tectonic, and land use changes; therefore, flights of terraces often result
- Across I-90 and in Thorp, we lie on the floodplain of the braided Yakima River

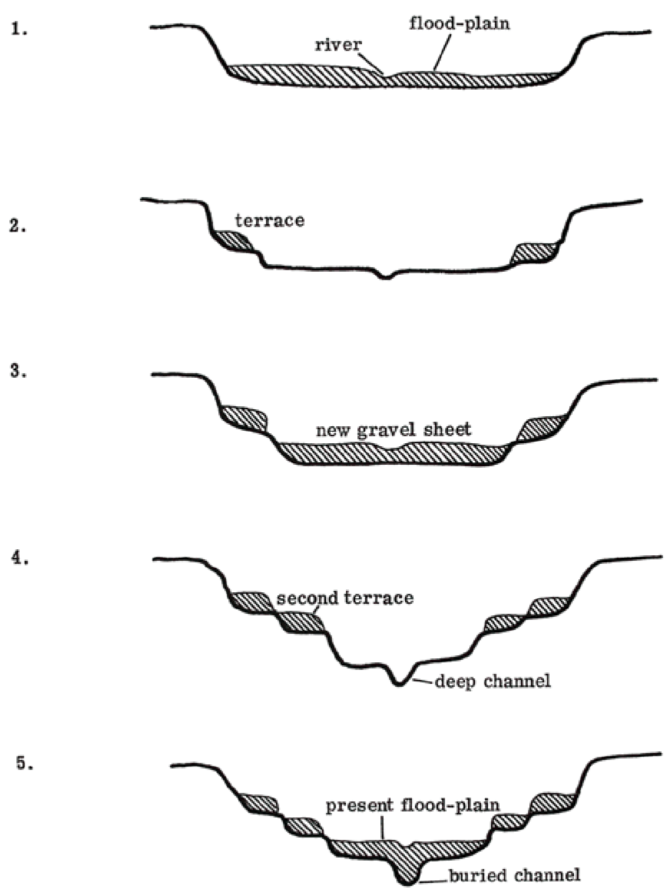


Figure 24. Model of river terrace development. From http://www.pengellytrust.org/museum/ice_age.htm

Figure 25. Overhead view of alluvial fans, scarps, terraces, and floodplain in the Ellensburg area.

- Stop 4--Thorp Grist Mill
  - Lunch!

- En route to Stop 5
  - We take South Thorp Highway north and west to SR 10. Stop 5 lies about one mile west of this junction on SR 10.

Stop 5—Upper Yakima River Canyon

- Cascade glaciers & glaciation
  - At present:
    - 14 small glaciers within upper Yakima River drainage with average elevation of 6100 feet (Porter, 1976)
  - In Pleistocene:
    - likely 100’s of cirque glaciers merged to form large valley glaciers
    - at maximum extent, >600,000 yr BP, Upper Yakima Valley Glacier was >40 km long, >400 m thick, and terminated at Thorp Prairie and Swauk Prairie (Swanson and Porter, 1997)
    - at about same time as more recent Missoula Floods, glaciers filled valleys now occupied by Lake Cle Elum, Lake Kachess, and Lake Keechulus. However, needed successively higher elevations eastward to support glaciers and those high areas are lacking; therefore, far less glaciation in Teanaway River drainage and none in Swauk Creek drainage.
    - By latest Pleistocene, glaciers had retreated to higher elevations including Snoqualmie Pass area. I-90 passes through the moraine of the late Pleistocene Hyak end moraine.
- Outwash terraces
  - Prominent terraces in foreground traceable upvalley to moraines indicate they are same ages
  - Terraces originated from heavy sediment deposition during glacial periods and subsequent incision of thick valley fill during interglacials when sediment was more sparse.

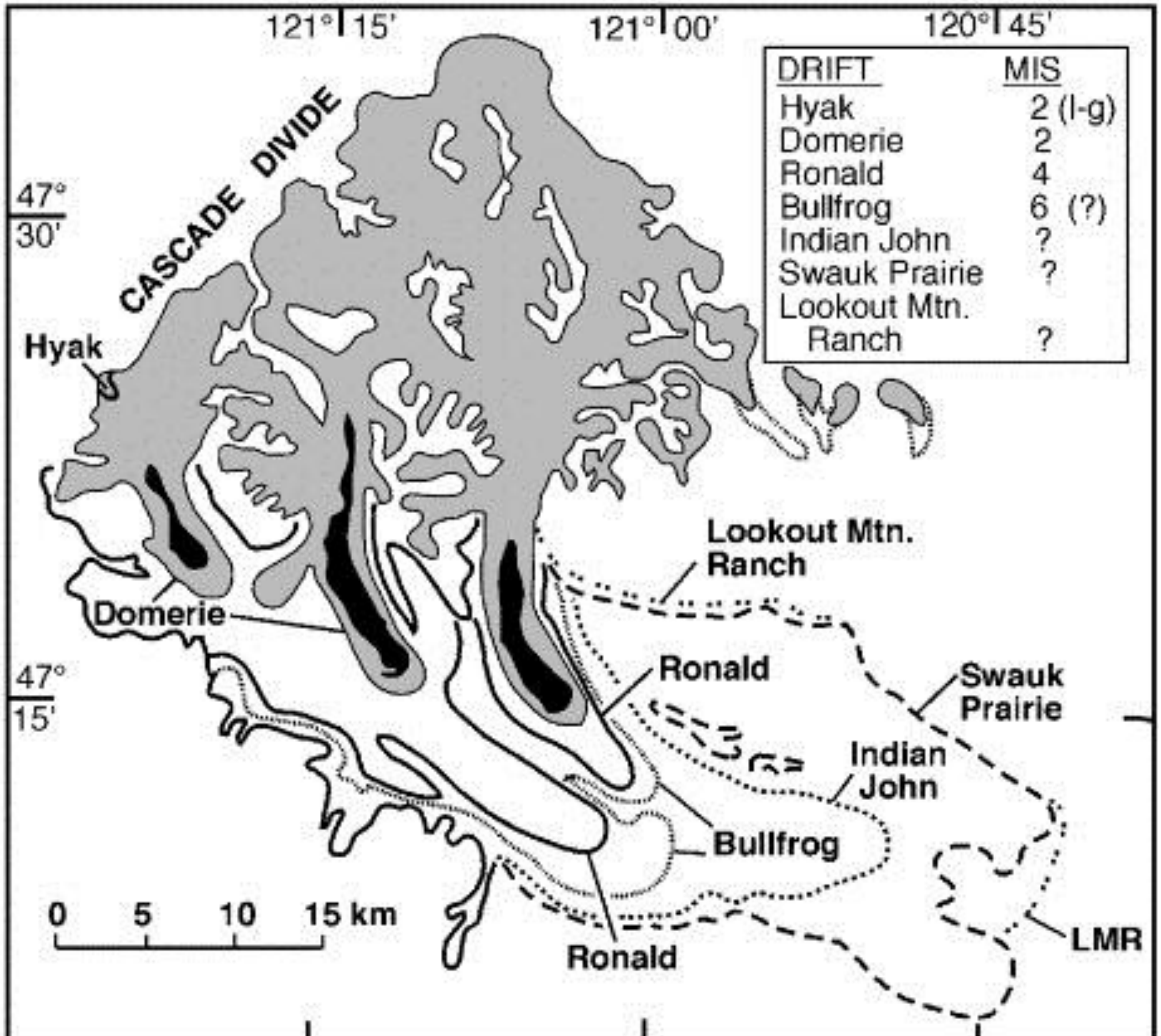
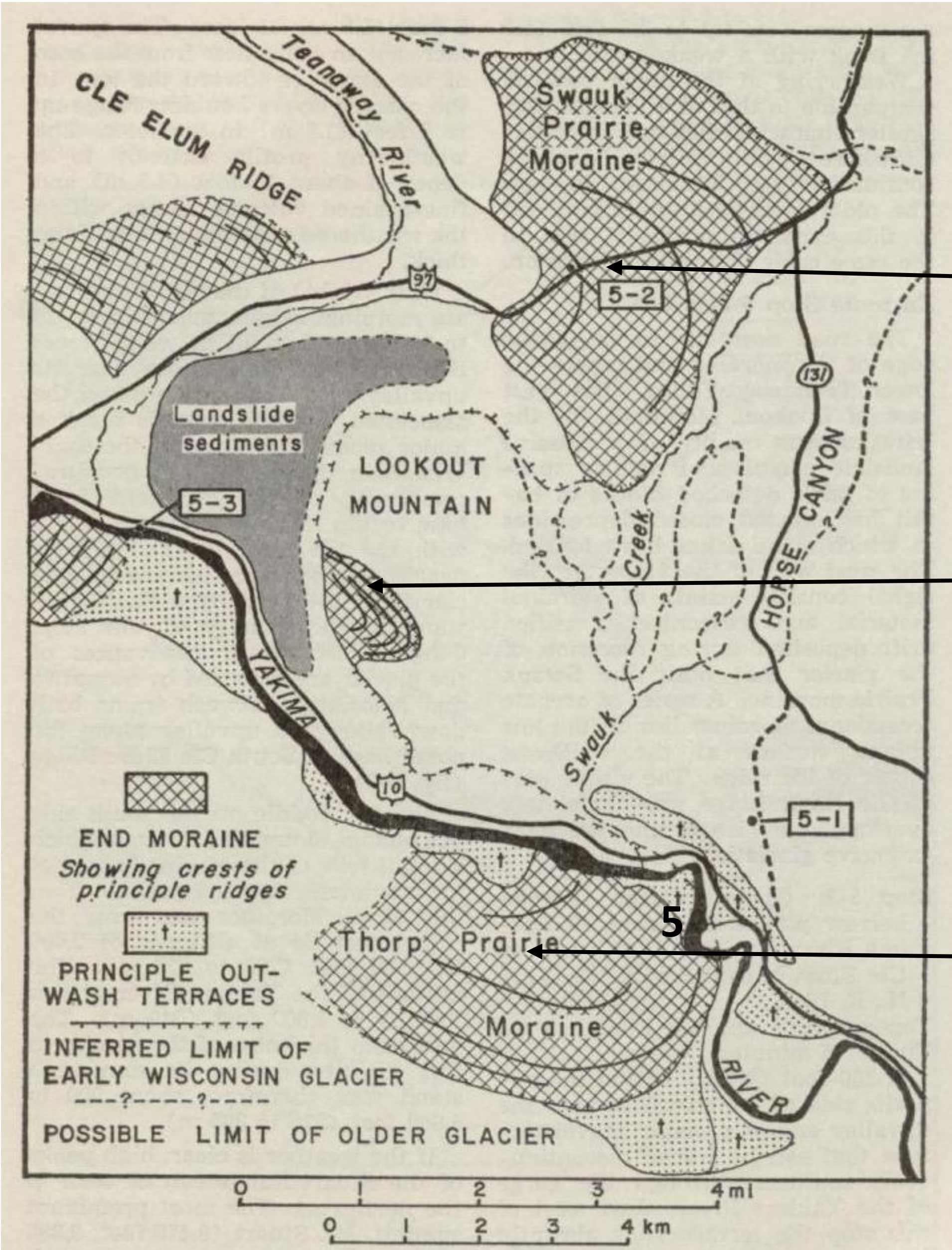


