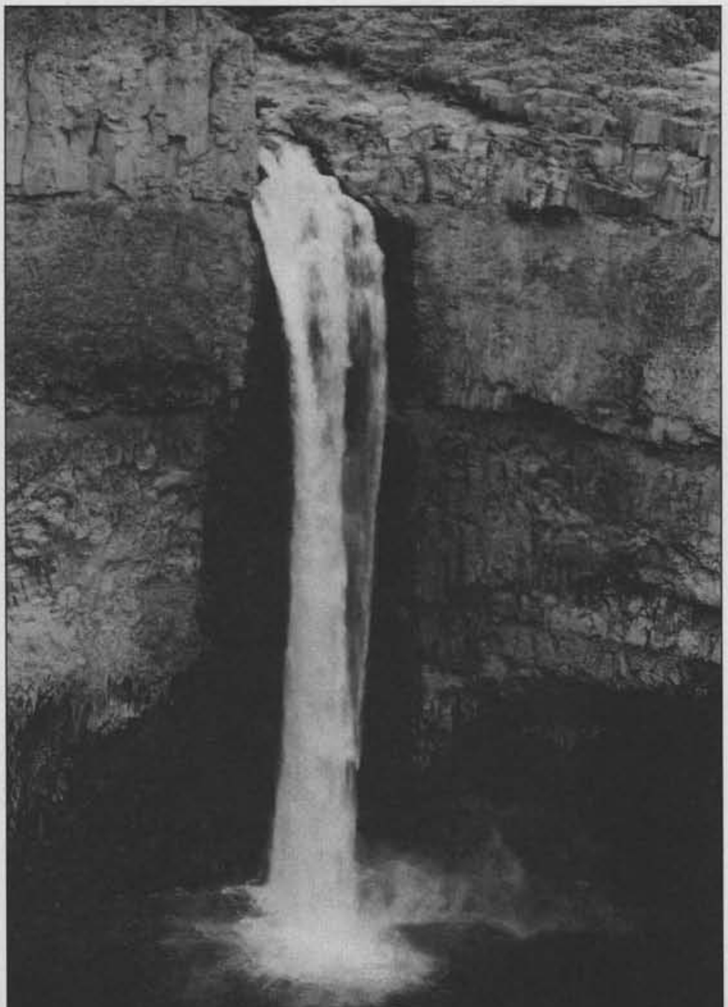
NATURAL RESOURCES

FLOOD BASALTS AND GLACIER FLOODS: Roadside Geology of Parts of Walla Walla, Franklin, and Columbia Counties, Washington



by Robert J. Carson
and Kevin R. Pogue

WASHINGTON
DIVISION OF GEOLOGY
AND EARTH RESOURCES

Information Circular 90
January 1996

WASHINGTON STATE DEPARTMENT OF
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Front Cover: Palouse Falls (56 m high) in the canyon of the Palouse River.

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Flood Basalts and Glacier Floods: Field Trip Guide to the Geology of Parts of Walla Walla, Franklin, and Columbia Counties, Washington

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GENERAL GEOLOGY OF SOUTHEASTERN WASHINGTON

This field trip guide covers the geology of some of the areas affected by two of the best documented catastrophic events in Earth's history: enormous basaltic lava flows that began to cover the land about 17 million years ago (Baksi, 1989) and giant glacier outburst floods (termed jökulhlaups) that started about 15,300 years ago (Waitt, 1985). These events are in large part responsible for the shape of the landscape of eastern Washington, where the Earth's youngest basalt plateau was swept by the largest documented floods in geologic history.

The Columbia Plateau is a physiographic province, an area that has somewhat similar rocks, landforms, soils, climate, and vegetation. Most of the rocks at the surface are basalt. Erosion and deposition by jökulhlaups shaped much of the surface, but streams have cut the land and left deposits as well, and wind has piled up sand dunes. The soils are thick on windblown silt (referred to as loess) and immature to nonexistent on sand, gravel, and basalt. The area receives as little as 20 cm annual precipitation and is considered arid. The natural vegetation is sagebrush shrubland and short-grass prairie (Hunt, 1974).

The Columbia Plateau is bordered on the north and east by the Rocky Mountains, on the south by the Basin and Range Province, and on the west by the Cascades (Fig. 1). The plateau province is divided into several physiographic sections. This field trip takes us through the central part of the Walla Walla Plateau section, adjacent to the northwest flank of the Blue Mountains section. On the Walla Walla Plateau, two of the largest rivers in North America meet: the Snake River, which originates on the Yellowstone Plateau, Wyoming, and the Columbia River, which starts at Columbia Lake in eastern British Columbia (Dietrich, 1995, p. 100).

The oldest rocks in the Blue Mountains are 'exotic terranes' composed of large fragments of continents and ocean floor. These range in age from about 350 million to about 200 million years and were accreted to western North America about 100 million years ago. These terranes were later intruded by Late Mesozoic granitic rocks and covered by Tertiary volcanic rocks. Most of the Miocene basalt flows (Fig. 2), which total as much as 3 km thick in the Walla Walla Plateau section, originated in the Blue Mountains section, where there were long fissures through which the lava poured. Magma in the fissures solidified to form dikes.

Magnetic Polarity

From time to time, at apparently random intervals, the Earth's magnetic field reverses. Currently, it is 'normal' or N, but about 800,000 years ago it was 'reversed' or R. There have been numerous polarity reversals over geologic time, and

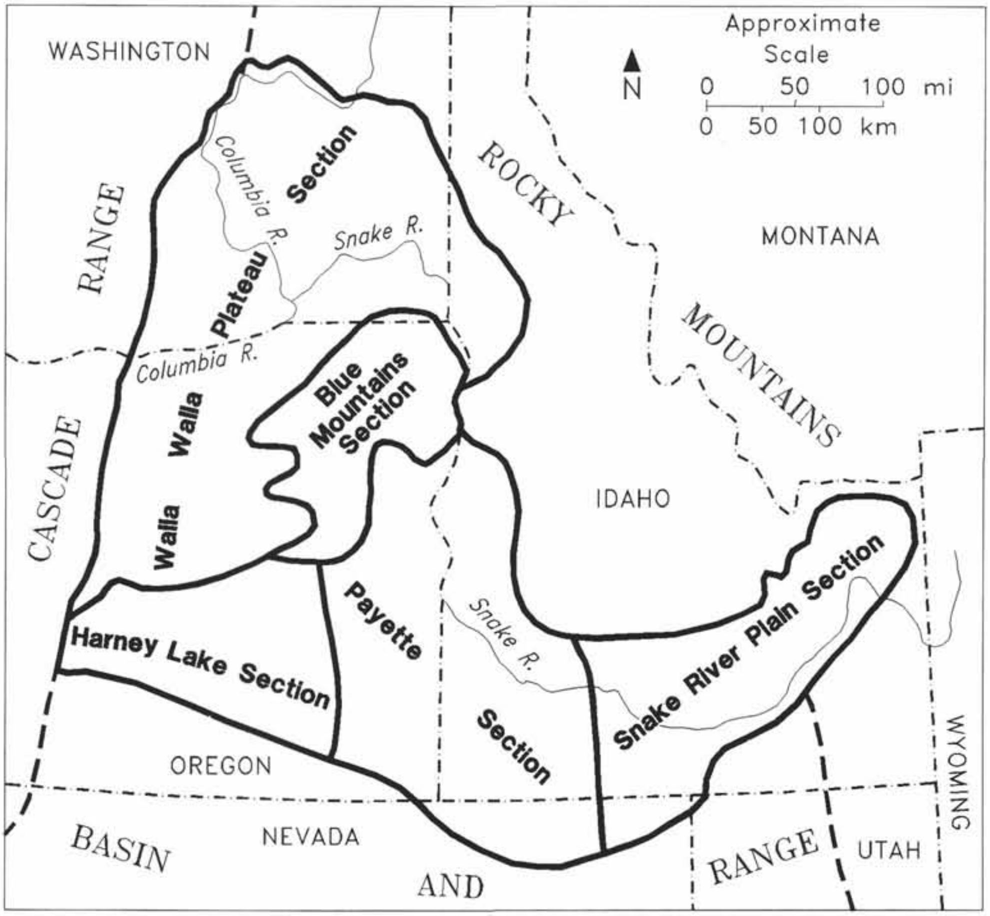

Figure 1. Physiographic map of the Columbia Plateau. (Modified from Hunt, 1974.)

these reversals are recorded in the rocks. One of the physical properties that geologists use to distinguish the lava flows in the Columbia River Basalt Group is magnetic polarity. In Figure 3, this is indicated by the N and R in the Magnetic Polarity column. A few flows have transitional polarity (T), which means that the flow erupted during one of the pole reversals. Other flows erupted during a geomagnetic excursion (E). At these times, the paleomagnetic north or south poles were at intermediate to low latitudes. Transitions of polarity and geomagnetic excursions took place over fairly short periods, probably less than 10,000 years.

Geologic Time

Geologists have special abbreviations for time: m.y. for million years, as in 'for 10 m.y.'; Ma for mega (million)-annum, used to indicate a point in geologic time or age, as in 'age estimate of 23 Ma'; and ka, for kilo (thousand)-annum, used to express ages of younger rock units. We will use these abbreviations from here on in this guide.

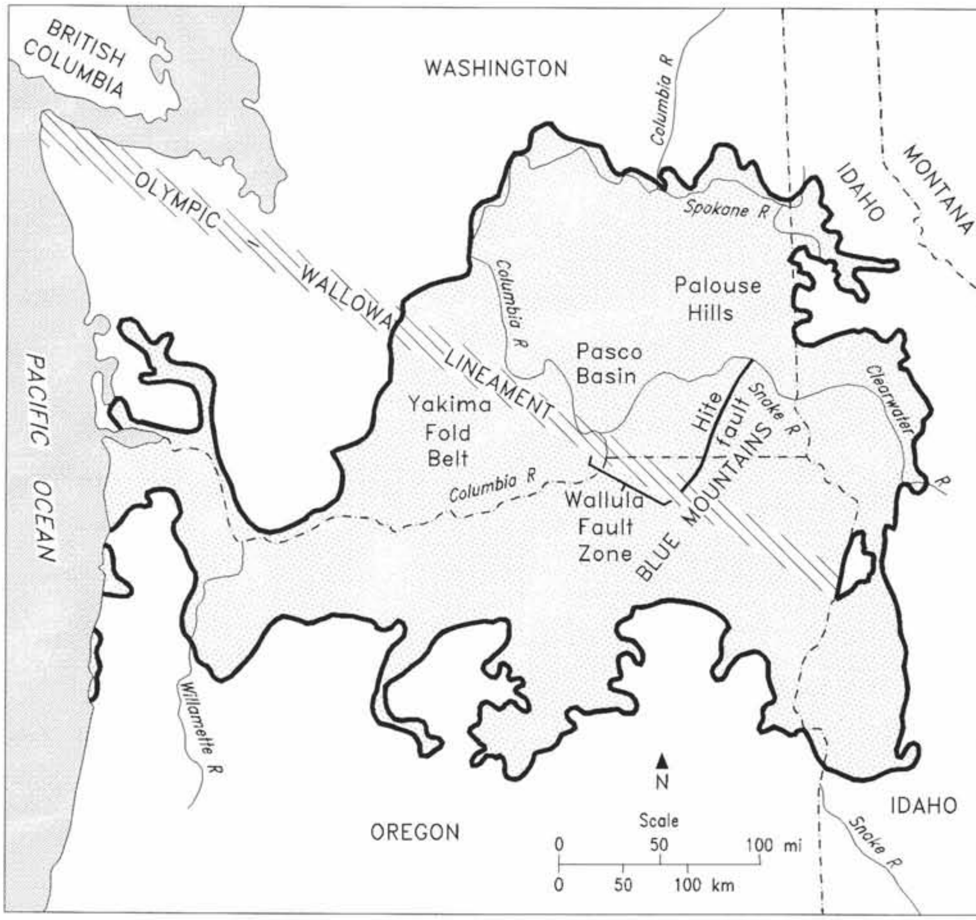

Figure 2. Distribution of the Columbia River Basalt Group. (Modified from Tolan and Reidel, 1989.)

Columbia River Basalt Group

The Columbia River Basalt Group covers an area of about 163,700 km^2 (Fig. 2) and has an estimated volume of 174,300 km^3 (Tolan and others, 1989). More than 99 percent of the basalt was erupted between 17 and 14 m.y. ago (Swanson and Wright, 1978); eruptions occurred less often between 14 and 6 m.y. ago. Concurrent with volcanism were subsidence (for example, in the Pasco Basin), deformation (for example, in the Yakima Fold Belt shown on Fig. 2), erosion by rivers (many of whose valleys were later filled by intracanyon flows), and sedimentation (for example, the Ellensburg Formation). Figure 3 is a simplified stratigraphic column for the Columbia River Basalt Group and younger strata in the area traversed on this trip.

The ages of the lava flows that make up the Columbia River Basalt Group have been determined by radiometric dating, most commonly the potassium-argon (K-Ar) method. This technique is based on measuring the ratio of the radioactive isotopes ^{40}K to ^{40}Ar. Most igneous rocks contain some potassium; a fraction of a percent of this potassium is radioactive and decays at a known rate to argon. With time, there will be less radioactive potassium and more argon gas trapped in the rock. By making careful measurements of these chemical components, geologists can estimate the age of the rock. Baksi (1989) discusses K-Ar dating of the Grande Ronde Basalt, which erupted in about 1.3 m.y, between 16.9 and 15.6 Ma.

Tectonic Features

Anticlinal Ridges. The north–south compressional stresses of south-central Washington that created the anticlinal ridges (convex-upwards folds that include lava flows and any interbedded sedimentary rock), have existed from the mid-Miocene to the present (Reidel and others, 1992). According to Reidel and others (1992), the structural relief of some anticlines in the Yakima Fold Belt has increased by as much as 1,000 m in the past 10 m.y.

Olympic–Wallowa Lineament. A major tectonic feature in southeastern Washington is the northwest-trending Olympic–Wallowa lineament (commonly referred to as the OWL) (Figs. 2 and 4). In central and southeastern Washington, the OWL is marked by the aligned anticlinal ridges of the Yakima Fold Belt and faulted escarpments (Tolan and Reidel, 1989). Most of the fold belt structures plunge to the east and die out before reaching the field trip area, but the Horse Heaven Hills anticline continues east across southern Washington and intersects the larger Blue Mountains anticline in northern Oregon. Between the Columbia River and the Blue Mountains, the OWL is marked by a 200-m-high escarpment along the trace of the Wallula fault zone, a series of high-angle en echelon faults that display evidence for both dip-slip and strike-slip motion.