Figure 26. Extent and inferred ages of glaciation in Upper Yakima River drainage. From Kaufman, Porter, and Gillespie (2004, p. 82)

Figure 27. Moraines and outwash terraces In vicinity of Stop 5. From Porter (1965, p. 37). Location of Stop 5 shown with 5.



~600,000 yr BP
(Swanson & Porter, 1997)

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(Swanson & Porter, 1997; Kaufman, Porter and Gillespie, 2004)

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(Swanson & Porter, 1997)

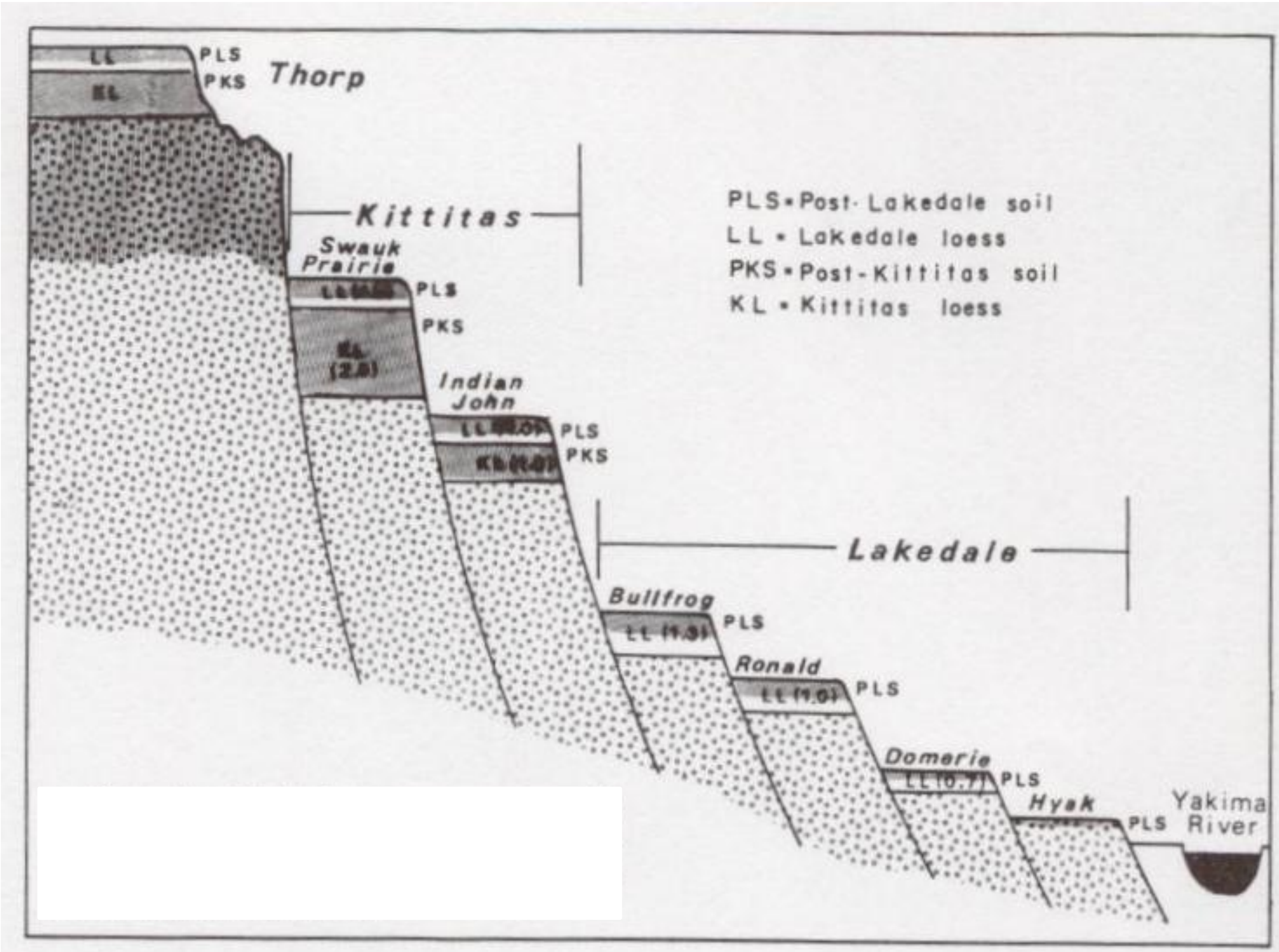


Figure 28. Principal terraces along upper Yakima River, showing stratigraphy of loess and soils on outwash gravels. Figure not to scale. Loess thickness in meters. From Porter (1976, p. 64).

En route to Stop 6

- Our route: We drive SR 10 east from Stop 5. Once in Ellensburg, we follow University Way east to Vantage Highway. State Route 10, as well as University Way and Vantage Highway are all part of old US 10 ,a primary highway that once ran from Seattle to Detroit, Michigan. This route was replaced by I-90 in the late 1960's.
- High surfaces to north of bus: Note the high, burned surfaces north State Route 10. These are composed of Ellensburg Formation unconformably overlain by the Thorp Gravels. Also, note the "hummocky" topography at the base of steep slopes on these high surfaces. These represent old landslides.
- Thorp Gravels: The Thorp Gravels were originally thought to be part of the Ellensburg Formation (Smith, 1904) and later thought to be glacial outwash (Porter, 1976). However, Waitt (1979) argued that the Thorp Gravels were non-glacial, fluvial deposits based on:
  - very different rock types included in the Lookout Mountain and Swauk Prairie drifts compared to the Thorp Gravels
  - Thorp "terrace" heights are very different than those of the Swauk Prairie
  - highly-cemented nature of the Thorp Gravels compared to Lookout Mountain drift
  - problem of Thorp Gravel "till" post-dating Thorp Gravel "outwash" in vicinity of Horse Canyon
- The Thorp Gravels likely accumulated in the Kittitas Basin syncline because uplift of Manastash Ridge lowered the grade of the Yakima River and tributaries to the Yakima River causing aggradation. Age is roughly 3.0-4.5 Ma (Waitt, 1979).
- Thorp Gravel aggradation in the basin likely occurred in the form of large alluvial fans. Over time, these fans became stable (slowing of tectonic activity?) developing thick calcium- and clay-rich B horizons in their soils. Subsequent erosion by side streams from the Wenatchee Range has dissected the once continuous? Thorp Gravel deposits to leave erosional remnants (Figure28). The surfaces of the Thorp Gravels has also been stripped down to the cemented and clay-rich horizons in many places leaving once-depositional surfaces now primarily erosional. These Thorp Gravels remnants could now be called "pediments" because of their erosional nature.
- Whiskey Dick Anticline and Wind and Solar Power: Wildhorse Wind Farm takes advantage of the relatively high elevation of the summit of the Whickey Dick Anticline to generate sufficient electricity for 80,000 homes. This was the first of three large wind power generating facilities to come into the Kittitas Basin Area.
- Upper limits of Missoula Floods: As we near the western edge of Ginkgo Petrified Forest State Park, we also pass across the upper limit of Missoula Flood slackwaters at 1,263 feet elevation in Schnebly Coulee (Karlson, 2006).

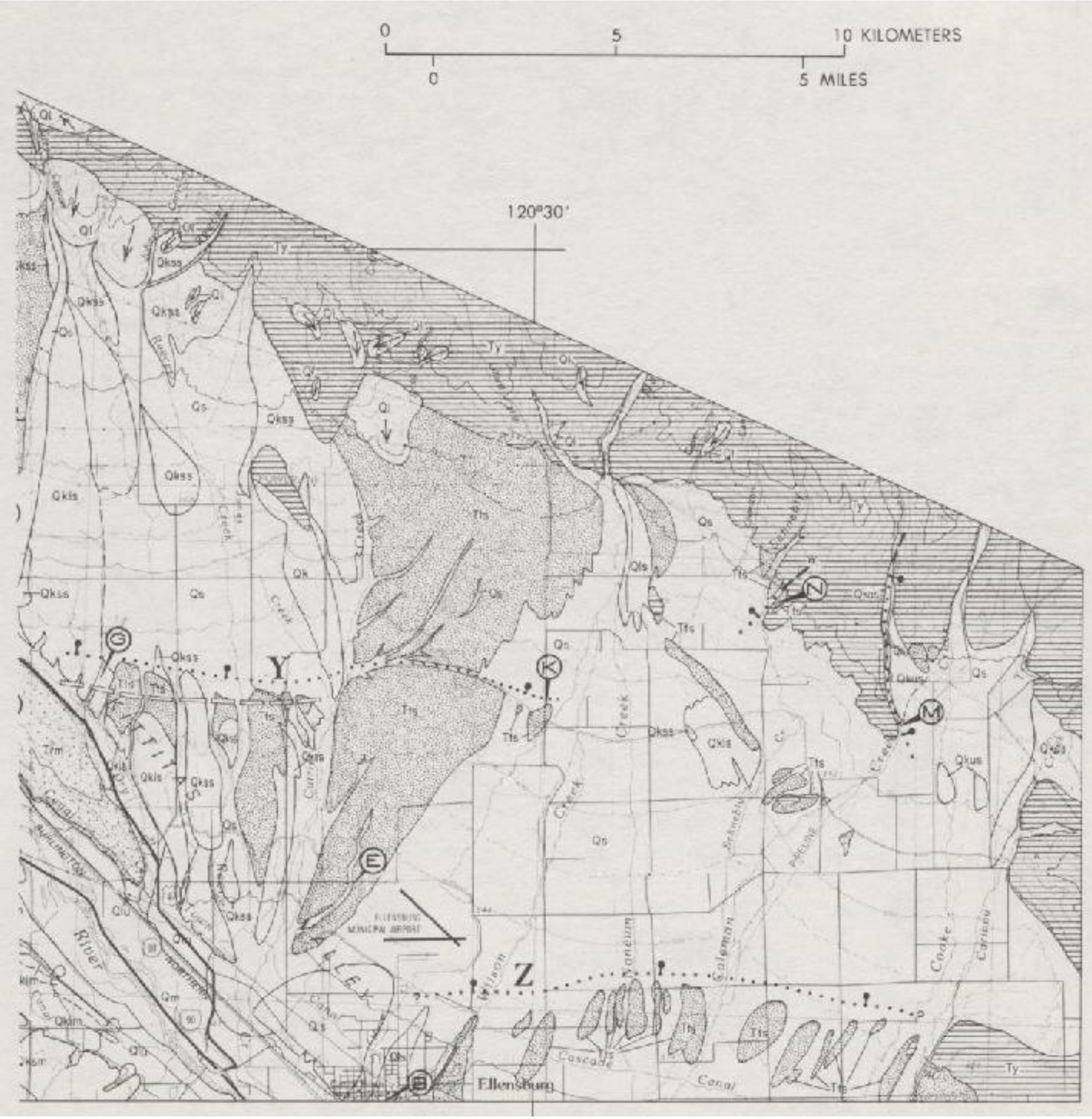


Figure 29. Geologic map of the north central part of Kittitas Basin. Note Thorp Gravel (Tts and Ttm) remnants separated by more recent alluvial fans. From Waitt (1979, p. 5).

Figure 30. Wind resource potential in Washington state. From http://www.ecy.wa.gov/climatechange/greenenergy_maps.htm .