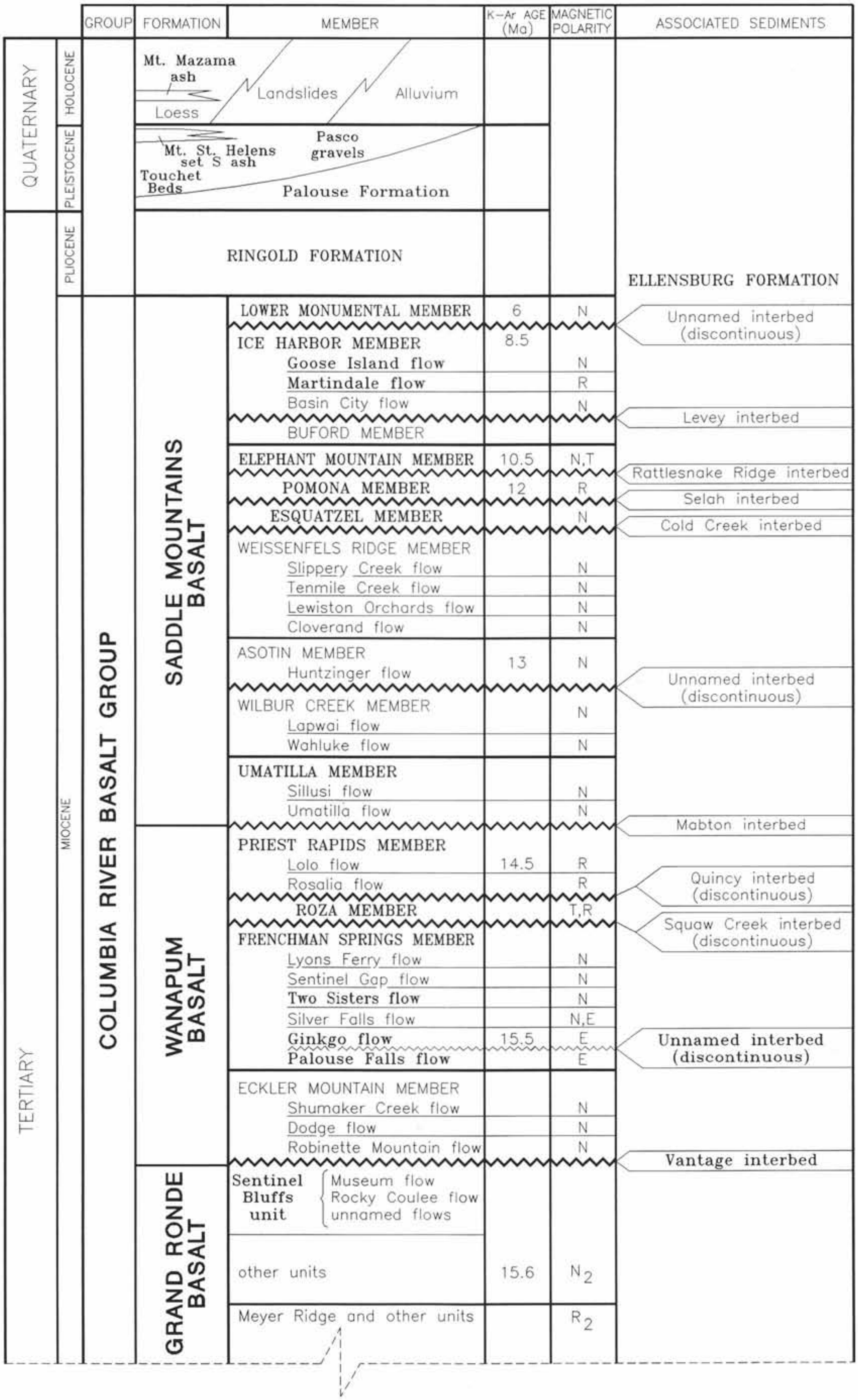

Figure 3. Diagrammatic stratigraphic section for the central and southeastern Columbia Plateau. The Ellensburg Formation is composed of sediments overlying the Grande Ronde Basalt and underlying the Ringold Formation; it includes the named and unnamed interbeds. Members and flows not mentioned in the text are in lighter print. Flows in members not mentioned in the text are omitted from this figure. See p. 1 for an explanation of magnetic polarity. (Modified from Campbell and Reidel, 1991.)

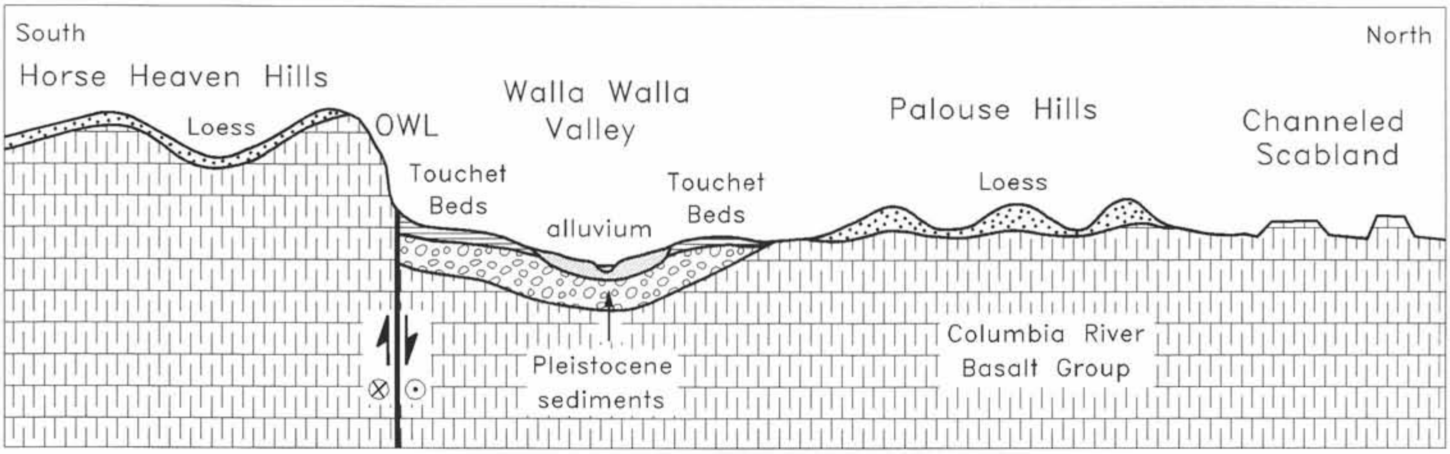

Figure 4. General north–south cross section of the field trip area. OWL, Olympic–Wallowa lineament. The basalt flows are gently folded, particularly in the Horse Heaven Hills.

Figure 5. Late Pleistocene glaciers, lakes, and floods in the northwestern United States. Dark pattern shows areas flooded by the waters released by failures of the ice dams that created glacial Lake Missoula during the Pleistocene. (Modified from Baker, 1983.)

Hite Fault. The Hite fault intersects the Olympic–Wallowa lineament at approximately a right angle 35 km (22 mi) southeast of Walla Walla. This northeasterly striking fault can be traced to Lower Granite Dam on the Snake River (Tolan and Reidel, 1989). The Walla Walla area experienced an intensity VII (approximately Richter magnitude 6) earthquake on July 15, 1936 (Brown, 1937). The earthquake and its aftershocks may have been caused by movement on the Wallula fault zone and (or) the Hite fault (Deborah Grubb, Whitman College, written commun., 1991).

Quaternary Sedimentation

After volcanism ceased on the Columbia Plateau, tectonism continued, and the Quaternary brought a new group of processes that modified the landscape. In the Pasco Basin were many sources for wind-blown detritus: the Pliocene Ringold Formation (weakly indurated gravel, sand, silt, and clay) (Newcomb, 1958) and sediment deposited by the Columbia and Snake Rivers. The sediment load of these rivers was augmented during the glaciations of the Pleistocene; glaciers grew and shrank in the Cascades to the west, British Columbia to the north, the Rockies to the east, and the Wallowa and Elkhorn Mountains to the southeast. The prevailing southwesterly winds transported fine sediment from the Pasco Basin; sand accumulated in the Juniper Dunes and other dune fields, and silt makes up the thick loess deposits in the Palouse Hills (Fig. 4). A somewhat dated but still useful field guide to the loess of the Palouse area was written by Fryxell and Cook (1964).

Palouse Loess. Alan Busacca and Eric MacDonald have done much of the research on the loess of the Palouse Hills (for example, Busacca, 1991, and Busacca and MacDonald, 1994). The following text summarizes these two reports:

The mineral content of the loess of the Palouse Hills is dominated by quartz and feldspar. The loess ranges in thickness from 1 cm to 75 m, but it becomes both finer grained and thinner to the northeast. Within the loess unit are dozens of volcanic ash layers and remnants of old soils that provide information about the age of the loess and help to correlate parts of the unit from place to place. Deposition of this silt has been occurring for perhaps 2 m.y.

"Zones of relatively unaltered loess probably represent periods of rapid eolian sedimentation, whereas paleosols apparently represent periods of slower eolian sedimentation when landscapes were fairly stable and little erosion and deposition were taking place" (Busacca and Macdonald, 1994, p. 183).

Flood Deposits. The Cordilleran ice sheet originated—several times during the Pleistocene, in fact—in the mountains of British Columbia and expanded southward into northern Washington, Idaho, and Montana. Of particular significance to the landscape of eastern Washington was a lobe of the ice sheet that flowed southward along a valley called the Purcell Trench and blocked the northwest-flowing Clark Fork River near Cabinet Gorge on the Idaho–Montana border. The ice

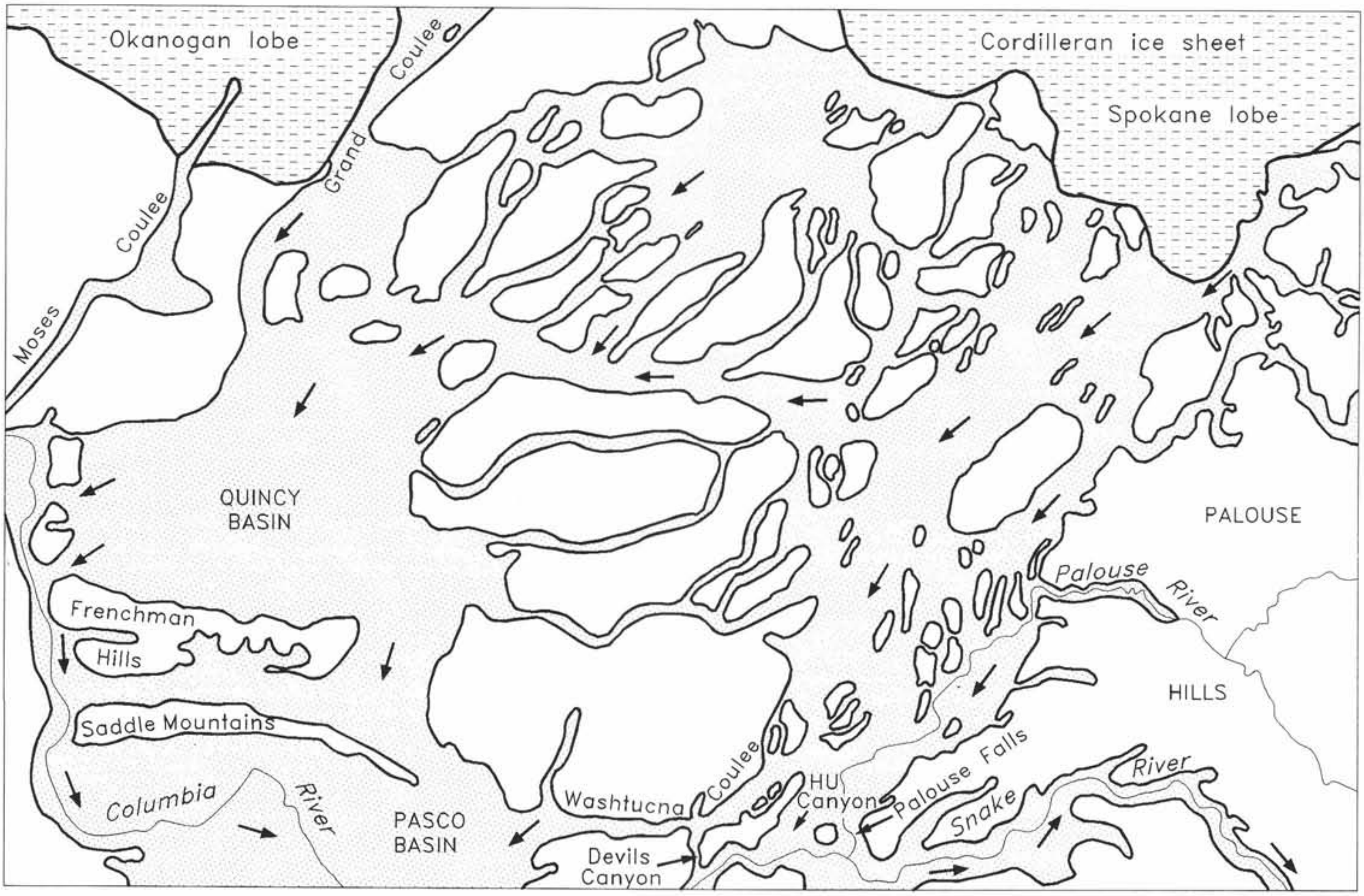

Figure 6. The Channeled Scabland of Washington. Arrows indicate direction of flood flow. (Modified from Bretz, 1959.)

formed a dam that created glacial Lake Missoula (Pardee, 1910), which covered 7,800 km^2 of western Montana (Weis and Newman, 1989) and held 2,500 km^3 of water (Waitt, 1985, p. 1280). At the ice dam, the water was approximately 600 m deep (Weis and Newman, 1989). This dam failed repeatedly (Waitt, 1980), releasing gigantic jökulhlaups that swept across northern Idaho, through the Spokane valley, southwestward across eastern Washington, through the Columbia River Gorge, and out into the Pacific Ocean (Fig. 5). In eastern Washington, the floods created the Channeled Scabland (Fig. 6), an area of intense study by J Harlen Bretz in the 1920s. (See Baker and Nummedal, 1978, or Waitt and others, 1994, for a summary of the Channeled Scabland and a list of papers by Bretz.)

In general, where water velocities were highest, the Missoula floods eroded channels and left 'scabs' or erosional remnants of basalt between the channels—hence the name Channeled Scabland for this topography in eastern Washington. Where the floods slowed down a little, such as in eddies, giant gravel bars were deposited. The Pasco gravels were transported as bed load by the floods and contain many lithologies from sources outside the Columbia River basin. Where the floods ponded, for example in the Walla Walla and Willamette Valleys, fine slackwater sediments were deposited (Bretz, 1928a); where these graded flood sediments (in which coarse sediment, pebbles and sand, is at the base of a bed and gradually becomes finer upward so that there is silt at the top of a bed) are 'repeated' vertically, they are called rhythmites. These are the Touchet Beds, named by R. F. Flint in 1938, although their origin was not then identified.

Large icebergs rode the jökulhlaups and, where they were stranded by retreating water, melted and left erratic boulders along the main route of the floods and far up tributary valleys. (See, for example, Carson, 1990, and Bartlett and Carson, 1995.)

Waitt (1980) argued that each of the approximately 40 Touchet Beds resulted from a separate catastrophic flood. These floods could only occur at times when glacial Lake Missoula existed, which Waitt (1985) estimates at between 15,300 and 12,700 years ago. Part of the reason we know the age of these strata is that ash from an eruption of Mount St. Helens, known as the set S ash (Fig. 3), fell in eastern Washington about 13,000 years ago. The ash lies on the twelfth rhythmite below the top of the Touchet Beds (Waitt, 1980).

Although the last floods from glacial Lake Missoula created the spectacular Channeled Scabland, geologic evidence suggests that jökulhlaups swept across eastern Washington long before 15,300 years ago. Other series of glacier outburst floods deposited gravels, sands, and silts at about 200,000 years ago and more than 790,000 years ago (Reidel and Fecht, 1994).

When each jökulhlaup swept through the area where Spokane is today, much of the floodwater was dumped into glacial Lake Columbia at the northern edge of the Columbia Plateau (Atwater, 1984). This lake formed when the Columbia River was blocked at the present site of Grand Coulee Dam by the Okanogan lobe of the Cordilleran ice sheet. Atwater (1984, 1986) counted flood deposits and varves (pairs of light and dark glaciolacustrine layers deposited annually) that accumulated in glacial Lake Columbia. The average interval between Missoula floods was about 30 years (Waitt and others, 1994).

Smith (1993) made a sedimentological study of Missoula flood slackwater sediments along the Columbia and Tucannon Rivers. He reasoned that a single graded flood bed was deposited at most sites during most floods, but that as many as nine graded beds were deposited during repeated surges of some floods. Smith (1993, p. 97) re-examined Waitt's (1980) sites in the Walla Walla and Yakima valleys and supports the one graded bed per flood hypothesis for those areas.

By convention, geologists place the boundary between the Pleistocene and the Holocene at about 10 ka. In the late Pleistocene and early Holocene, the climate became warmer and drier. Most of the glaciers disappeared, and the vegetation changed. (See Heusser, 1965, for a summary of vegetation and climate changes as deduced from analyses of pollen.) During the Holocene, the explosion and collapse of Mount Mazama about 6,845 years ago formed Crater Lake and showered southeastern Washington with materials blown out of the crater. Coarse pumice settled near the volcano, but finer ash drifted downwind for some distance. This erupted or pyroclastic material is collectively referred to as Mazama tephra (Bacon, 1983). About a meter of loess later blanketed the area, and dunes migrated downwind from areas along major rivers until modern dams made reservoirs that drowned the sand and silt supply. Most dunes are no longer active.

Intense agricultural activity has resulted in extreme erosion of the fine soils. This sediment is filling the reservoirs, demonstrating that pollution can be defined as a resource out of place.

ROAD LOG

This geologic road log begins and ends in the main parking lot at Whitman College, which is just east of downtown Walla Walla. The parking lot has a north entrance on Isaacs Avenue and a west entrance on Park Street. Examples of features recording the geologic history of the area are described at various stops along the way. The route of the 203-mile field trip is shown on Figure 7 (p. 8) and the back cover.