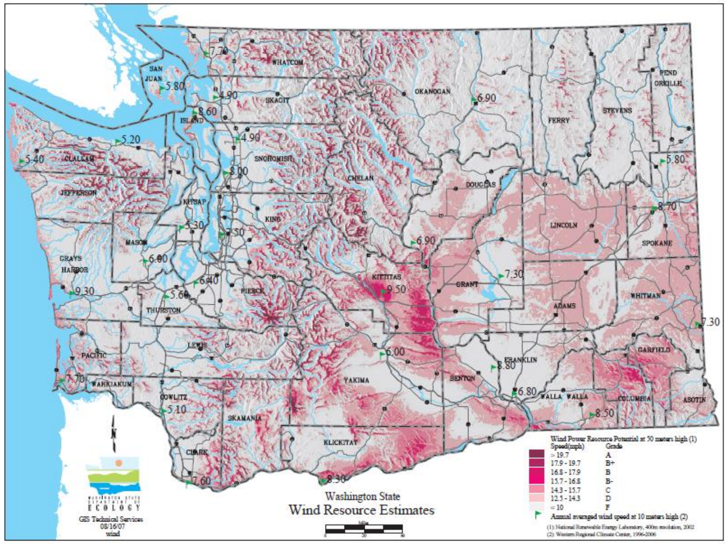
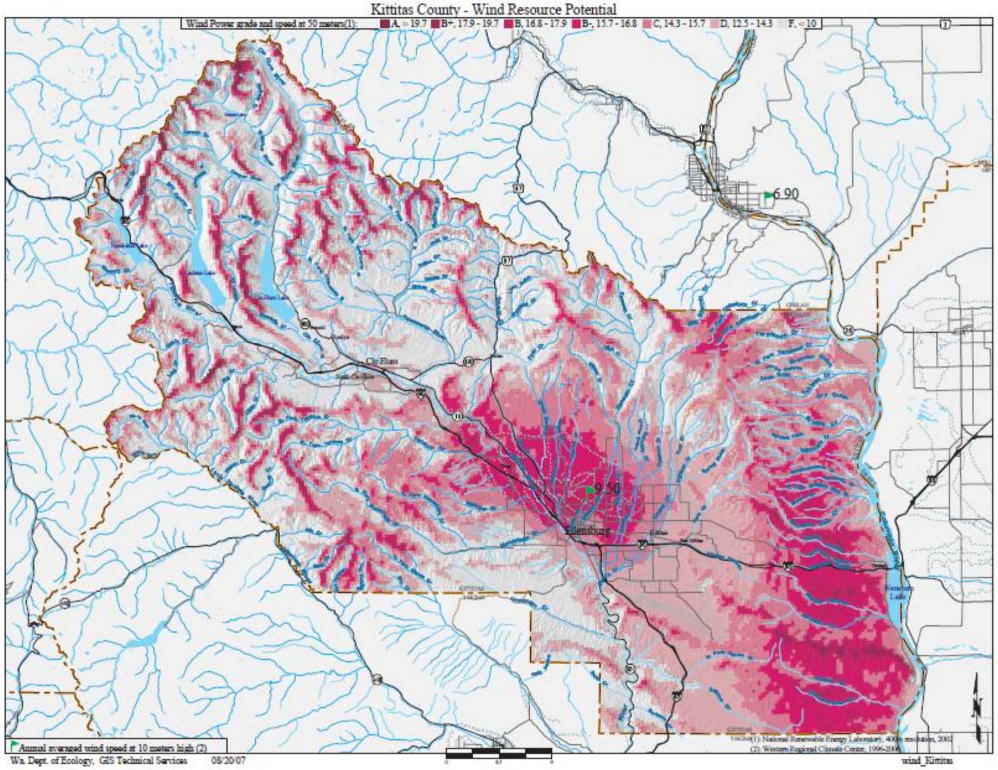


Figure 31. Wind resource potential in Kittitas County, Washington state. Note the influence of topography on wind resources. From ttp://www.ecy.wa.gov/ climatechange/greenenergy_maps.htm.



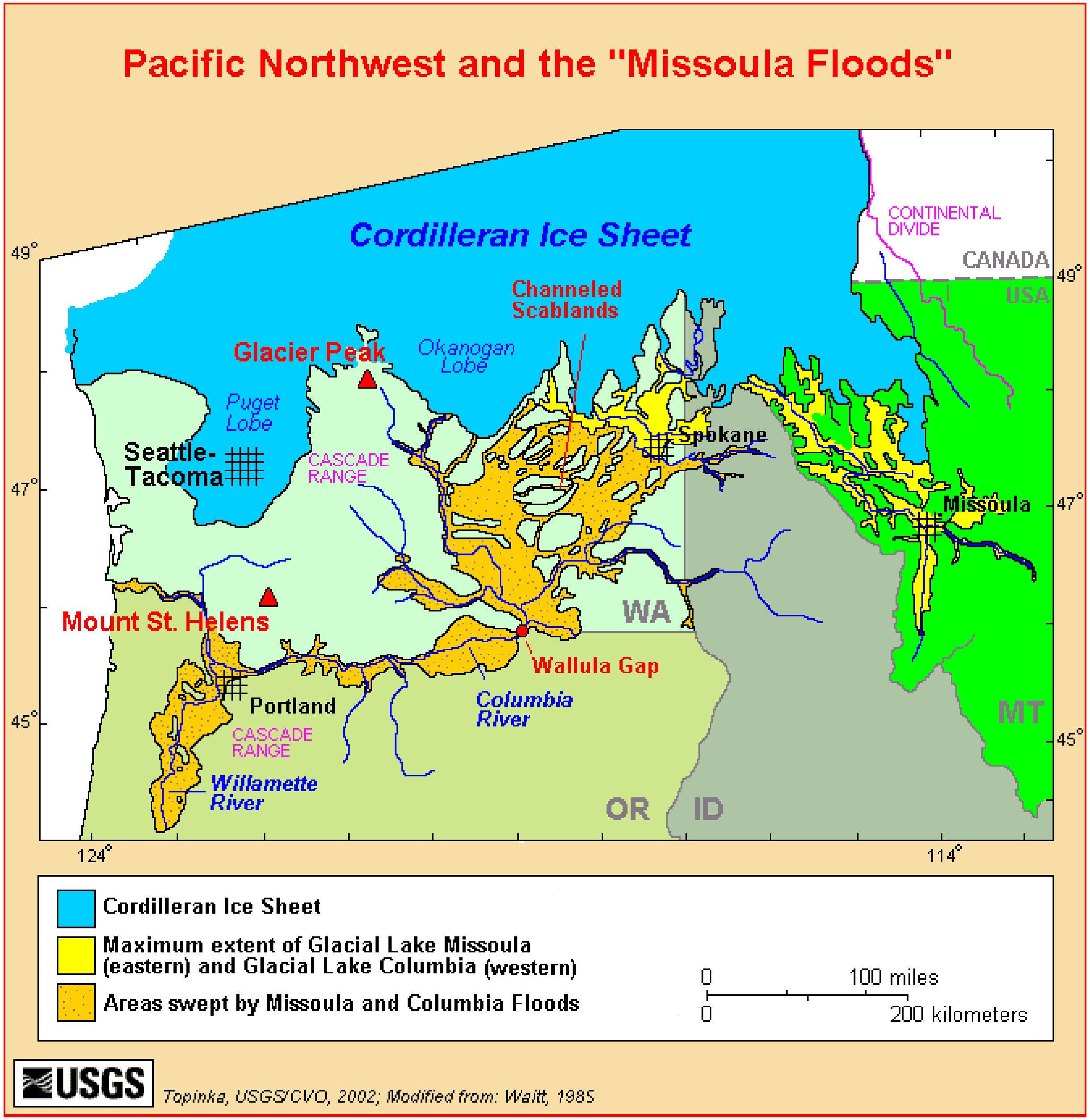


Figure 32. Missoula Flood and Cordilleran Icesheet extents in the Pacific Northwest.

En route to Stop 5 (entering Ginkgo State Park)

- At the western boundary of Ginkgo Petrified Forest State Park, we enter western margin of Pleistocene Lake Lewis
- “Iceberg Pass” is located south of highway from Petrified Forest interpretive trails.

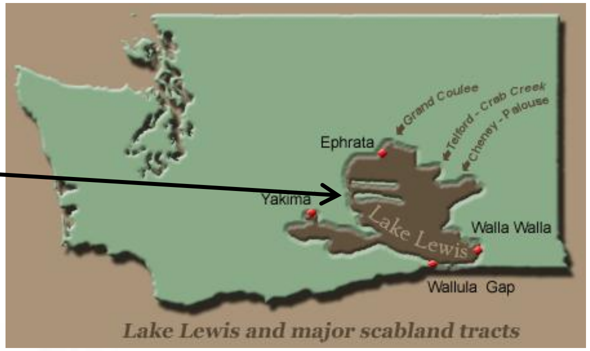


Figure 33. Pleistocene Lake Lewis. From hugefloods.com.

Figure 34. The Ginkgo Petrified Forest interpretive trails traverse the western margin of the Lake Lewis Basin. The highest ice-rafted erratic deposits recorded in this area are located just north of the trail system. Image courtesy of the University of Washington, Lindsley Collection, September 5, 1938.

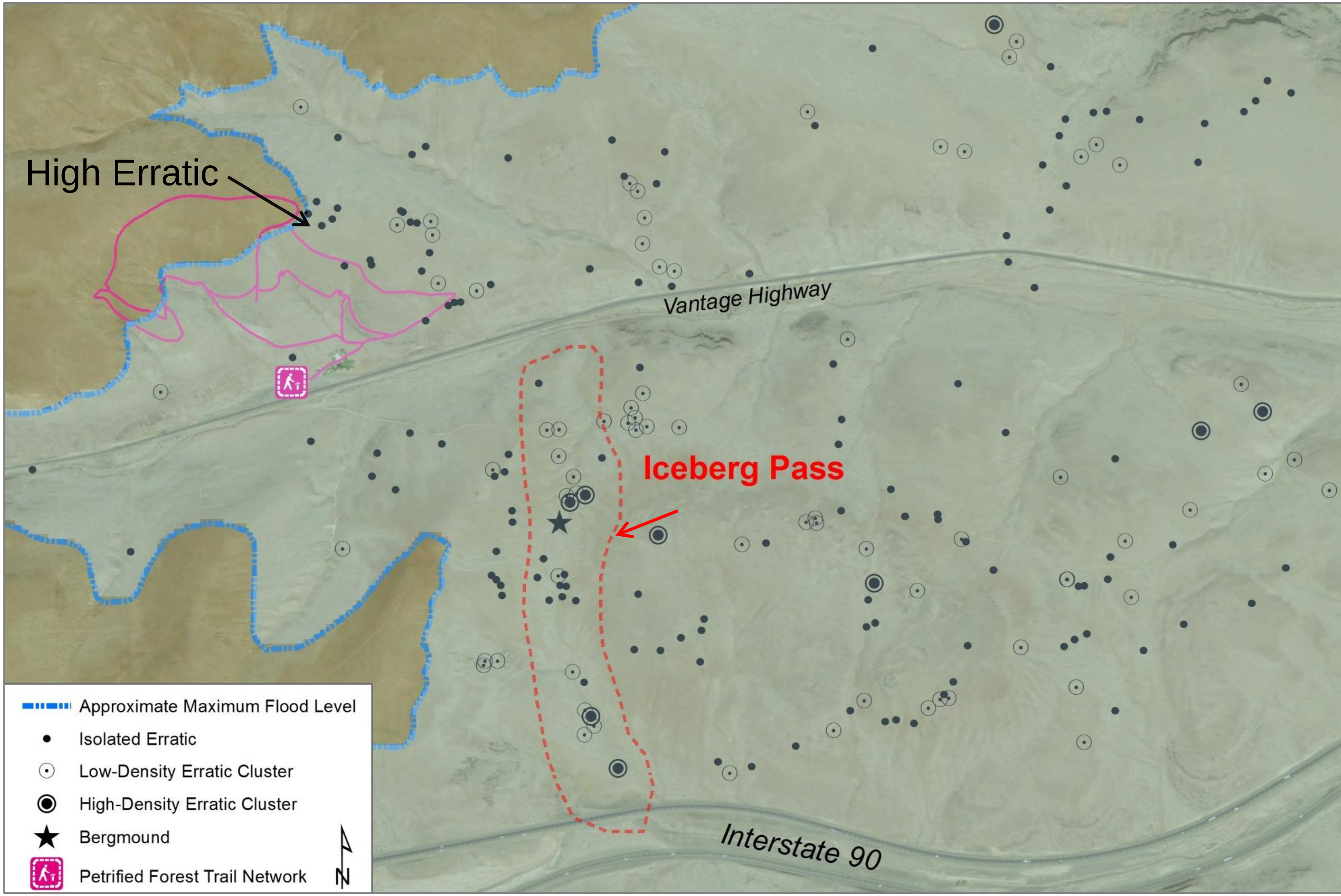


Figure 35. Iceberg Pass is an informal name associated with the concentration of high-density, ice-rafted erratic deposits found between Schnebly Coulee (route of Vantage Highway) and Ryegrass Coulee (route of Interstate 90) within Ginkgo Petrified Forest State Park. Several icebergs grounded in this low-angle divide during Pleistocene flood events.

Stop 5 – Ginkgo Petrified Forest State Park

- Hydraulic damming and Pleistocene flood features
- Iceberg graveyard of the western Channeled Scabland

Figure 36. The original town of Vantage was located below the park interpretive center prior to inundation behind Wanapum Dam. The modern reservoir pool is approximately 90 feet deep. During the largest Pleistocene flood events, floodwaters reached depths of at least 780 feet . Image courtesy of Grand County PUD, Lewis Collection, 1958.

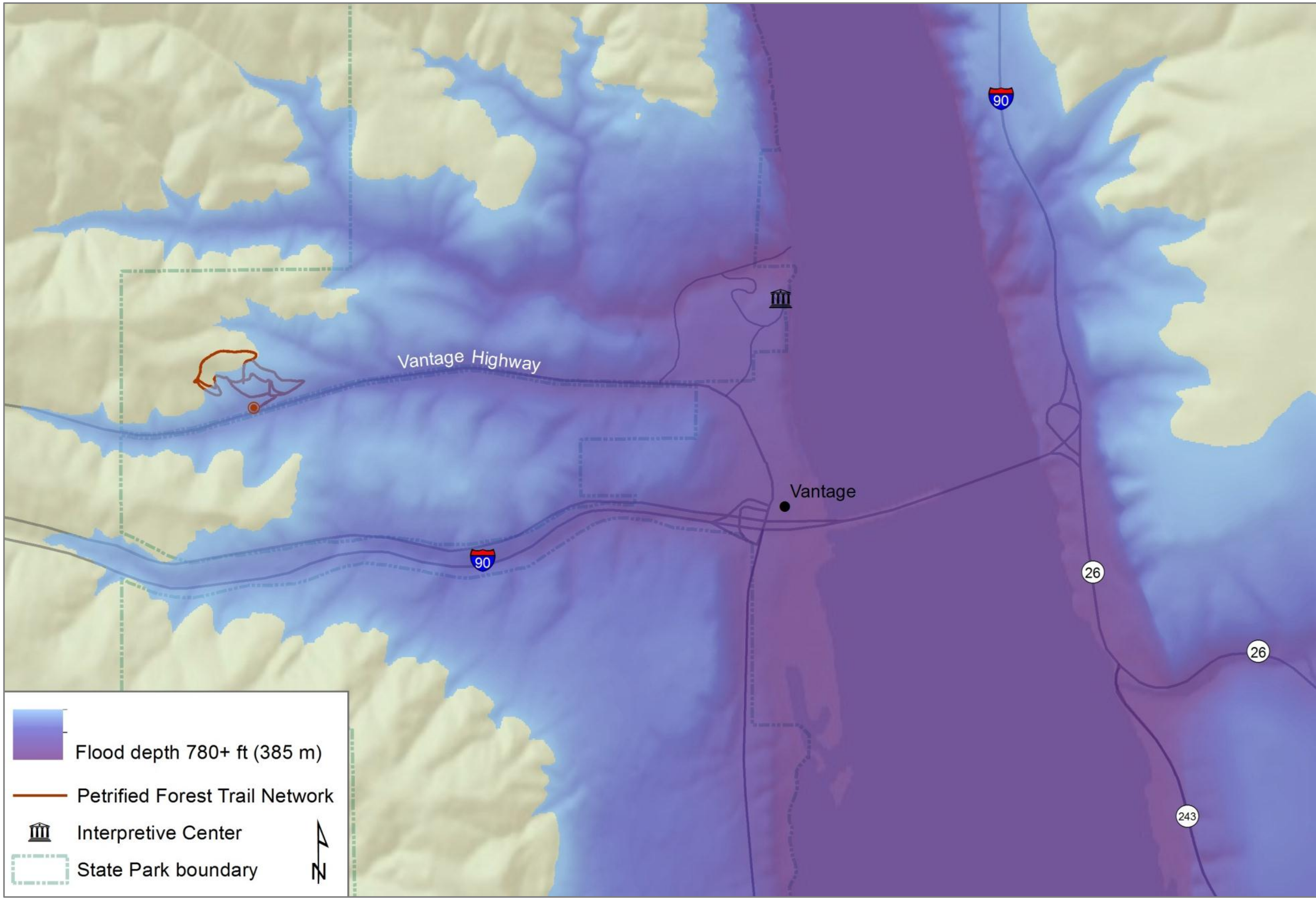


Figure 37. Map illustrating estimated maximum Pleistocene flood inundation levels in Ginkgo Petrified Forest State Park. The 780+ ft (239 m) maximum depth is based on an ice-rafted erratic surveyed at 1,263 ft (385 m).