In general, dimensions in this guide are given in metric units because most scientists, including geologists, communicate in this system. Two exceptions are distances on the road logs and elevations. Few U.S. cars record distance in kilometers. Elevations are given as feet above mean sea level. Most maps published in the United States still show elevations in feet. We note elevation at many locations because you may want to set your altimeter or you may want to know whether you are above or below the water level of the cataclysmic glacial floods. For example, at Wallula Gap, the maximum elevation of floodwaters was about 1,200 feet. Farther north, flood elevations were somewhat higher. This elevation information may give you a better picture of events in the Pasco Basin and Walla Walla valley.

Some Cautions Before You Set Off on This Trip

- Many of the stops are roadcuts. Be careful to park well off the pavement and beware of traffic.
- Watch out for rattlesnakes and black widow spiders. Both of these poisonous animals live in southeastern Washington. Leather boots are good protection against snakes, burrs, and sharp rocks.

FURTHER READING

For those interested in learning more about the geology of southeastern Washington and adjacent areas, the following books and articles are recommended.

General

Baker, V. R.; Greeley, Ronald; Komar, P. D.; Swanson, D. A.; Waitt, R. B., 1987, Columbia and Snake River Plains. *In* Graf, W. L., editor, Geomorphic systems of North America: Geological Society of America Centennial Special Volume 2, p. 403-468.

McKee, Bates, 1972, Cascadia (The geologic evolution of the Pacific Northwest): New York, McGraw Hill, 394 p.

Orr, E. L.; Orr, W. N., 1996, Geology of the Pacific Northwest: McGraw Hill, 409 p.

Volcanism and tectonism

Reidel, S. P.; Hooper P. R., editors, 1989, Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America Special Paper 239, 386 p.

Missoula floods

Allen, J. E.; Burns, Marjorie; Sargent, S. C., 1986, Cataclysms on the Columbia—A layman's guide to the features produced by the catastrophic Bretz floods in the Pacific Northwest: Timber Press [Portland, Ore.] Scenic Trips to the Northwest's Geologic Past 2, 211 p.

Parfit, Michael, 1995, The floods that carved the West: Smithsonian, v. 26, no. 1, p. 48-59.

Weis, P. L.; Newman, W. L., 1989, The Channeled Scablands of eastern Washington—The geologic story of the Spokane Flood; 2nd ed.: Eastern Washington University Press, 24 p.

Conversion Factors

Metric	*English*
Units of Length	
1 millimeter (mm)	0.039 inch
1 centimeter (cm)	0.39 inch
1 meter (m)	3.28 feet
1 kilometer (km)	0.621 mile
Units of Area	
1 square meter (m^2)	10.8 square feet
1 square kilometer (km^2)	0.386 square mile
Units of Volume	
1 cubic meter (m^3)	35.3 cubic feet
1 cubic kilometer (km^3)	0.240 cubic mile

ACKNOWLEDGMENTS

The original version of this field guide was prepared for the Keck Geology Consortium Symposium, supported by the W. M. Keck Foundation and held at Whitman College in April 1993. We are indebted to Karen White for work on that manuscript. Whitman College provided vehicles for field work in connection with preparation of this guide. Ron Urban provided the plane and was the pilot for the flight to take the aerial photographs. We also acknowledge the assistance of Keith Ikerd (cartographer) and Jari Roloff (production editor/designer) for preparing final copies of illustrations and the text. Finally, we are grateful to Eric Schuster and Kitty Reed of the Washington Division of Geology and Earth Resources, Steve Reidel of Westinghouse Hanford Co., and Richard Waitt of the U.S. Geological Survey for their reviews.

Road Logs

PART 1 - WALLA WALLA TO PALOUSE FALLS

Miles

0.0 Proceed north out of Whitman College's parking lot and turn right (east) on Isaacs Avenue (elevation 990 ft). (The route for all five segments of this trip is shown in Figure 7 and on the back cover.)

0.3 At the stoplight, turn left (north) onto Clinton Avenue.

0.9 At the stop sign, turn right (east) on U.S. Highway 12. In the distance, the Palouse Hills (Fig. 8) are to the left (north), the Blue Mountain anticline to the southeast. The highest point in the Blue Mountains is Oregon Butte, which, at 6,387 ft, was not high enough to be glaciated. As you drive east, note the low surface, or flood plain, along Mill Creek to the right (south) and the higher surface or terrace to the north. The high surface is probably the floor of the intermittent lake caused when Missoula floods were temporarily backed up (or hydraulically dammed) at Wallula Gap.

2.9 Walla Walla Airport (elevation 1,196 ft) is to the north on the high surface.

5.6 to 7.0 You are crossing a small part of the Palouse Hills. The roadcuts are in Quaternary loess. At least one caliche-rich paleosol (ancient, buried soil) can be seen. During the Quaternary, episodes of loess (windblown silt) deposition alternated with periods of relative stability or reduced rates of deposition. Soils formed during the stable periods. When the climate was warm and dry, a layer or crust of calcium carbonate called caliche accumulated in the soils.

8.0 Loess over lava of the Frenchman Springs Member of the Wanapum Basalt (Columbia River Basalt Group), about 15.3 Ma.

10.2 Enter Dixie (elevation 1,547 ft).

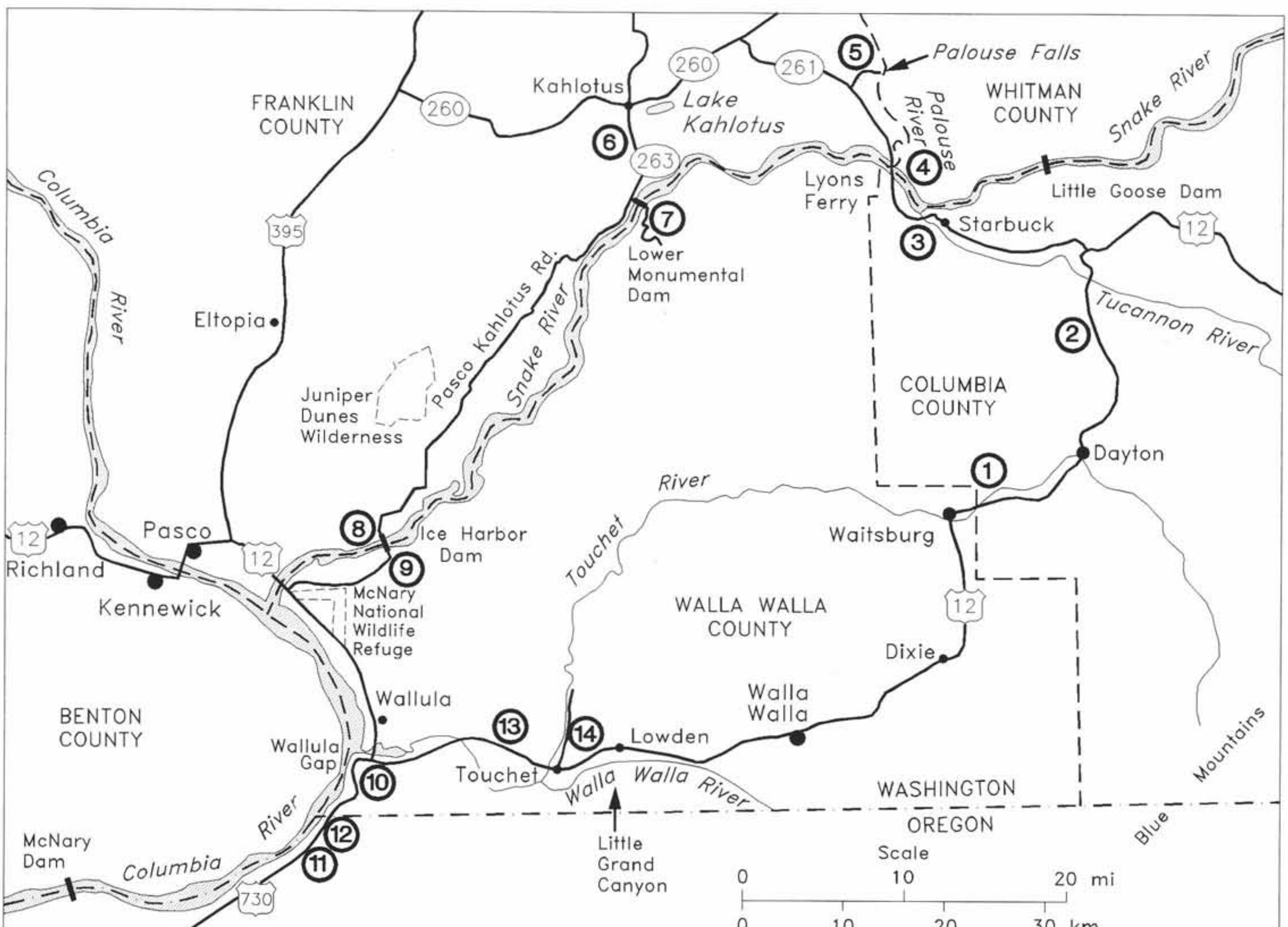

Figure 7. Route of the field trip. Stop locations are indicated by the circled numbers.

10.8 Leave Dixie (old high school to the right, or south). Roadcuts for the next 2 mi expose Quaternary loess over Miocene basalt.

12.8 Drainage divide between Walla Walla and Touchet Rivers (elevation 1,914 ft) (Fig. 9). The road is on thick loess with several caliche-rich paleosols. From here to past Dayton, green fields are mostly growing winter and (or) spring wheat; tan/yellow/brown fields are wheat ready for harvest, wheat stubble after harvest, or fields with various degrees of tillage. The mean annual precipitation in Walla Walla County ranges from about 20 cm at the western edge in the Pasco Basin to about 100 cm in the higher parts of the Blue Mountains. To get a wheat crop every year requires about 50 cm of precipitation. In areas with less moisture, the field may lie fallow every other year, storing moisture for the next year's wheat crop.

Figure 8. The Palouse Hills between Walla Walla and Starbuck. Runoff and streams have cut a parallel drainage pattern into the thick Quaternary loess. The predominant land use is wheat farming.

Figure 9. Loess north of Dixie, at the drainage divide between the Walla Walla and Touchet Rivers; this sediment blankets the Palouse Hills. The thick Quaternary loess contains caliche-rich paleosols. The unconformity (pale band above the road sign) indicates erosion of the north-dipping older loess (lower right) before deposition of the south-dipping younger loess (upper half of the photo). Thickness of the beds is suggested by the sign, which is about 3 m high.

18.2 Stripcropping of hillsides is prominent from here to just past Dayton (Fig. 10). The loess of the Palouse Hills is highly erodible soil. Soil losses of 0.3 to 0.4 cm/yr are common, and erosion of 1.4 to 2.7 cm/yr occurs on steep slopes (Higgins and others, 1989, p. 887). Much of the sediment is deposited in the reservoirs along the Snake and Columbia Rivers. Factors influencing soil loss include soil erodibility, rainfall, slope, length of slope, vegetation, and cultivation techniques. Stripcropping (commonly alternating wheat crops and fallow fields) effectively reduces the length of bare slope, thereby reducing erosion.

19.6 Enter Waitsburg (elevation 1,268 ft).

20.2 Turn right (east), continuing on U.S. Highway 12. Then cross the Touchet River; note the artificial levees designed to reduce flooding of Waitsburg, which lies on the Touchet River's flood plain. Most historic floods in this area are caused by rain-on-snow events or summer thunderstorms.

21.0 Leave Waitsburg. You are driving across the flood plain of the Touchet River.

22.5 Turn left (north) at the grain elevators; cross the railroad tracks.

22.6 Turn left (west) on the paved secondary road along the north edge of the Touchet Valley.

23.2 **STOP 1:** Quarry in a tiered or banded lava flow of the Frenchman Springs Member (Wanapum Basalt) (Fig. 11).

"Are tiers the result of some process completely internal to a ponded flow and related to its cooling history, or does each tier record a separate pulse of lava into a gradually deepening pond? In other words, is a tiered flow a single or multiple-flow cooling unit?" (Swanson and Wright, 1981, p. 20).

McDuffie and Winter (1988) studied this banded lava flow:

"There are no significant compositional difference between the bands. However, there is a consistent pattern of increasing mesostasis in the center of each band, suggesting a relationship to cooling. Platy fracture horizons and curves in the columnar joints are considered to be related to propagation of the joints. The regular spacing of the bands suggests a cyclic event that varies the cooling rate, such as variations in seasonal precipitation."

The causes of bands in some lava flows of the Columbia River Basalt Group have not been clarified. Vesiculation (formation of gas-bubble cavities in a volcanic rock) and (or) jointing may influence the bands. For studies of vesicles and joints in Columbia River basalts, see papers by McMillan and others (1989) and Long and Wood (1986), respectively.

Turn around and return to U.S. Highway 12.

Figure 10. Stripcropping south of Waitsburg. The soils of the Palouse Hills are highly erodible. Horizontal strips of alternating fallow fields and crops effectively reduce slope length, which in turn reduces erosion.

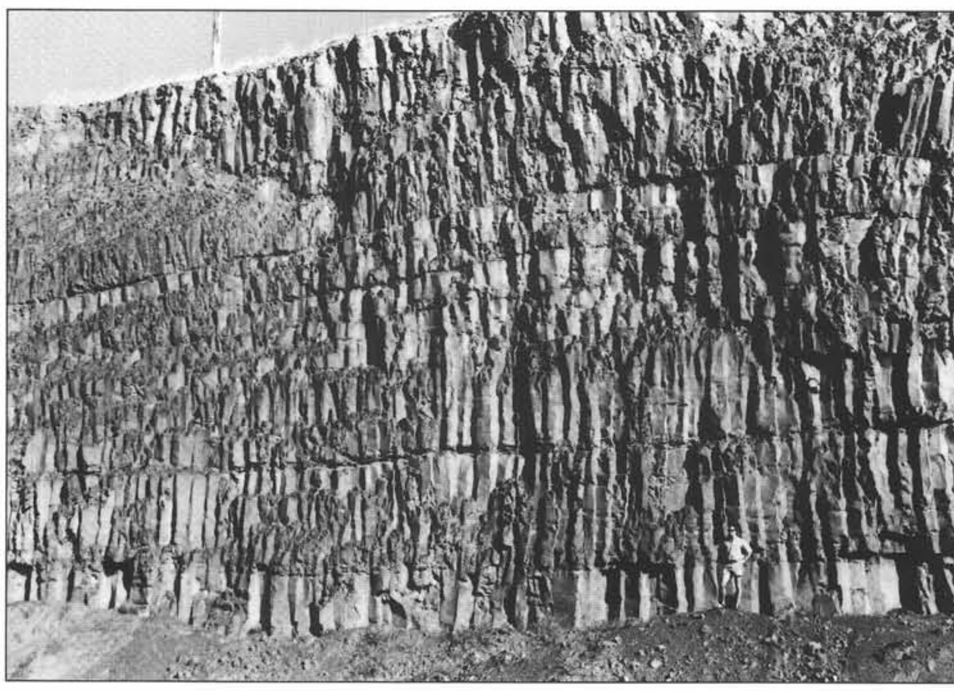

Figure 11. Quarry east of Waitsburg (Stop 1). This banded lava flow is in the Frenchman Springs Member of the Wanapum Basalt. The man standing at the lower right corner of the photo is about 2 m tall.

23.5 Enter Columbia County.

23.9 Turn left (west) on U.S. Highway 12.

25.5 Cross the Touchet River.

25.9 Lewis and Clark Trail State Park (rest area).

30.2 Enter Dayton (elevation 1,613 ft). The Lewis and Clark Expedition camped just east of town in May 1806 (Majors, 1975).

30.9 Cross the Touchet River. More than once, dams have been proposed for the North Fork Touchet River upstream of Dayton. While an earth–rock dam 8 km upstream of Dayton was being considered in the mid-1970s, the Teton Dam in eastern Idaho was under construction. The dam on the Teton River was an earth–rock dam, and it failed while the reservoir was first being filled. A huge hole developed adjacent to the right abutment of the dam in June 1976. The right side of the dam was destroyed, and the ensuing flood inundated four towns downvalley and killed 11 people (Reisner, 1986, p. 422). The Teton dam failure led the citizens of Columbia County to decide that they did not need a similar dam near Dayton.

31.9 Leave Dayton. The quarry on the right (east) side of the road is in a banded Frenchman Springs (Wanapum Basalt) flow. The same banded lava flow is exposed at Stop 1.

37.2 Divide between drainage basins of the Touchet and Tucannon Rivers. Both rivers originate in the Blue Mountains, but the Tucannon River is a tributary of the Snake River, whereas the Touchet River flows into the Walla Walla River. The high bluffs at the divide are loess beds that contain paleosols.

On a clear day, on the northeast horizon you can see conical Steptoe Butte approximately 100 km to the northeast. Steptoe Butte (elevation 3,612 ft) rises about 300 m above the surrounding Miocene Columbia River basalt flows and the overlying Pleistocene loess (Fig. 12). Steptoe Butte consists of quartzite that probably correlates with the Precambrian Belt or Windermere Supergroup and is essentially a western outlier of the Rocky Mountains of Idaho.

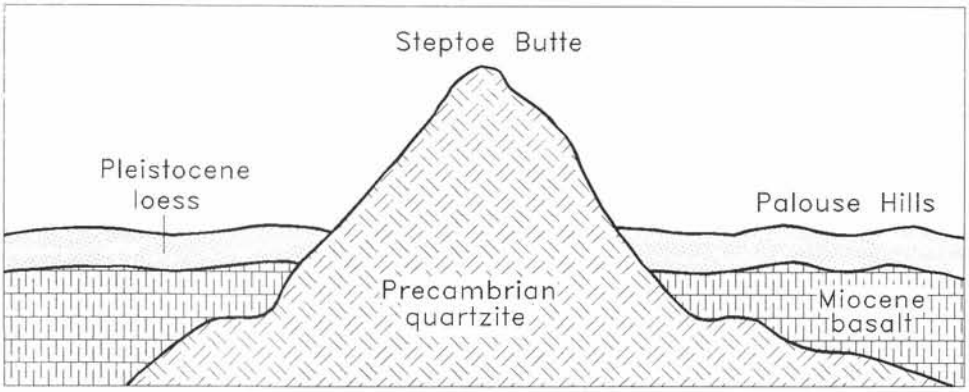

Figure 12. Diagrammatic cross section of Steptoe Butte.

39.7 **STOP 2:** Roadcuts on U.S. Highway 12. *Beware of traffic!*

The contact between the Grande Ronde and Wanapum Basalts is exposed on the west side of the highway (Fig. 13). This 15.6-m.y.-old contact is called the Vantage horizon. This is an unconformable contact, meaning that there was a significant period of time between the eruption of the flows below and above the contact. The pause in volcanism lasted about 100,000 years (Carson and others, 1987). In the western part of the Columbia Plateau, the sediments that were deposited during this time are called the Vantage Member of the Ellensburg Formation. Here, weathering produced the reddish oxidized zone, which is an incipient residual soil developed on the uppermost lava flow of the Grande Ronde Basalt (Swanson and Wright, 1981). Above the contact is the lowermost flow of the Frenchman Springs Member of the Wanapum Basalt (Swanson and others, 1980). The climate here was warmer and moister during the Miocene. Evidence includes the residual, lateritic soil and many species of trees preserved as petrified wood at the Vantage interval at the Ginkgo Petrified Forest State Park near Vantage (Carson and others, 1987). The lateritic soil (like laterites today) is composed mostly of iron and aluminum oxides and hydroxides.

Figure 13. Contact between the Grande Ronde and Wanapum Basalts (Stop 2). At the base of this roadcut north of Dayton is the weathered top of the Grande Ronde Basalt. A reddish oxidized zone is the dark band in this photo. The lava flow left of the man's head is part of the younger Frenchman Springs Member of the Wanapum Basalt. The overlying Quaternary loess is in contact with the Wanapum Basalt on the left and with the Grande Ronde Basalt on the right.

On the east side of the highway are both subaerial and subaqueous portions of a basalt flow (Frenchman Springs Member), indicating that here the lava flow entered a lake or stream. The lower part contains rounded blobs of lava, or pillows, that formed as the lava came in contact with the water (Fig. 14). Individual pillows exhibit radial cooling joints. The glassy rinds on the margins of the pillows indicate that the water quickly cooled the outside of the pillow before any crystallization could occur. The lava between the pillows underwent phreatic brecciation; that is, when the hot lava came in contact with cool water, the quick chilling caused small steam explosions that shattered the cooling lava into angular, glassy fragments called hyaloclastite. The hyaloclastite was once black, but a reaction between the water and the brecciated debris altered the basaltic glass to orange palagonite (Carson and others, 1987, p. 361-362). The upper part of the flow was not affected by the water; it has polygonal columns that formed during cooling and contraction.

The weathered top of the Grande Ronde basalt flow is a zone of weakness in the roadcut along which rock falls may be common. The highway department has sprayed concrete (referred to as dental work) and installed wire mesh to keep the mass-wasting products from falling on the road.

Above the basalt is the 'Palouse loess' or Palouse Formation (Fig. 13). The silty sediment was carried by winds from sources to the southwest of the Palouse Hills. Four morphologically distinct units are recognized in the Palouse loess; these range in age from mid- or early Pleistocene to Holocene. At least three of these units are complex, consisting of two or more depositional phases indicating pauses in sedimentation (Fryxell and Cook, 1964). Busacca and McDonald (1994) have worked on the stratigraphy of the Quaternary loess in the Palouse Hills, using buried caliche-rich soils and volcanic ash layers to make correlations.

Notice that the silty soil is thin over the basalt highs and that the loess fills lows on the pre-loess topography. After the basalts erupted in the Miocene, erosion gradually created an undulating land surface with relief of a few meters. Quaternary loess covered the surface, but it is thinner over the basalt ridges or hills and thicker in the swales or valleys.

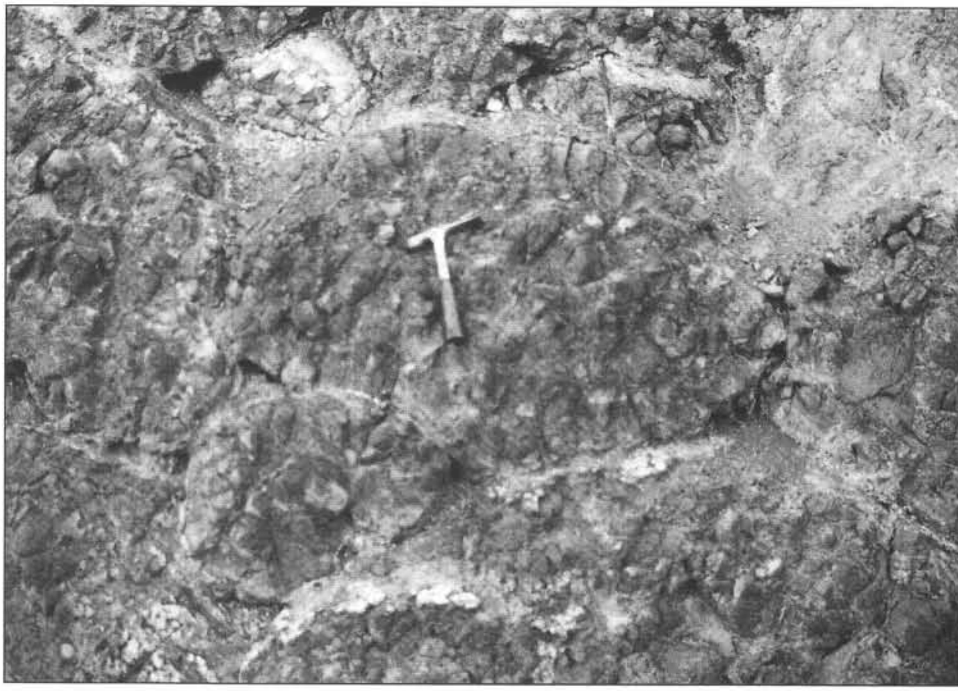

Figure 14. Pillow lava north of Dayton (Stop 2). This lava flow of the Frenchman Springs Member of the Wanapum Basalt entered water and quickly formed pillows with glassy rinds. See text for details.

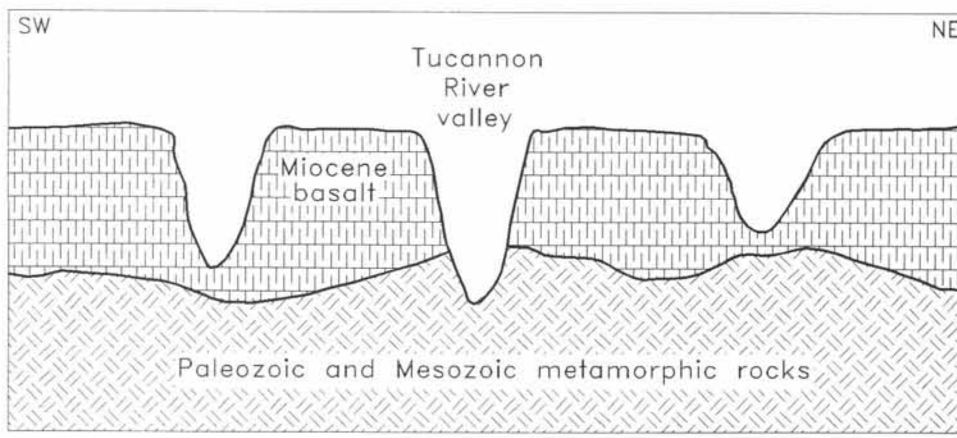

Figure 15. Diagrammatic cross section of the Blue Mountains near the upper Tucannon River valley.

Continue north on U.S. Highway 12.

44.4 Cross the Tucannon River. In this area of steep topography and thin soils, the chief land use is grazing. Approximately 40 to 50 km up the Tucannon River are exposures of the Baker exotic terrane (ribbon chert, greenstone, argillite, minor marble and amphibolite) (Dave Blackwell, formerly with Whitman College, written commun., 1992; Swanson and others, 1980). Exotic terranes are fragments of old continents or oceanic floor that were accreted to western North America. Accretion in this region occurred about 100 m.y. ago and was accompanied by mountain building. The eroded remnants of the mountains were covered by the Columbia River basalts about 17–15 m.y. ago. Later, the Blue Mountains (to the southeast) were uplifted and eroded. The Tucannon River cut through the basalts and reached some of the buried mountains of the 'Baker terrane' (Fig. 15).

46.1 Turn left (west) toward Starbuck on State Route 261 (elevation 936 ft). Here at Delaney, the roadcuts reveal late Pleistocene Touchet Beds, slackwater sediments deposited by the jökulhlaups from glacial Lake Missoula. Each bed or rhythmite is graded and is believed to represent a separate flood from western Montana (Waitt, 1980). The floods rushed up the Tucannon River from the Snake River, carrying icebergs. When the floodwaters receded, the icebergs were grounded. They then melted, depositing whatever rocks they were carrying as erratics. The Touchet Beds are coarser and thicker downvalley (toward the source). For a discussion of the rhythmites here at Delaney, see Waitt and others (1994, p. 57-59).

Figure 16. Terracettes on the side of the Tucannon River valley east of Starbuck. The distance between the tops of adjacent 'steps' is about 1 m. What is the relative importance of biologic factors (such as cattle) versus geologic factors (such as mass wasting) at sites like this?

46.2 As we proceed down the Tucannon River valley, we will try to unravel the geologic history of cut and fill. The late Cenozoic uplift of the Blue Mountains caused the Tucannon River to deeply incise the basalts. The late Pleistocene Touchet Beds partly filled this valley. The Tucannon River then partially eroded the Touchet Beds and filled the new valley with silts derived from erosion of loess and Touchet Beds. This valley filling event is at least partly early Holocene because the silts locally include Mazama ash (6,845 ± 50 years old; Bacon, 1983). The ash washed down into the valley from the surrounding hills. Most recently (perhaps due to agricultural activity in the past century), the Holocene fill has been incised again by the Tucannon River.

48.7 In this general vicinity, particularly on the south side of the Tucannon valley, are small-scale landforms whose origin has been vigorously debated. They have been called steps, terracettes, and cattle tracks (Fig. 16). Similar features have been called sheep-tracks or cattle terraces (Sharpe, 1938, p. 70-74). They even look somewhat like the cold-climate landforms called steps by Washburn (1956, p. 833-836). Are they purely geologic, due to mass wasting and possibly cold climate? Are they purely biologic, having been cut by domestic and (or) hoofed mammals? Are the terracettes produced by a combination of factors? Sharpe (1938, p. 70-74) reviewed their origin and stated (p. 71) that there are all gradations from true animal paths that have had no surface movement to miniature slump or fault blocks in which animals have played no role.

53.3 Enter Starbuck (elevation 645 ft). In the 1960s, this was a boom town during construction of Little Goose Dam about 12 km to the northeast on the Snake River (Miklancic, 1989b).

54.3 Leave Starbuck.

54.7 Road to the right (northeast) leads to Little Goose Dam. Continue northwest (straight) on State Route 261.

54.9 to 55.1 **STOP 3:** Roadcuts in Touchet Beds. Except that they are coarser than normal, these are typical Touchet Beds, the slackwater sediments deposited by the Missoula floods (Figs. 17, 18, 19). At this stop, the Touchet Beds are coarse because they were deposited near the mouth of the Tucannon River; they are transitional between gravel bars on the Snake River and more typical (finer grained) Touchet Beds just upvalley of Starbuck. The Touchet Beds commonly exhibit rhythmites that have graded bedding and are cross-cut by clastic dikes (Fig. 19). There have been at least eight origins proposed for the clastic dikes (Carson and others, 1978).

An ideal Touchet bed here has the following vertical sequence (Baker, 1973b, p. 43): (1) basal layer of poorly sorted, angular flood gravel, (2) structureless coarse sand and granules, (3) horizontally stratified medium and fine sand (4) current ripple bedding in the uppermost fine sands and lowermost coarse silts, and (5) parallel lamination in the medium and fine silts.

Smith (1993) restudied the Touchet Beds in the Tucannon River valley. He determined that most of the flood sediments were deposited by energetic surges (6 m/sec) of the floods from glacial Lake Missoula. Smith (1993, p. 88) defined a flood sequence as "one or more beds that are bounded by nonflood sediments, horizons of bioturbation, or desiccation structures, but that lack such features between beds and are thus inferred to record deposition during a single flood."

This stop is at Smith's (1993, p. 92-94) section 3, that is actually a composite of four sections that he measured over a distance of 400 m. According to Smith (1993, p. 92):

"At least 35 flood beds, comprising 9 flood sequences, appear in this outcrop. Lateral variations are extreme, as a consequence of erosion between, or during, floods, and no single vertical section can accurately reflect the flood stratigraphy."

Many sedimentary structures are present; according to Smith (1993) most of the paleocurrent indicators (such as cross-beds) indicate downvalley flow, but there is some evidence for upvalley currents.

Waitt and others (1994) disagreed with some of the interpretations of Baker (1973b) and Smith (1993).

Waitt and others (1994, p. 57) described a rhythmite at this location as having: (1) a basal basaltic pebble gravel with upvalley-directed foreset beds, (2) a middle portion of laminated sand revealing evidence of upvalley-directed currents, and (3) an upper portion of very fine sand to silt. Waitt and others (1994) counted 10 or perhaps 11 flood-laid beds here.

Continue northwest on State Route 261.

56.3 Cross the Tucannon River.

57.2 Eastward from the road are a marsh, a gravel bar, and an intracanyon flow (Figs. 20–23). The marsh covers the top of the delta deposited by the Tucannon River (Fig. 2). Construction of Lower Monumental Dam (in the 1960s) about 30 km downstream drowned the lowermost Tucannon valley. The delta formed where the Tucannon River dropped its sediments in the ponded reach of the river.

This gravel bar is an eddy bar related to the Missoula floods. As jökulhlaups surged up the Snake River, gravels were deposited by the floods in an eddy at the mouth of the Tucannon River.

The intracanyon flow is the Lower Monumental Member of the Saddle Mountains Basalt. The Lower Monumental flow, at 6 m.y. old, is the youngest of all Columbia River basalts. It "occupies a broad valley eroded through the Wanapum Basalt into the Grande Ronde Basalt..." (Swanson and Wright, 1981, p. 20). Just to the east of the Lower Monumental flow is an intracanyon flow of the Pomona Member (12 m.y. old) of the Saddle Mountains Basalt (Swanson and others, 1980).

57.8 Mouth of the Tucannon River. On the north bank of the Snake River is a huge Missoula floods gravel bar, that Bretz called "great bar" according to Waitt and others (1994) (Fig. 21).