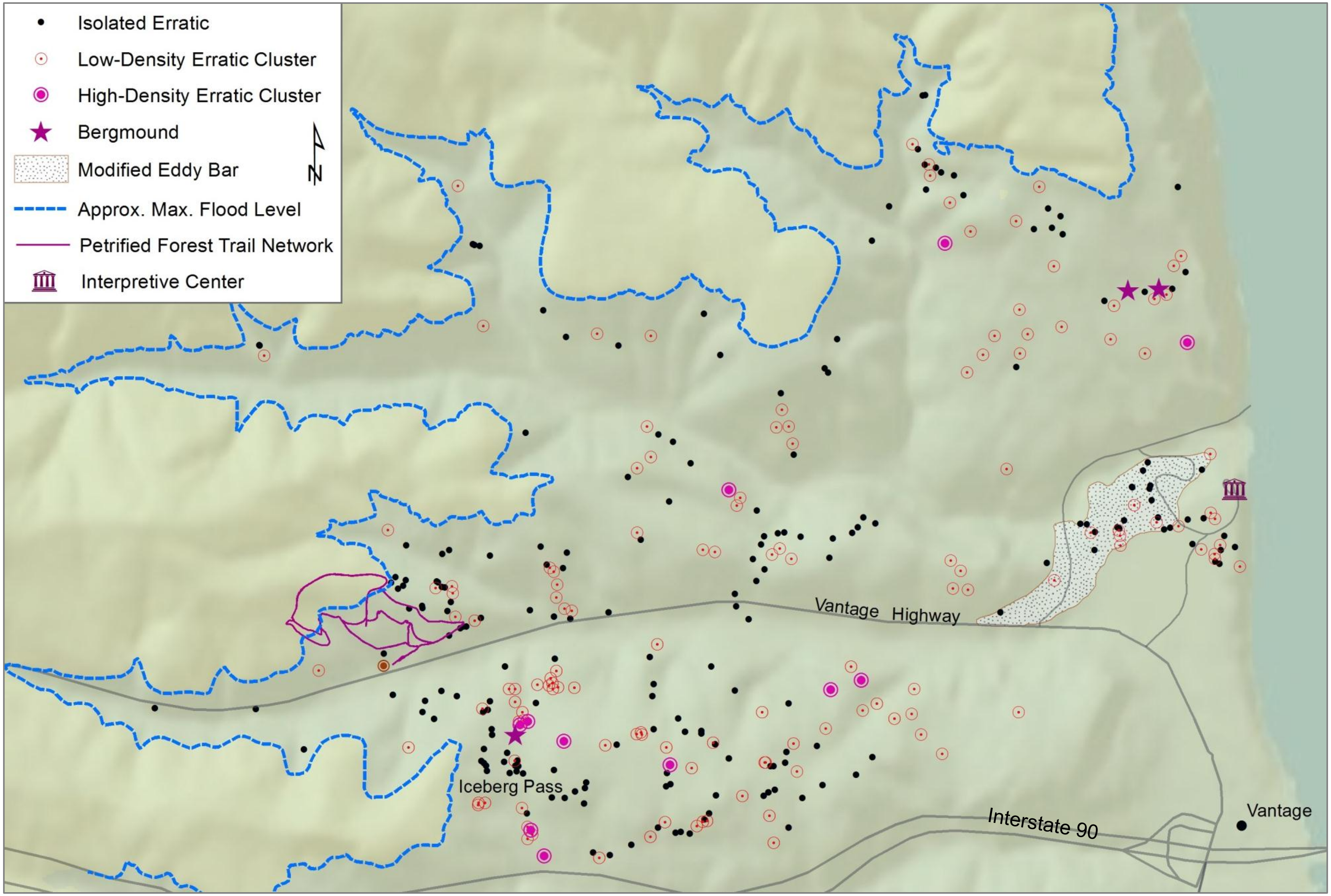
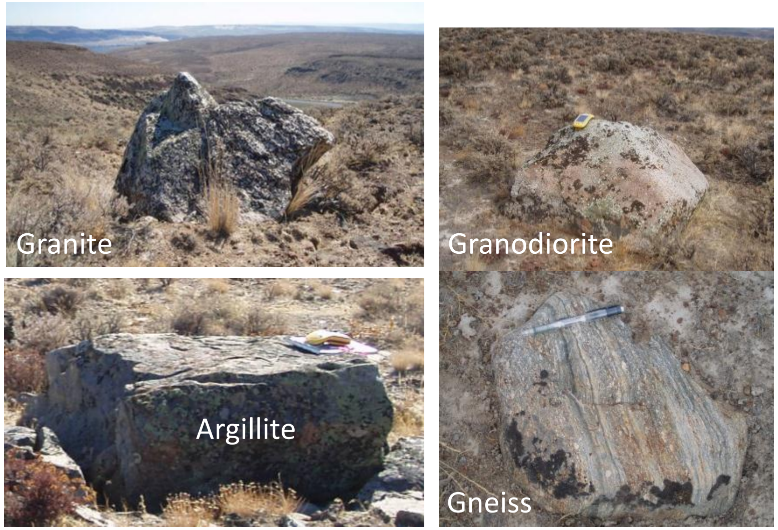


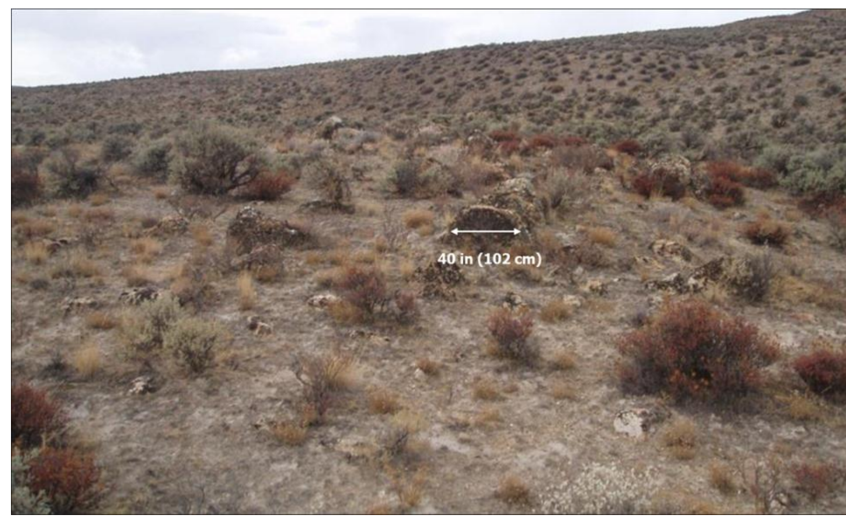
Figure 38. Distribution of ice-rafted erratic deposits and a modified eddy bar in northern section of Ginkgo Petrified Forest State Park. High-density erratic cluster and bergmound deposits likely resulted from deposition of larger icebergs.