Lewis and Clark 'discovered' the mouth of the Tucannon River in October 1804 and

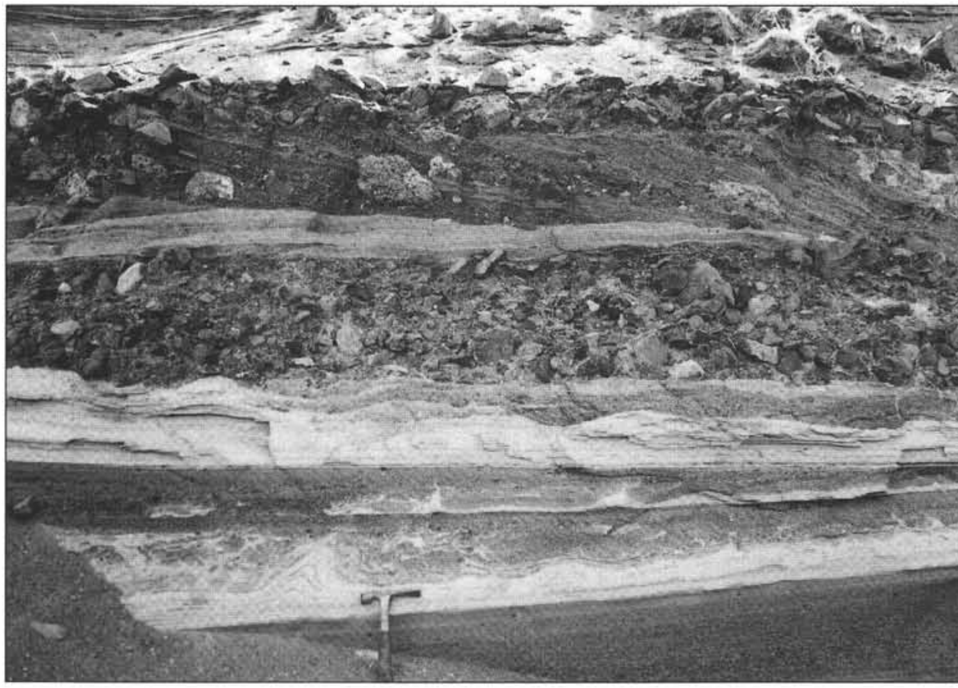

Figure 17. Touchet Beds in a roadcut just northwest of Starbuck (Stop 3). There are four rhythmites visible here. The lowest one has pebbly sand at the base; it fines upward to stratified silt at the top. Just to the left of the rock hammer is a flame structure, indicating a current to the right (up the Tucannon River valley) as the second rhythmite (that also grades from pebbly sand to stratified silt) was deposited. The third rhythmite has angular gravel at its base, and its fine top has been eroded away on the right. The fourth rhythmite fills a channel cut into the third rhythmite; at its base are cross-beds of sand and gravel that dip to the right (upvalley). The laminated sands and silts at the top are partly covered. The contact between the first and second rhythmite appears to be transitional; the upper two contacts are definitely erosional.

Figure 18. Contact between two rhythmites in the Touchet Beds just northwest of Starbuck (Stop 3). The lower rhythmite becomes finer upward from gravelly sand to silt. Behind the middle of the hammer is cross-bedded sand that dips upvalley. The top of this rhythmite was eroded, and a flame structure (to the right of the hammer head) formed as the next Missoula flood rushed up the Tucannon River valley. The base of the upper rhythmite consists of sand and angular gravel.

called it "Kimooenim Creek". Col. George Wright constructed a temporary log fort here in August 1858; that site is probably now in the reservoir (Majors, 1975).

58.1 Start up a topographic feature locally called Midcanyon bar (Figs. 21 and 23) that is composed of gravel deposited by Missoula floods. This bar is covered by giant ripples whose asymmetry indicates flow eastward up the Snake River (Webster and others, 1976). Just to the left (southwest) above the railroad tracks is a banded (or tiered) flow of the Grande Ronde Basalt (Swanson and Wright, 1981).

60.5 Entrance to Lyons Ferry Marina. Continue northwest on State Route 261.

60.8 Leave Midcanyon bar; cross the Snake River. Enter Franklin County. To the north is the mouth of the Palouse River.

"Upstream along the Palouse River, approximately 2 miles from this point, was the Marmes Rockshelter. The Marmes Rockshelter archaeological site received worldwide attention in the spring of 1968 when human remains were discovered *in situ* 14 feet beneath the surface of the modern flood plain. These remains were established reliably as being at least 10,000 years old—[then] the oldest well-documented human remains in the New World. Numerous artifacts, cultural features and animal bones were associated directly with the human remains. Because the site was to be flooded by the impoundment behind Lower Monumental Dam in less than a year, emergency salvage excavations were begun in May 1968 and continued through February 1969 when the reservoir and the site were flooded. Marmes Rockshelter contains an unparalleled stratigraphic and cultural record spanning more than 10,000 years. It serves as a basis for comparison with most other sites in the Columbia Basin" (Webster and others, 1976, p. 18).

See reports by Fryxell and others (1968) and by Sheppard and others (1984) for more information about the Marmes Rockshelter (Figs. 21 and 24).

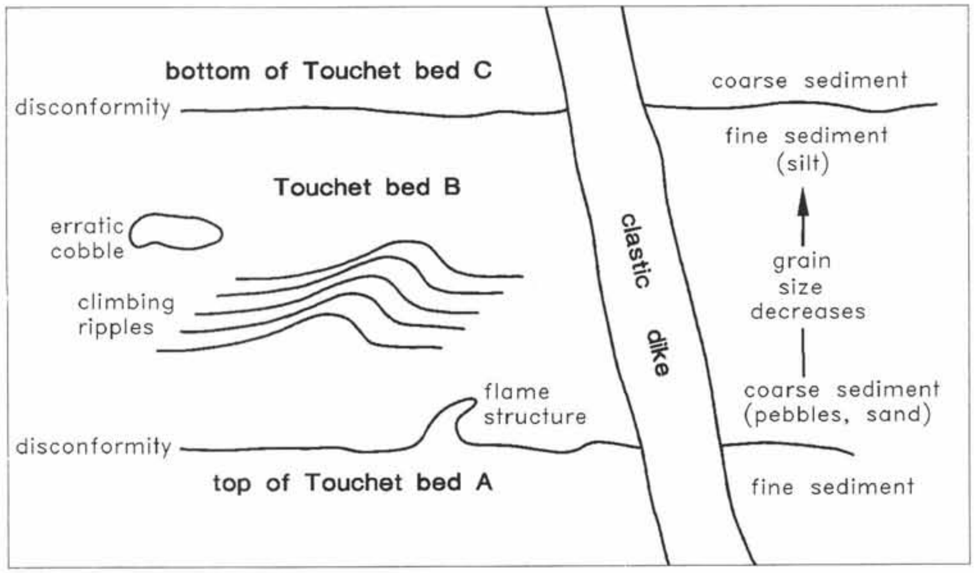

Figure 19. Some characteristics of the Touchet Beds. Shown is one complete Touchet bed separated from those above and below by erosional surfaces. All the beds are cut by a clastic dike that may have internal bedding.

Figure 20. View to the north across the Snake River at the mouth of the Tucannon River. Just right of center is a remnant of the Lower Monumental intracanyon flow. Just left of center (immediately to the right of the mouth of the Tucannon River) is an eddy bar deposited by the Missoula floods. On the far side of the Snake River is Great bar. (See Figure 21 for a map of this area.)

61.4 Entrance to Lyons Ferry State Park (rest area).

61.7 **STOP 4**: Park on the left (southwest) side of the road under the railroad bridge near the junction of the Palouse and Snake Rivers. (See Fig. 21.) The ancestral Palouse River ran west to the Pasco Basin down what is now called Washtucna Coulee (Fig. 6). Here may have been the mouth of a small south-flowing stream dissecting the east–west ridge between the Snake River and the ancestral Palouse River. About 25 of the Missoula floods overtopped the ridge, cutting a broad

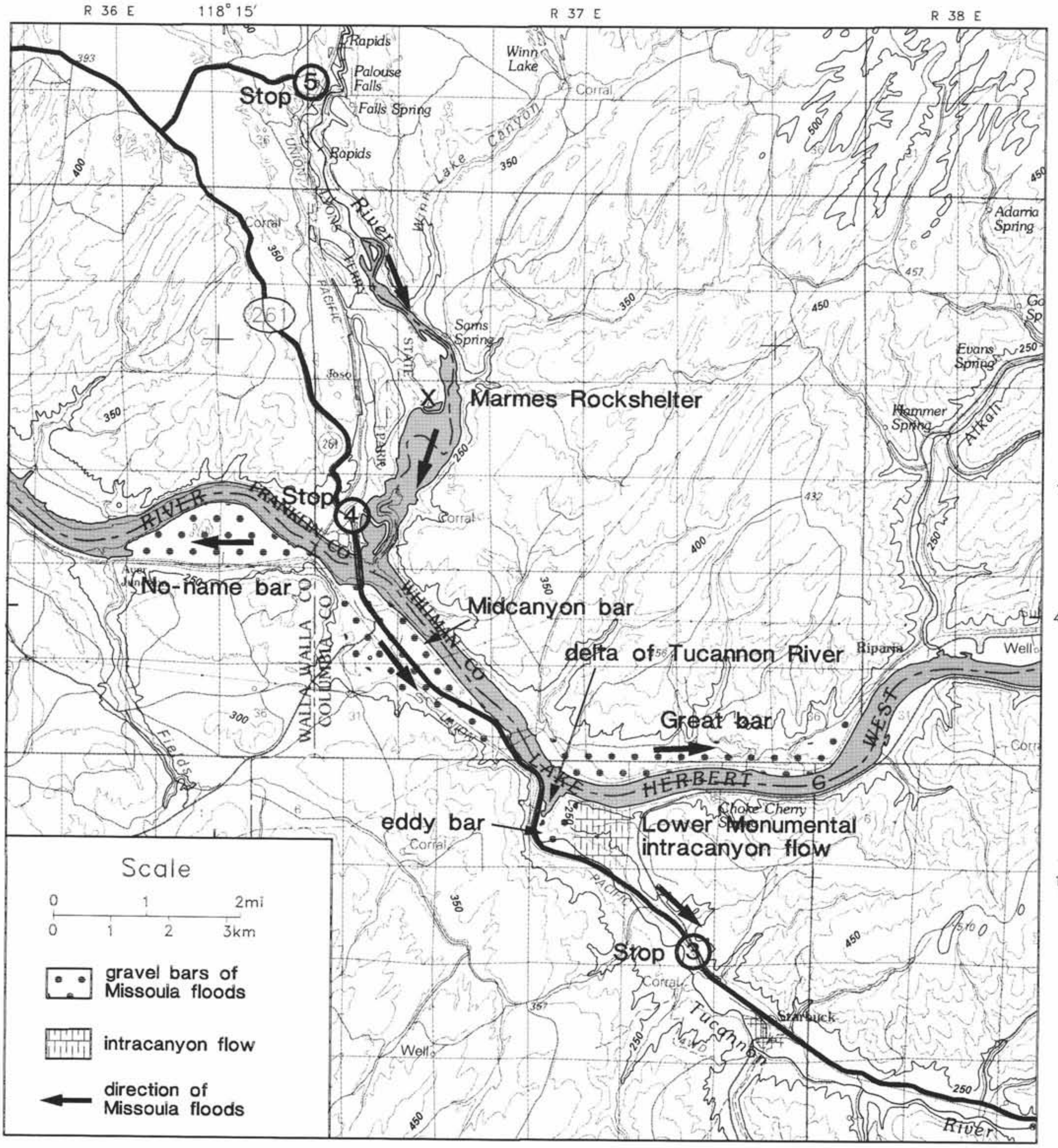

Figure 21. Part of the Starbuck 15-minute topographic map (1948). The dotted pattern indicates locations of gravel bars of Missoula floods; the arrows indicate direction of Missoula flood flow. (See Bretz, 1928b, fig. 6.)

north-to-south path including a narrow canyon now occupied by the modern Palouse River (Smith, 1993, p. 95). As each Missoula flood rushed south across the divide and down the original south-flowing stream, the water hit the basalt cliffs on the south side of the Snake River. Some of the floodwaters rushed west down the Snake River, depositing No-name gravel bar (Fig. 21). "The surface of the bar is covered with giant current ripples whose asymmetry clearly indicates flood flow down the Snake Valley" (Webster and others, 1976, p.17). The rest of the floodwaters rushed east up the Snake River, depositing Midcanyon Bar.

For details about gravel bars and current directions in this area, see Bretz and others (1956, p. 1020-1024), Bretz (1959, p. 41-46) and Waitt and others (1994, p. 55-58).

Many Missoula floods extended up the Snake River at least as far as Lewiston, Idaho (130 km upriver). The evidence for this is 20 or 21 Touchet Beds overlying Tammany Bar (located upstream from Lewiston on the Snake River); this gravel bar was deposited by the late Pleistocene flood from pluvial Lake Bonneville (Waitt, 1983, 1985) (Fig. 5).

Pluvial Lake Bonneville was a large freshwater lake that repeatedly formed in the general vicinity of its salty remnant, the Great Salt Lake of Utah (that has no outlet). Pluvial periods were somewhat cooler than today, and there was more precipitation and less evaporation. In the western United States, pluvial periods coincided with glaciations; that is, pluvial lakes were most extensive at about the same time as the maximum advances of the glaciers. Although Lake Bonneville formed during many pluvial periods, there is no evidence that it overflowed before about 15,000 years ago (Scott and others, 1983). The initial overflow from this huge lake caused rapid downcutting of about 100 m at Red Rock Pass in southeastern Idaho. The catastrophic Bonneville flood took place when much of the lake quickly drained, sending enormous volumes of water west and north across Idaho. For more information about the Bonneville floods, see reports by Malde (1968), Malde and O'Connor (1993), and Jarrett and Malde (1987).

Figure 22. View up the Snake River from southeast of Lyons Ferry. The basalt cliffs (right) are the upper part of the Grande Ronde Basalt. The mesa (above the person) is capped by an intracanyon lava flow, the Lower Monumental Member of the Saddle Mountains Basalt. Below the mesa is the mouth of the Tucannon River. Gravel bars deposited by the Missoula floods are visible. In the foreground is the southeast end of Midcanyon bar. Above the mouth of the Tucannon River is an eddy bar. On the north side (left, looking upriver) of this reservoir is Great bar.

Figure 23. View northwest along the Snake River. In the left center is the mouth of the Tucannon River. At the right (north) end of the two bridges in the distance is the mouth of the Palouse River. A remnant of the Lower Monumental intracanyon flow is in the lower left (below the mouth of the Tucannon River). There are two prominent gravel bars deposited by the Missoula floods: Great bar is in the right center on the north side of the Snake River, and Midcanyon bar is in the center (between the near and far bridges) on the south side of the Snake River. The Missoula floods were traveling toward the viewer. (See Figure 21 for a map of this area.)

The bedrock geology from here to the turnoff to Palouse Falls State Park consists of four units of the Columbia River Basalt Group. From river level to the approximate elevation of this stop are the upper flows of normal magnetic polarity (N_2) of the Grande Ronde Basalt (Fig. 3). Overlying the Grande Ronde Basalt are flows of (from oldest to youngest) the Frenchman Springs Member, the Roza Member, and the Priest Rapids Member of the Wanapum Basalt (Swanson and others, 1980).

Continue north on State Route 261. You soon enter scabland topography (Fig. 25). The area of eastern Washington eroded when glacial Lake Missoula's ice dam failed repeatedly is called the 'Channeled Scabland'. This term was first used in the early 1920s by J Harlen Bretz (e.g., Bretz, 1923, 1928c). The floods cut channels, called 'coulees', many with scour depressions. Most of the coulees are dry except for lakes in some scour depressions. The remnants of basalt flows left after the eroding floods drained away are called 'scabs'.

Bretz discovered half a dozen erosional features or characteristics of the Missoula floods (summarized in Allen and others, 1986, p. 98):

- Relative scarcity of loess below the flood crests
- Scabs—mesas and buttes formed as the floods plucked joint blocks from the Columbia River basalt
- Loess 'islands'—erosional remnants of loess that are streamlined in the direction of flood flow
- Channels—valleys that were widened and deepened by flood scour; in general these 'coulees' have steep (commonly vertical) walls
- Scour depressions in valley bottoms—closed depressions (that may contain permanent or intermittent lakes) formed where flood velocities were locally higher or the basalt was more easily eroded
- Braided or anastomosed pattern of channels—channels divide and reunite around the scabs and loess islands

Baker (1973a,b, 1978) classified the erosional and depositional landforms in the Channeled Scabland and described the processes by which the Missoula floods formed these features.

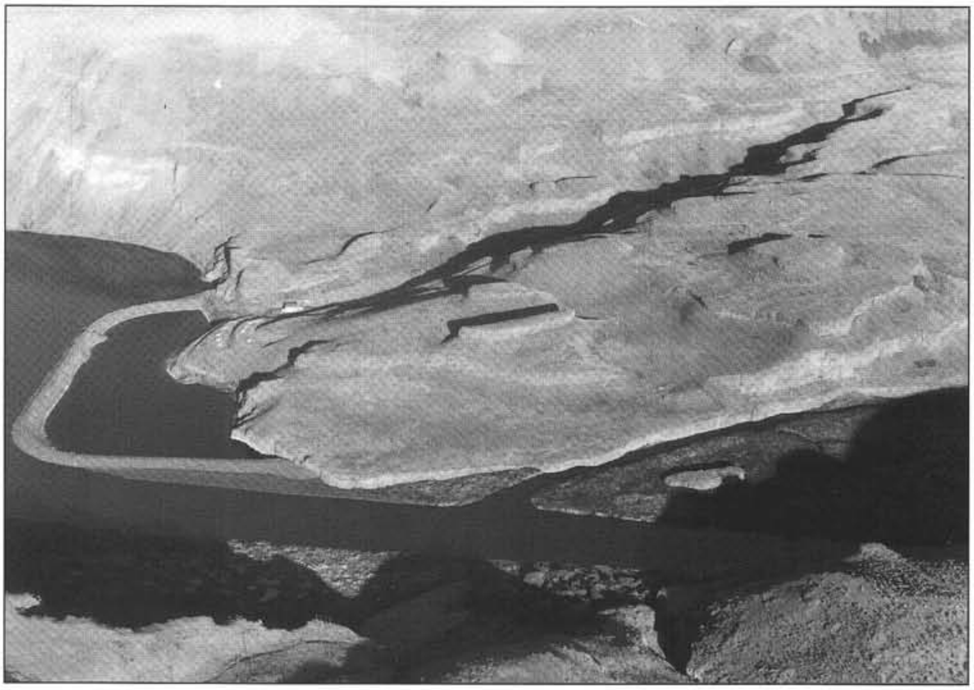

Figure 24. View to the west across the lower Palouse River. In the left center is the top of the dike built in an attempt to prevent flooding of the Marmes Rockshelter. The construction of Lower Monumental Dam downstream on the Snake River raised the level of the lower Palouse River. (See Figure 21 for the location of the rockshelter.)

Figure 25. View to the south along the lower Palouse River. In the background the Snake River flows from left to right. Erosional remnants of basalt are prominent in this part of the Channeled Scabland. The Missoula floods were traveling away from the viewer.

61.9 Small dune field to the west.

62.5 Small dune field to the east.

64.0 Loess 'islands' (Fig. 26) to the southwest. The long loess hills are aligned northeast and cover much of the broad path that the floods cut between the ancestral Palouse River and the Snake River. Bretz and others (1956) believed these hills were fluvially eroded; they thought the break-in-slope at the basalt/loess contact was the high-water mark. On the basis of high-water mark reconstruction, Baker (1973b) believed that the hills were not islands, that they were eroded subfluvially. Baker (1973a) calculated that water velocities averaged about 14 m/sec where flood waters were 30–60 m deep.

66.2 Turn right (northeast) to Palouse Falls State Park (elevation of the road intersection 1,281 ft). This is near the middle of a 12-km-wide flood channel, part of the Cheney–Palouse tract that stretches from Spokane to the Pasco Basin via Palouse Falls. This is the easternmost of various channels that carried floodwaters across eastern Washington. (Grand Coulee was another major channel to the west; see Fig. 6). The channel displays canyons cut along fracture sets, basalt scabs, and elongate loess 'islands'.

Most of the basalt boulders from here to Palouse Falls were bed load of the Missoula floods. Imagine the force of water (or discharge) needed to move these large rocks!

Lava flows between here and Palouse Falls are of the Roza and Frenchman Springs Members of the Wanapum Basalt.

On both sides of the road are tilled firebreaks.

Figure 26. Streamlined loess hills southwest of Palouse Falls State Park. The loess 'islands' are on the drainage divide between the ancestral Palouse River and the Snake River. The streamlined shape of these erosion remnants is due to the passage of the Missoula floods from the lower left (northwest) to the upper right (southwest). (See text for details.)

69.0 **STOP 5:** Palouse Falls (Figs. 21 and 27). The falls are 56 m high; the canyon below the falls is 377 ft (115 m) deep. There are four lava flows exposed in the canyon walls, and more in the distance (Figs. 28 and 29 and cover photo). The upper flow in the canyon walls is the Ginkgo flow of the Frenchman Springs Member (Wanapum Basalt; about 15.5 Ma) (S. P. Reidel, Westinghouse Hanford Co., oral commun., 1993). The thick upper flow is chiefly an entablature of small irregular columns; its basal colonnade has been eroded into a 'picket fence' or 'organ pipes' just above and to the left of the falls. The lip of the falls is carved into the second flow down, the Palouse Falls flow of the Frenchman Springs Member (Swanson and Wright, 1981). The two lowest flows are part of the Sentinel Bluffs unit of the Grande Ronde Basalt (S. P. Reidel, oral commun., 1993). The third flow down has an easily distinguished upper entablature and a lower colonnade. The lowest flow is thick and extends below the water level of Palouse Falls' deep plunge pool.

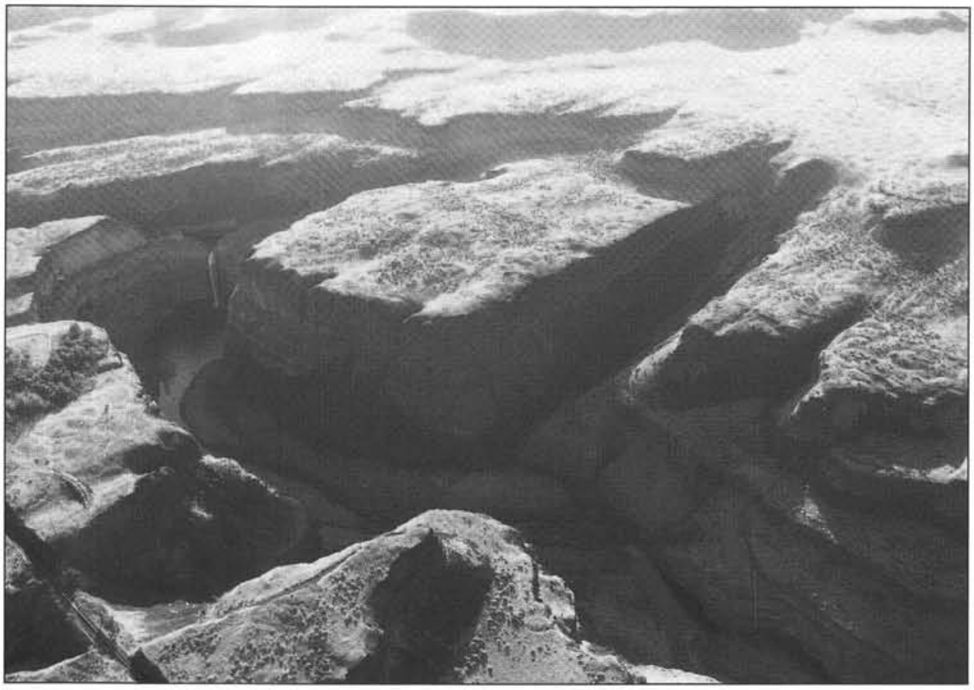

Figure 27. The canyon of the Palouse River. Palouse Falls (56 m high) is visible in the upper left. Passage of the Missoula floods (toward the viewer) resulted in erosion of the basalts, particularly along fractures. The resulting angular drainage pattern is clear in this view. (The linear feature in the lower left is a railroad cut.)

Between the Palouse Falls flow and the Ginkgo flow is an unnamed interbed that is exposed just upriver from Palouse Falls (see Fig. 3). It appears to be the filling of an ancient shallow lake. The 1-m-thick sediments include ash, peat, and sand (Swanson and Wright, 1976).

Notice the angular drainage pattern (Fig. 27) in this area. The Palouse River and other flood-excavated canyons follow fracture sets (faults or joints) striking approximately N50°E, N20°W, and N55°W.

In 1984, the Franklin County Public Utilities District proposed that a 30-m-high concrete dam be constructed just upstream of Palouse Falls. The 9-km-long reservoir would have supplied water to conduits leading 0.6 km downstream to a powerhouse. This hydroelectric facility would have provided as much as one-third of the power used by the county. However, the majority of the ratepayers did not want the PUD to fund a feasibility study, so the commissioners decided against the dam. (Articles about this dam can be found in the April 20 and October 21, 1984, editions of the *Walla Walla Union-Bulletin*.)

Return to State Route 261 to start the next leg of the trip.

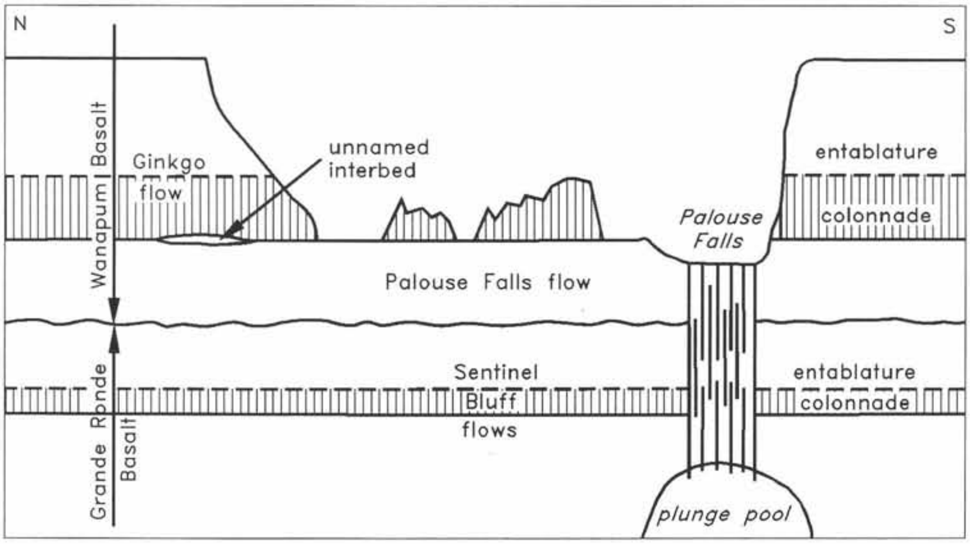

Figure 28. Geologic cross section at Palouse Falls.

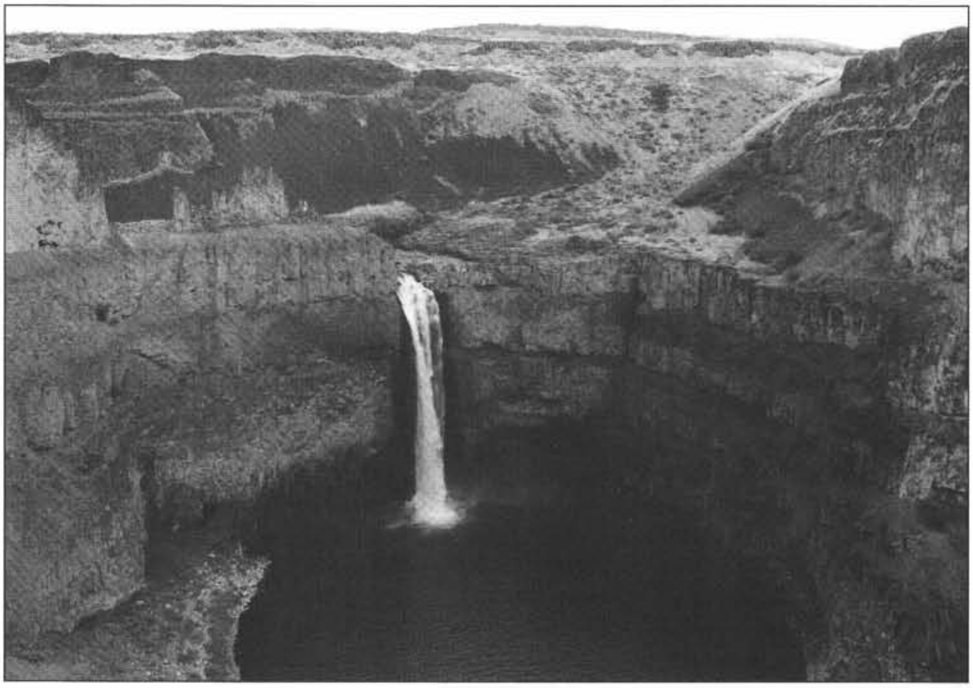

Figure 29. Palouse Falls (Stop 5). The Palouse River plummets 56 m into a plunge pool. See Figure 28 for the basalt stratigraphy here. Notice the talus that has accumulated at the bases of the cliffs since the passage of the last Missoula floods about 12,700 years ago.

PART 2 – PALOUSE FALLS TO LOWER MONUMENTAL DAM

Miles

71.4 Turn northwest on State Route 261. Elongate loess 'islands' can be seen to the southwest.

74.6 HU Ranch. Roadcuts to the east and west expose the Roza and Frenchman Springs Members of the Wanapum Basalt (Swanson and Wright, 1981).

To the south is a cataract at the head of HU or Davin Canyon (Figs. 6 and 30). Before the Missoula floods, there was probably a small stream here flowing south to the Snake River. When the Missoula floods overtopped the south valley wall of the ancestral Palouse River and crossed the divide to the Snake River, they excavated HU or Davin Canyon. It is likely that during each flood the waterfall at the head of the coulee retreated farther north. Today the cataract is a 'dry falls' (like the classic one between Upper and Lower Grand Coulee) except for a tiny waterfall on the northeast rim. Cataract retreat was a common result of erosion of the Columbia River basalts by the Missoula floods. Each flood washed basalt columns and blocks bounded by joints away from the lava flows, causing the waterfalls to 'retreat' upstream. This migration resulted in lengthening of the coulees below the falls.

75.6 Cross the west margin of the Cheney–Palouse tract of the Channeled Scabland. Enter a portion of the Palouse Hills bounded by the Cheney–Palouse tract on the east, Washtucna Coulee on the north, Devils Canyon on the west, and the Snake River on the south. The Palouse Hills are underlain by thick loess deposits. This part of the Palouse Hills is at about the same elevation as the maximum water levels of the Missoula floods. Although most of the floodwater went around this area, some of the water probably crossed it.

78.8 to 78.9 Mazama ash is exposed in cuts on the southwest side of the road. A thin blanket of ash fell in this area during the catastrophic eruption of Mount Mazama volcano at what is now Crater Lake about 6,845 years ago (Bacon, 1983). The ash washed off the Palouse Hills and filled gullies, where it is preserved.

80.0 Junction of State Routes 260 and 261 (elevation 964 ft). The abandoned railroad stops and (or) towns called Sperry and McAdam are at this location.

Turn left (southwest) down Washtucna Coulee (Fig. 6). This dry valley was the course of the ancestral Palouse River to the Pasco Basin. Between here and Kahlotus, the highest continuous basalt flow along the coulee walls is the Roza Member of the Wanapum Basalt. Above it are discontinuous exposures of the Priest Rapids Member, the youngest unit of the Wanapum Basalt (Swanson and Wright, 1981). In places loess is visible at the top of the coulee walls.

84.4 to 85.2 Near Harder and Wacota, the ancestral Palouse River made a meander, swinging first northwest and then southeast. The two meander loops became eddies when Missoula floods rushed southwest along Washtucna Coulee. Whereas many giant gravel bars are on the insides of bends, gravel bars here are on the outsides of the meander loops (Figs. 31 and 32).

86.4 Lake Kahlotus, also called Washtucna Lake, is a scour depression on the floor of Washtucna Coulee. Note that the Missoula floods left a scab or erosional remnant of basalt; this is an island in the spring when the water table is high enough for the intermittent lake to exist.

87.6 Enter Kahlotus, a boom town while Lower Monumental Dam was under construction in the 1960s.

88.0 In Kahlotus (elevation 901 ft), turn left (south) toward Windust, Pasco, and Lower Monumental Dam.

88.4 Leave Kahlotus and Washtucna Coulee.

88.7 Part way up the hill, turn left (south) toward Lower Monumental Dam and enter Devils Canyon (Figs. 6 and 33). This is the third (and westernmost) place where the Missoula floods jumped the divide between the ancestral Palouse River and the Snake River. As in the mod-

Figure 30. View southwest of the Channeled Scabland at the head of HU or Davin Canyon. The linear features are fractures that were eroded by the passage of the Missoula floods (traveling away from the viewer). HU or Davin Canyon extends from right center toward the upper center. (See text for details.)

ern canyon of the Palouse River and dry HU Coulee, there most likely was a small intermittent stream flowing south to the Snake River. The Missoula floods turned it into a northward-retreating waterfall or cataract as the coulee of Devils Canyon was eroded. The sides of Devils Canyon are composed almost entirely of lava flows of the Frenchman Springs Member of the Wanapum Basalt. However, at the top of the east side is the Roza Member, and at the top of the west side are both the Roza and Priest Rapids Members of the Wanapum Basalt (Swanson and others, 1980).