Isolated Erratic

Low-Density Erratic Cluster

High-Density Erratic Cluster



Bergmound

Figure 39. Examples of Ice-Rafted Erratic Deposit Types In Ginkgo Petrified Forest State Park.

En route to Stop 6

- Missoula Floods:
  - During the largest flood events, floodwaters were well over 650 feet above the modern Vantage Bridge
  - Wind, sand & dunes: As we cross the Columbia River on I-90, note evidence of wind. Of particular interest are the abundance of sand dunes east of the river
  - This is a windy place and the winds here have a strong westerly component
  - The Columbia River floodplain was the sand supply for the dunes east of the Columbia River. This supply has been cut off by the dams and associated reservoirs leadings to the slow demise of the dunes
- Rockfall:
  - Note the ample rockfall "talus" that serves as an apron on many of the basalt cliffs.
  - Oversteepened slopes in highly jointed basalts in a ~continental climate are ideal talus generators
- Flood-induced? Landslides:
  - As we travel north on I-90 on the prominent bench (i.e., erosional terrace) above the Columbia River, note the hummocky terrain at the base of the steep slopes at approximately 3:00. These deposits represent landslides that occurred due to failure of a weak interbed and/or undercutting by Missoula Floods
- Take Exit 143 and follow Silica Road under the freeway and to the north for ~1 mile. There, take a left onto Vantage Road SW. This will take us into Frenchman Coulee.

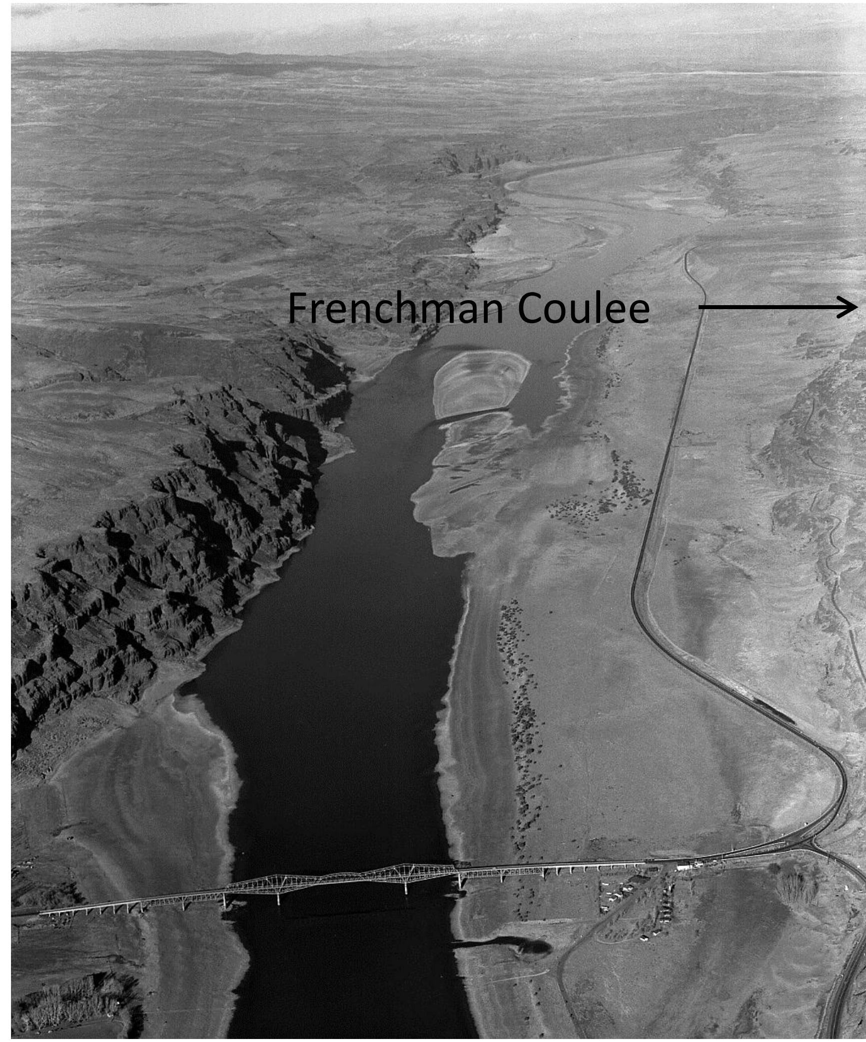


Figure 40. Looking north along the Columbia River. Old Vantage Bridge in the foreground. Image courtesy of Grant County PUD, Lewis Collection, Old Vantage bridge – Vantage to Rock Island right back, December 4, 1958.

Stop 6—Frenchman Coulee

- "Coulees" (a Washington state definition):
  - Steep sided, ~flat-floored, ~straight valleys eroded into bedrock by floodwaters
- Quincy Basin:
  - As a structural low between Beezley Hills anticline to north and Frenchman Hills anticline to south.
  - Received floodwaters from five main coulees to the north and east. These coulees (and those below) are a key part of the "Channeled Scablands"
  - Water exited basin through four main coulees to the south and west. Frenchman Coulee as one of these floodwater outlets. The location of each of these outlets was determined by a structural "sag" (recall Yakima River) (Bretz, 1956).
  - Were all outlets contemporaneous?
- Frenchman Coulee:
  - Water flowing from Frenchman Coulee into the mainstem Columbia River "gorge" dropped ~660 ft leading to a significant waterfall (as a comparison, modern-day Palouse Falls is just over 180 feet high) (Carson, Tolan and Reidel, 1987)
  - Headward erosion associated with this waterfall led to two parallel coulees—Frenchman Coulee and Echo Basin. Frenchman Coulee is the largest at over 2 miles
- Frenchman Coulee (cont)
  - Flood erosion was enhanced by the highly jointed nature of the Columbia River Basalts

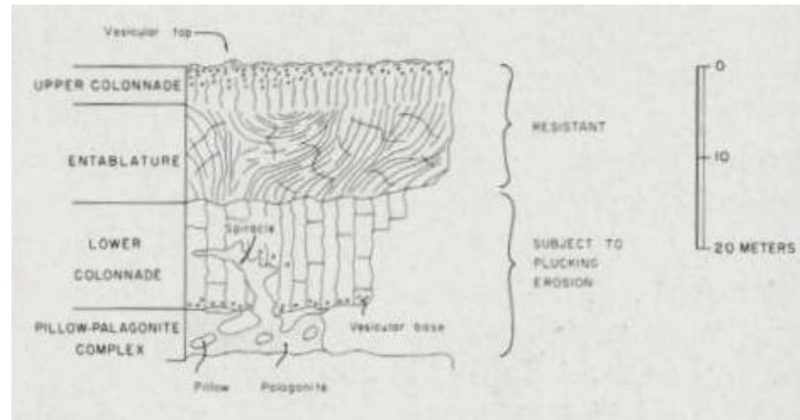


Figure 41. Cross section of idealized Columbia River Basalt flow showing structural features important to flood erosion. The pillow-palagonite and upper colonnade are not present with all flows. From Baker (1978, p. 69).