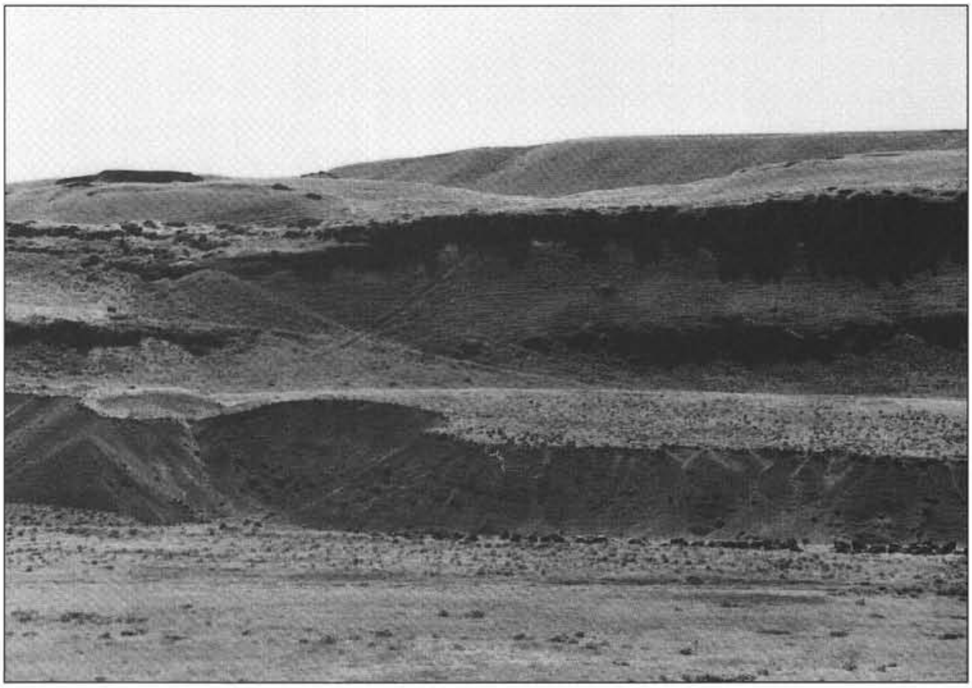

Figure 31. Gravel bar on the floor of Washtucna Coulee northeast of Kahlotus. The gravel bar (approximately 10 m high) is on the outside of a bend on the south side of the coulee. The Missoula floods tried to straighten this bend, so deposition occurred in an eddy. Behind the gravel bar are lava flows of the Wanapum Basalt. The distant ridge is composed of Quaternary loess. This is the southwestern of the two gravel bars at this meander.

91.7 **STOP 6:** Superimposed intracanyon basalt flows in Devils Canyon (Figs. 34 and 35). This was the course of the ancestral Clearwater–Salmon River from more than 12.5 m.y. ago until about 10.5 m.y. ago. Notice the Frenchman Springs flows (averaging about 15 m thick, with mostly vertical columnar joints) exposed to north and south along the canyon walls. Contrast them with thicker (varied but on the order of 50 m thick) intracanyon flows that have columnar joints oriented in many directions.

The ancestral Clearwater–Salmon River flowed from central Idaho to south-central Washington where it joined the ancestral Columbia River (Fecht and others, 1987).

Figure 32. View to the southwest of Washtucna Coulee at the location of a meander along the ancestral Palouse River. In the lower right is a gravel bar deposited by the Missoula floods (traveling away from the viewer) on the outside of the meander. This is the northeastern of two gravel bars, each with a gravel pit (right center). The partial circle in the distance is a field with center-pivot irrigation.

"From this vantage point, we can see an impressive natural cross-section through portions of three different Saddle Mountains Basalt flows that flowed down the canyon cut by the ancestral Salmon–Clearwater River between 14 and 10.5 Ma....The earliest two flows (Esquatzel Member, massive entablature, northern-third of the exposure; Pomona Member, curved columns, southern two-thirds of the exposure) did not fill the canyon and allowed the river to reoccupy it after these flows were emplaced. At about 10.5 Ma, the Elephant Mountain Member was emplaced (uppermost entablature/colonnade that unconformably lies upon the Esquatzel and Pomona flows) and was voluminous enough to fill and obliterate this canyon of the ancestral Salmon–Clearwater River..." (Reidel and others, 1994, p. 14).

After the Elephant Mountain intracanyon flow filled the west-trending canyon 10.5 m.y. ago, the ancestral Clearwater–Salmon River cut a new course 3 km to the south. At Stop 7A on the south side of the Snake River is exposed a younger intracanyon flow. All intracanyon flows here belong to the Saddle Mountains Basalt.

Continue south toward Lower Monumental Dam.

93.1 The basalt scabs on the floor of Devils Canyon are remnants of the Frenchman Springs Member.

93.3 A gravel bar deposited by the Missoula floods blocks the mouth of Devils Canyon (Fig. 33). Bretz (1928b, p. 662-663) stated that:

"a large deposit of poorly worn basaltic material was built a quarter of a mile out into Snake River canyon from the mouth of this trench. The deposit has no really definitive shape and no significant altitude, but it constitutes (or did constitute) a complete barrier 50 feet high in the middle of Devils Canyon, and its form, position, and composition indicate its origin in a flooded Snake River Valley by a large and vigorous stream through Devils Canyon."

Figure 33. View of Devils Canyon and the north shore of the Snake River, just upstream of Lower Monumental Dam. Devils Canyon is a deep coulee eroded by the Missoula floods. The bluffs (right) above the Snake River shoreline expose Wanapum Basalt. The small hills in the center (one on either side of the Devils Canyon) are intracanyon flows of the Saddle Mountains Basalt. In the distance is Washtucna Coulee, the ancestral course of the Palouse River. The Missoula floods traveled from right to left along Washtucna Coulee and toward the viewer down Devils Canyon. The gravel bar in the lower left was deposited by the Missoula floods. On the uplands on both sides of the canyon is Quaternary loess; the upland areas here were not eroded by the Missoula floods because they are higher than the highest floodwater level.

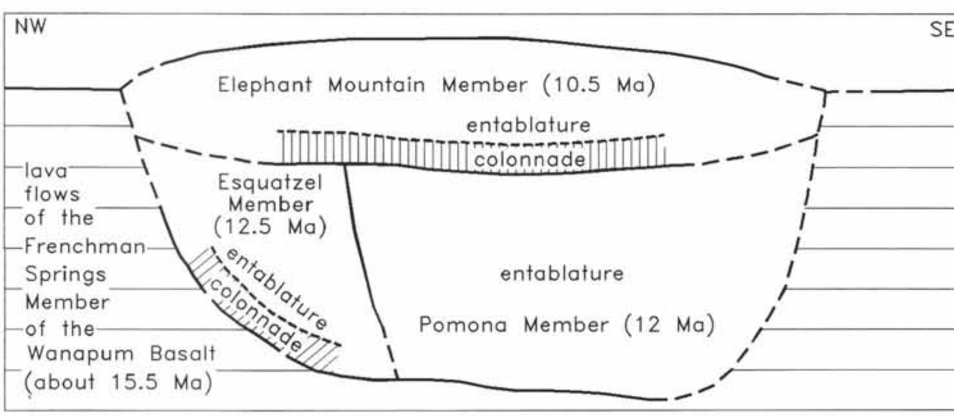

Figure 34. Intracanyon flows on the east side of Devils Canyon. The three are members of the Saddle Mountains Basalt.

93.9 Junction of the northwest end of Lower Monumental Dam with the road along northwest side of Snake River.

Exposed just north of this junction at about eye level is the unconformity between the Grande Ronde Basalt and the Frenchman Springs Member of the Wanapum Basalt (Fig. 36). There are radiometric age estimates of 15.6 Ma for upper flows of the Grande Ronde Basalt and 15.5 Ma for the Ginkgo flow of the Frenchman Springs Member (Campbell and Reidel, 1991), so this disconformity represents only a short time hiatus. The oxidized top of the Grande Ronde Basalt is the same incipient residual soil that we saw at Stop 2 (Swanson and Wright, 1981).

Turn left (southeast) and cross the dam (daylight hours only). From north to south, on Lower Monumental Dam (Fig. 37) note the fishway bypass, the fish ladder, the powerhouse, the spillways, another fish ladder, and the lock. The normal pool elevations of the reservoirs below and above the dam are 440 ft and 540 ft, respectively. (Miklancic, 1989c, summarized the geological and engineering aspects of this dam.)

94.6 Southeast end of Lower Monumental Dam (rest rooms). Turn right (southwest) on Lower Monumental Road and proceed under the railroad tracks.

95.3 **STOP 7A:** Lower Monumental intracanyon flow on the southeast side of the Snake River (Figs. 36–38). At 6 Ma, this is the youngest lava flow in the Columbia River Basalt Group. It can be traced as far east as Asotin (Swanson and Wright, 1981), 167 km up the Snake River from here. The intracanyon flow overlies fluvial gravels consisting of basalt, quartzite, metavolcanic rocks, and a few plutonic rocks (Swanson and Wright, 1976) (Fig. 38). Cross-beds dip to the southwest. After its channel to the northwest (Stop 6) was filled by flows of the Elephant Mountain Member of the Saddle Mountains Basalt, the ancestral Salmon–Clearwater river shifted south to this position and cut a new canyon in the Wanapum Basalt. The river deposited these gravels before the channel was filled by the intracanyon flow 6 m.y. ago. Subsequently, the Salmon–Clearwater river cut the channel now occupied by the Snake River. About 2 m.y. ago (in the late Pliocene or early Pleistocene), a tributary to the Salmon River captured the Snake River (Fecht and others, 1987); one result was the carving of Hells Canyon by the Snake River.

Continue south along Lower Monumental Road, which winds up the hill. Above the Lower Monumental intracanyon flow is a large eddy bar deposited by the Missoula floods.

95.7 Road intersection (elevation 808 ft). To the left (northeast) is the Lower Monumental airstrip. To the right (southwest) is a gravel pit in the lower part of the Missoula floods eddy bar. Continue uphill on Lower Monumental Road.

96.0 **STOP 7B:** Missoula floods eddy bar at the intersection of Lower Monumental Road and Matthew Road. Park at this intersection. To the east is a gravel pit in the eddy bar (Fig. 37). There are giant cross-beds composed mostly of sand and pebbles, with some silty layers; the trough cross-bedding dips 10° to 35° with the trough axes plunging easterly (Ryan Ott and Pat Spencer, Whitman College, written commun., 1995). In the west wall of the gravel pit Holocene fluvial (and eolian?) sediments, including Mazama ash, overlie the deposits of the Missoula floods. The Mazama ash is about 6,845 years old (Bacon, 1983). (See Stop 12 for details.)

Walk west along Matthew Road though giant ripple marks (Fig. 37). Roadcuts at the crest of each ripple reveal that the 'gravel' is mostly coarse sand, granules, and pebbles. The 'gravel' is overlain by approximately 1 m of loess.

Figure 35. Three intracanyon lava flows on the west side of Devils Canyon (Stop 6). The relations are complex, but the thin colonnades at the bases of the upper right and upper left flows are visible. See text for details. The cliff is approximately 60 m high.

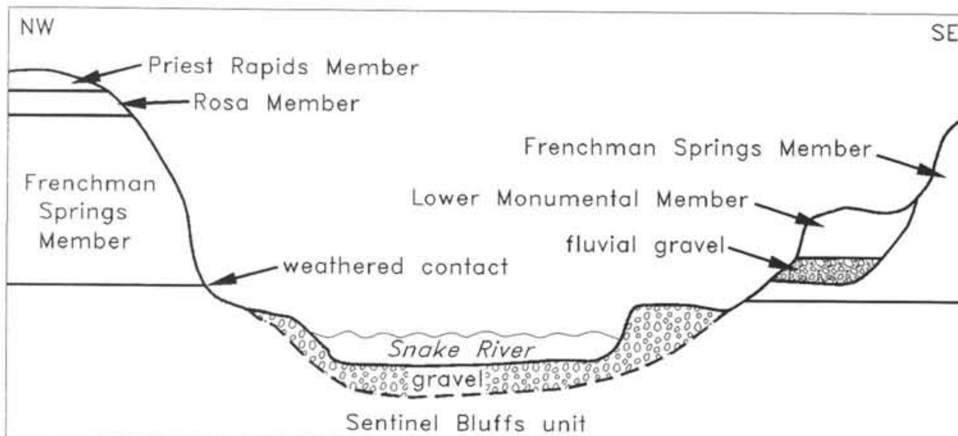

Figure 36. Geologic cross section near Lower Monumental Dam (view upriver). Basalt flows here belong to the Sentinel Bluffs unit of the Grande Ronde Basalt; the Frenchman Springs, Roza, and Priest Rapids Members of the Wanapum Basalt; and the Lower Monumental Member of the Saddle Mountains Basalt. The weathered contact at the top of the Grande Ronde Basalt is exposed next to the road junction northwest of the dam. The Lower Monumental intracanyon flow and the underlying gravels of the ancestral Salmon–Clearwater river are exposed in a roadcut south of the dam.

The giant ripple marks are arcuate, convex toward the northeast (Fig. 37). The eddy bar was deposited by an upstream current of the Missoula floods. The fact that this eddy bar consists of fairly fine sediment can be explained in two ways: (1) the upstream eddy had a lower velocity than the main current of the Missoula floods, and (2) the eddy bar is higher in elevation than nearby gravel bars.

Baker (1978, p. 95-96) summarized the characteristics of eddy bars deposited along the routes of Missoula floods. They occur in alcoves along the sides of valleys and in the mouths of tributary valleys. Grain sizes and sedimentary structures within eddy bars are varied. The amount of dip of the beds and the dip direction are also varied. The variation is due to the velocity of the currents that deposited the bars. "The stronger currents carried the coarsest flood debris up the tributary valley. Weaker back-flow currents then deposited the finer granule gravels" (Baker, 1978, p. 86).

Baker (1978, p. 86) goes on to state "that giant current ripples are never associated with eddy bars." This eddy bar is an exception. These giant ripple marks have amplitudes of approximately 1–4 m; however, in places the troughs have been accentuated by gullying. At about 50–60 m, their wave lengths are shorter than the wave lengths of the giant current ripples on most Missoula floods gravel bars.

North of Matthew Road is another gravel pit (approximately 1 km west of the eastern gravel pit) (Fig. 37). The gravel is mostly basaltic pebbles and cobbles, with one lens of silt. There are large cross-beds dipping in different directions. This western gravel pit is about 50 m lower in elevation than the eastern gravel pit and the eastern end of Matthew Road. These coarser gravels could be part of a different Missoula-floods gravel bar.

Return to and cross Lower Monumental Dam and begin the third leg of the trip.

Figure 37. View north toward Lower Monumental Dam. The cliff facing the river (between the dam and the runway) is the northwest edge of the Lower Monumental intracanyon flow, the youngest flow of the Columbia River basalts. The gravel pit in the right center is in an eddy bar deposited by the Missoula floods, which, in general, were traveling down the Snake River from Palouse Falls toward the Pasco Basin. The giant ripple marks (between right center and lower center) were deposited in an upstream eddy.

Figure 38. Basalt flow overlying gravels south of Lower Monumental Dam (Stop 7). The quartzite-rich gravels were deposited by the ancestral Salmon-Clearwater River and then covered by the Lower Monumental intracanyon flow. There is some brecciation of the base of the lava flow behind the hammer.

PART 3 - LOWER MONUMENTAL DAM TO ICE HARBOR DAM

Miles

98.1 Northwest end of Lower Monumental Dam. Turn southwest toward Windust.

98.3 Entrance to Lower Monumental Dam visitor parking lot. The visitor area is open April 1 through October 31 for self-guided tours of the fish-viewing window and the powerhouse. (The visitor area has rest rooms.)

Continue southwest along the northwest edge of Lake Sacajawea, the reservoir impounded by Ice Harbor Dam, 50 km farther down the Snake River. Across the Snake River is a gravel bar deposited by the Missoula floods.

100.9 East entrance to Windust Park (rest rooms). Continue west along the north side of the Snake River.

The Lewis and Clark Expedition camped just downriver of Windust Park in October 1805 (Majors, 1975).