  - Characteristic features of coulee floors are:
    - "plunge pools" eroded at the base of waterfalls
    - "bars" of gravel and sand deposited where velocity slowed. Bars often fill older, more downvalley plunge pools
    - large boulders that may be flood "bedload" or "talus" from the sides of the coulees

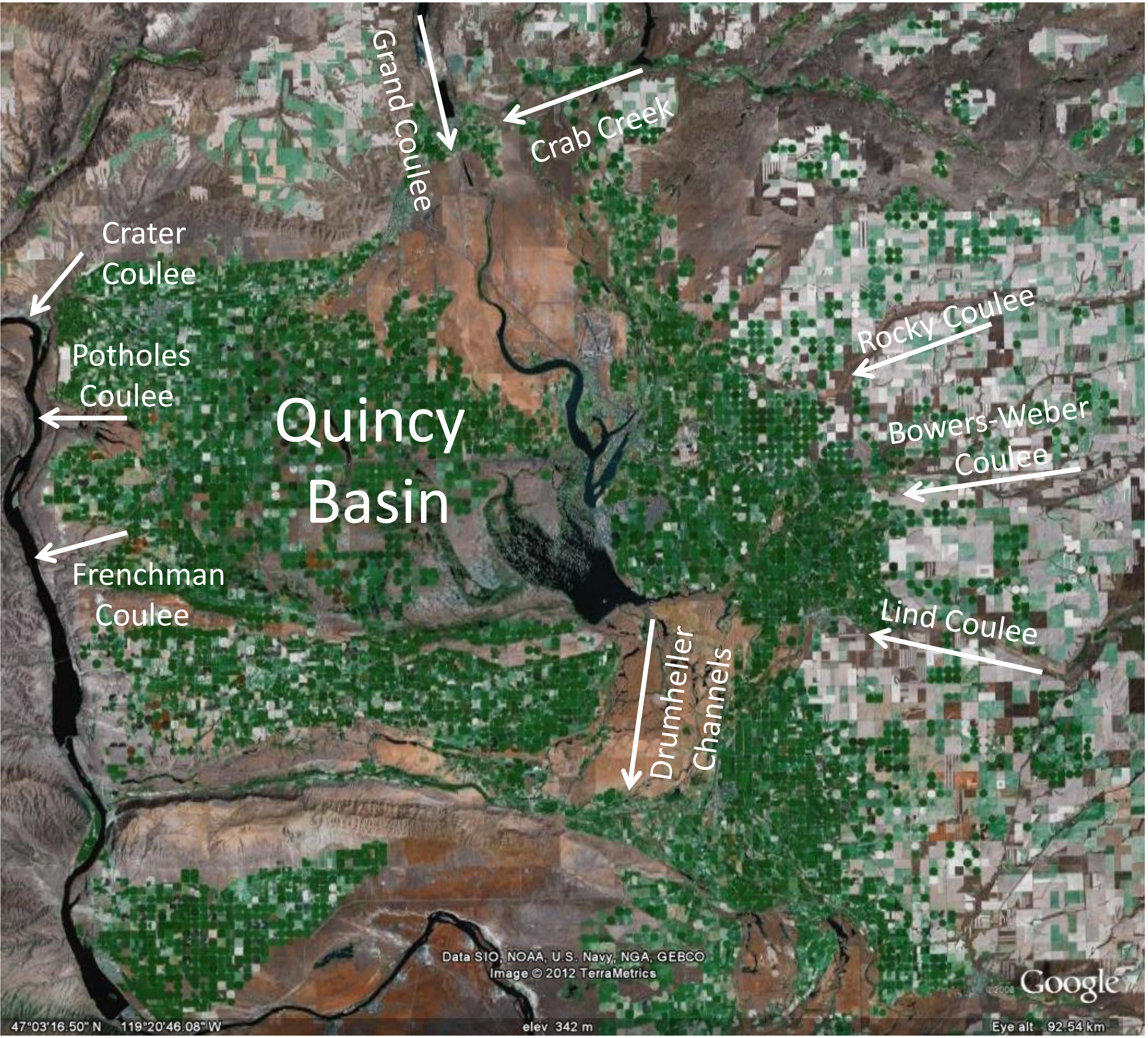


Figure 42. Quincy Basin and Missoula Flood paths. Note floodways that delivered water into the Quincy Basin (from north and moving clockwise--Grand Coulee, Crab Creek, Rocky Coulee, Bowers-Weber Coulee and Lind Coulee) and the floodwater outlets from the Quincy Basin (from southeast and moving clockwise—Drumheller Channels, Frenchman Coulee, Potholes Coulee and Crater Coulee). Map adapted from Baker (1978, p. 64).

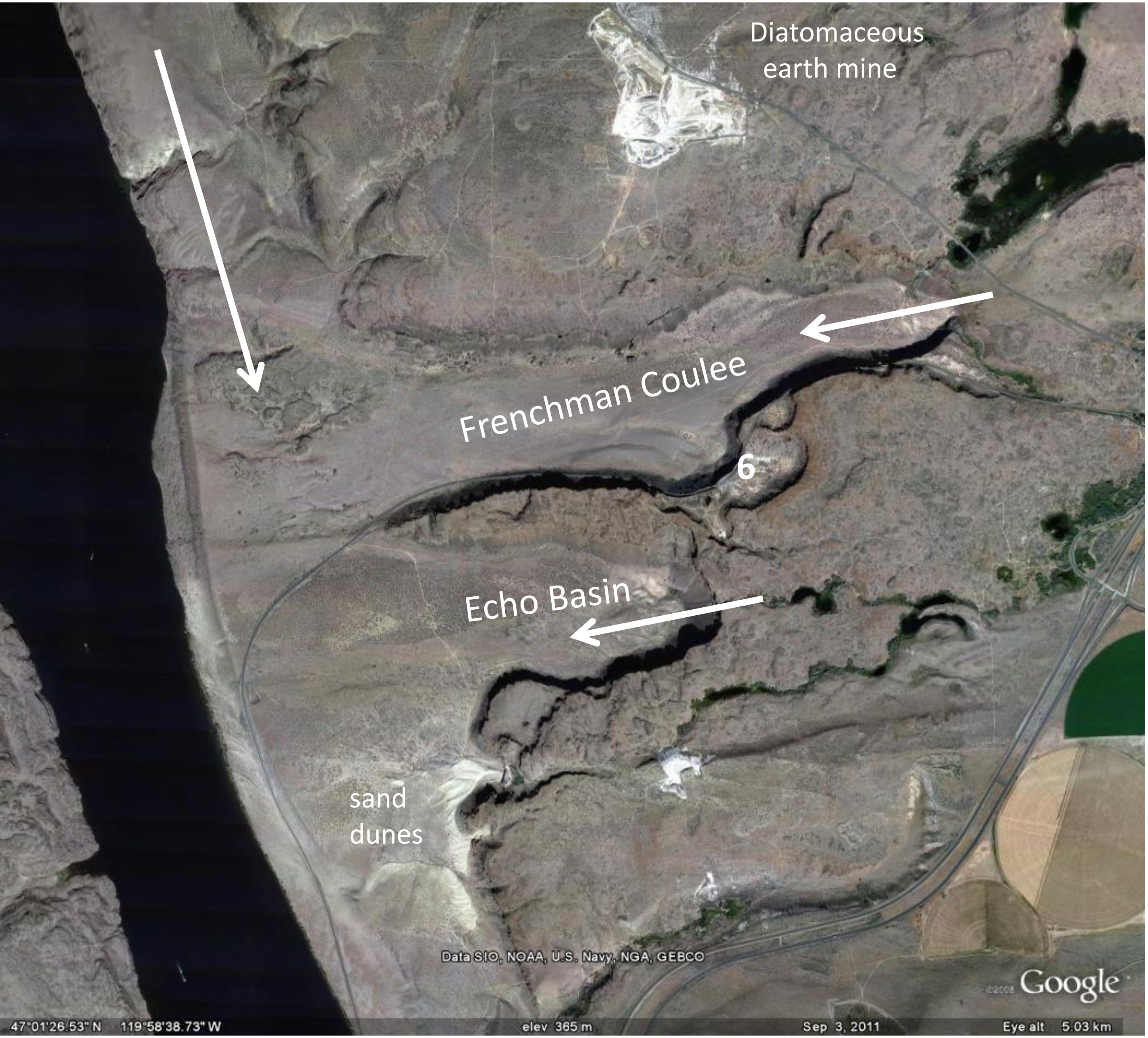


Figure 43. Frenchman Coulee cataract. Bold arrows indicate floodwater flow direction from Quincy Basin and down the mainstem of the Columbia River. Number 6 denotes approximate location of Stop 6.

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