On the opposite side of the Snake River is the northeast end of the Scott gravel bar (Fig. 39), which extends 9 km along the southeast side of the river. As much as 6 m of gravel (largest boulder 1 m in diameter) are exposed in railroad cuts in the giant ripple marks on the Scott bar. In places there are 2 m of slackwater sediments overlying the gravels, with perhaps a dozen Touchet Beds exposed. This stratigraphic relation suggests that the last dozen Missoula floods were going *up* the Snake River at this location; if true, the last Missoula floods did not descend the Cheney–Palouse tract, but reached the Pasco Basin only by other routes. The flood gravels and Touchet Beds are capped by 1 m of loess. The ripple marks have a wave length of approximately 150 m; their amplitude of 6-8 m has been accentuated by gullying of the troughs.

103.7 Leave the Snake River. Turn right (northwest) under a railroad bridge.

103.8 On the southwest side of the road are sediments deposited by the Missoula floods in the eddy that existed at the mouth of Burr Canyon.

104.7 Exposures of Touchet Beds, the slackwater sand and silt deposited by the Missoula floods.

106.4 Turn left (southwest) onto the Kahlotus–Pasco highway (elevation 1,215 ft). Drive southwest through a portion of the Palouse Hills, which are underlain by Quaternary loess as much as 75 m thick. Kahlotus is about 20 km to the right (northeast).

108.6, 115.2 Crests of hills (elevations about 1,420 ft and 1,195 ft, respectively). Visible in the distance to the southeast is the crest of the Blue Mountains anticline, a northeast-trending uplift of Miocene basalt flows. To the south and southwest are hills along the Olympic–Wallowa lineament (OWL).

Also visible to the southwest from mile 107.2, and present only 2 km west of mile 113.8, are the Juniper Dunes (Figs. 40–43). The Juniper Dunes Wilderness is administered by the Spokane District of the Bureau of Land Management. Information about the Juniper Dunes and a permit to visit this area can be obtained from the Bureau (East 4217 Main Ave., Spokane, WA 99202, phone (509) 353-2570). The wilderness area is 'landlocked' in that access is across private lands. Permission to cross private land must be obtained in advance from the landowner.

Much of the dune field was made a wilderness in 1984; land uses (sometimes in conflict) of the Juniper Dunes include wildlife habitat, agriculture, nonmotorized recreation, and off-road vehicle activity. The dunes support grasses, shrubs, and western juniper trees (*Juniperus occidentalis*).

Much of the Juniper Dunes is characterized by transverse dunes (Figs. 41 and 42), which form where there are fairly large supplies of sand. Slip faces of these dunes are oriented northwest and are a maximum of 40 m high. The sources of the sand are in the Pasco Basin: the Pliocene Ringold Formation (Newcomb, 1958), Pleistocene glaciofluvial sediments (including the Touchet Beds), and Holocene alluvium.

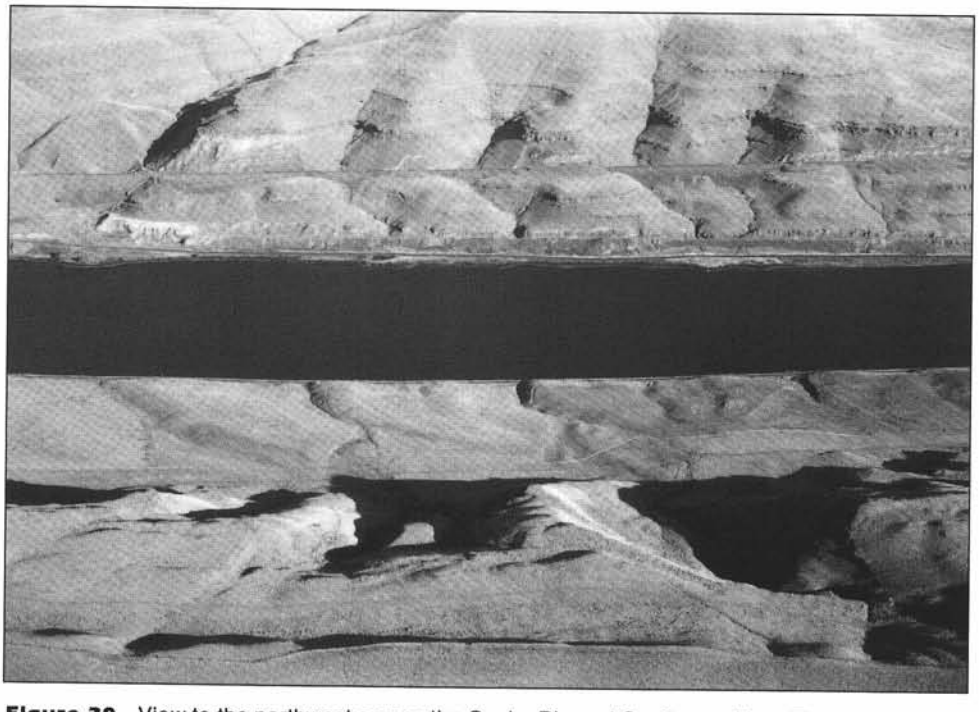

Figure 39. View to the northwest across the Snake River at Scott gravel bar. The Snake River, which flows from right to left, has cut through lava flows of the Wanapum Basalt. On the near (southeast) side of the river is Scott gravel bar, deposited by the Missoula floods. The troughs of the giant ripple marks have been accentuated by gullying. (See text for details.)

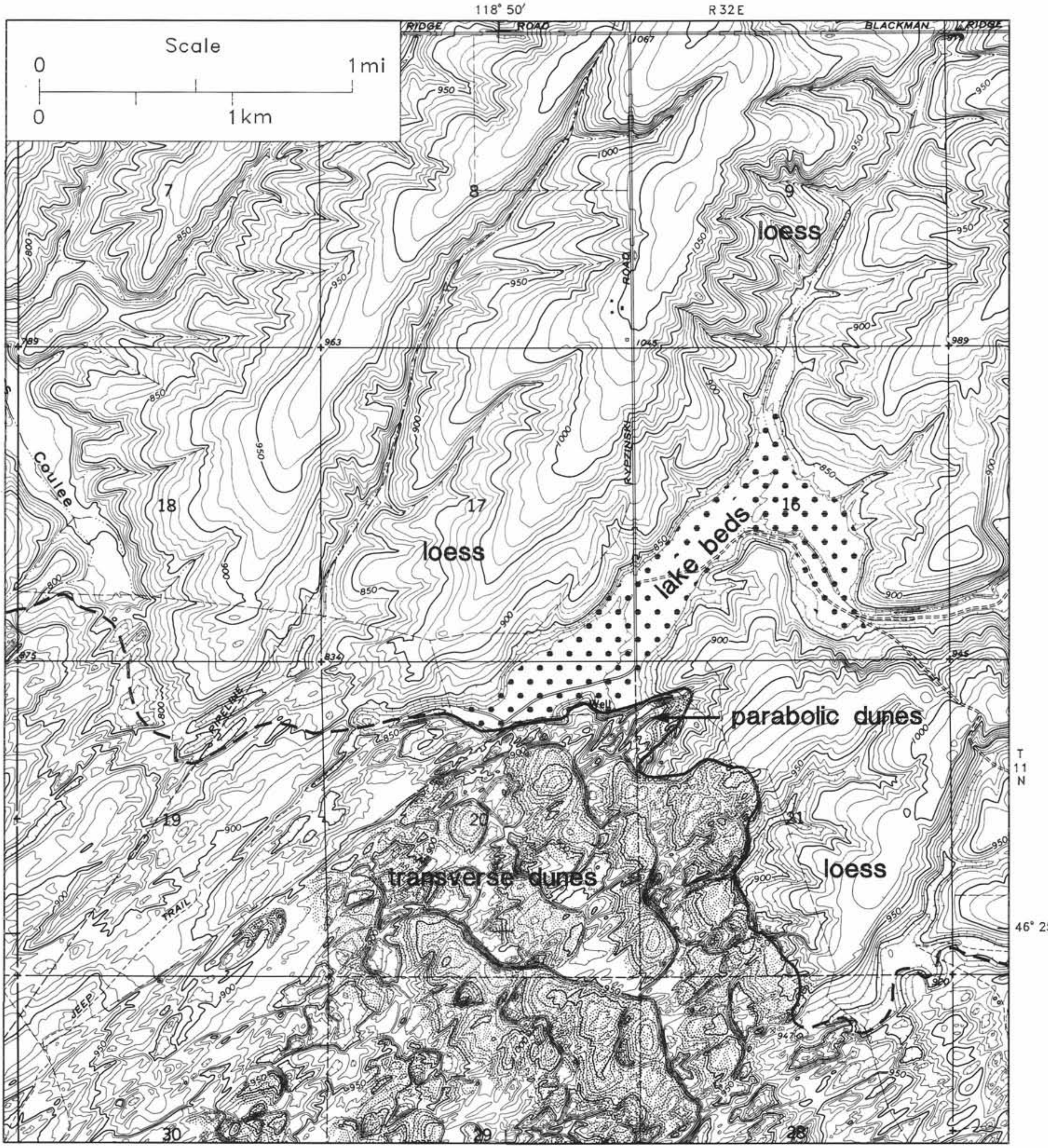

Figure 40. Part of the Levey NW 7.5-minute topographic map (1964 edition) showing surficial geology at the leading edge of the Juniper Dunes. Intermittent lakes form where intermittent streams flowing southwest from the Palouse Hills are blocked by northeast-migrating Juniper Dunes. The higher areas of the Palouse Hills are composed of loess, but in lower places, there may also be Missoula flood deposits. Note that the topography here is below the 1,200-ft elevation reached by the Missoula floods at Wallula Gap. Before this area was invaded by the Juniper Dunes, it was overtopped by Missoula floods. In addition to loess here, there are Touchet Beds with clastic dikes and erratic clasts.

At the leeward (north-northeast portion) of the Juniper Dunes are overlapping parabolic dunes (Fig. 43). One advancing parabolic dune has buried an old fence. Parabolic dunes have horns that point upwind and form on either side of a blowout or hollow created when an unstable portion of the dune migrates downwind (Cooke and Warren, 1973). In general there is more vegetation stabilizing the parabolic dunes; large parts of the transverse dunes are completely free of vegetation.

The orientation and asymmetry of the transverse and parabolic dunes reflect the prevailing southwesterly winds. During occasional periods of sustained northerly winds, the transverse dunes become reversing dunes—sand blown up the large slip faces forms crests with south-facing slip faces. The ripple mark asymmetry reveals the direction of the most recent wind strong enough to move the sand. Occasionally the right wind and moisture conditions reveal the giant cross beds inside the dunes.

Along the leading (northeast) edge of the Juniper Dunes, intermittent streams flowing southwest from the Palouse Hills have been blocked by the advancing dunes (Fig. 40). Fine sediment underlies the flat floors of the intermittent lakes.

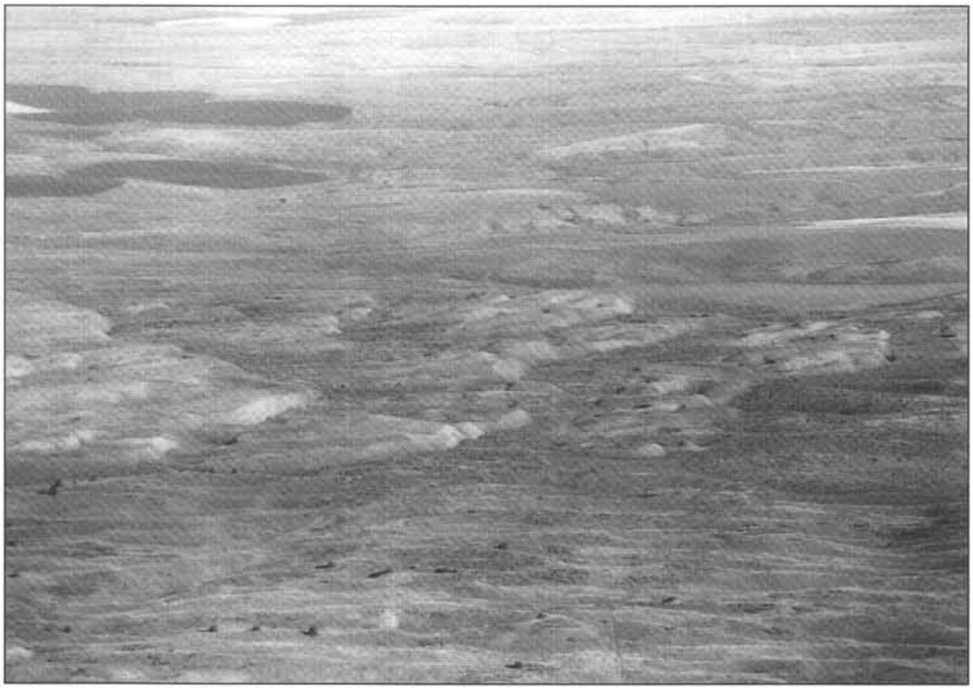

Figure 41. View westerly of the northern portion of the Juniper Dunes. The slip faces of the transverse dunes face northeast in the direction of slow migration (from left to right). See text for details. The dark areas in the upper left are irrigated fields.

116.2 to 117.5 Roadcuts in Quaternary loess. Our route is southwesterly into the Pasco Basin, which is structurally and topographically lower than the Palouse Hills to the northeast and the anticlinal ridges to the south. The Missoula floods were hydraulically ponded by the constriction of Wallula Gap where the Columbia River leaves the Pasco Basin. The highest hydraulic lake surface was at an elevation of about 366 m (1,200 ft) (O'Connor and Waitt, 1994, p. 38). Because the elevations here are only 1,100 to 900 ft, we are lower than the maximum elevations of the floods. There has been reworking of the top of the loess, and some erratics are present.

120.4 Intersection with Murphy Road (elevation 797 ft). Continue south on the Kahlotus–Pasco highway. Vegetation subdues the dunes just to the northwest. This is the southeast edge of the Juniper Dunes. The dune field has an area of about 130 km^2.

125.3 Intersection with Levey Road (elevation 700 ft). Continue west on the Kahlotus–Pasco highway. The geological materials underlying this 'terrace' between the Juniper Dunes and the Snake River can be viewed by turning left (southeast) on Levey Road. Nearby is a gravel pit with excavations in Missoula flood deposits. Beneath the late Pleistocene sediments, basalt forms a cliff facing the Snake River. The flows here belong to the Frenchman Springs Member of the Wanapum Basalt and the Pomona and Elephant Mountain Members of the Saddle Mountains Basalt (Swanson and others,

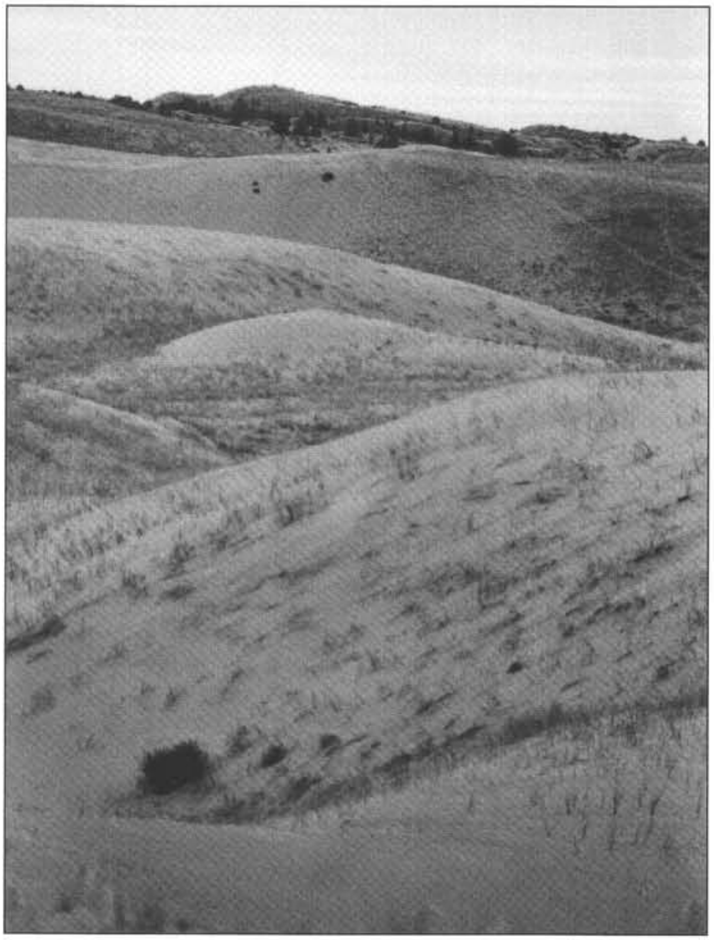

Figure 42. View upwind (southwest) of transverse dunes, Juniper Dunes Wilderness. The maximum slip-face height is 40 m. Note the relative lack of vegetation, except for the juniper trees in the distance.

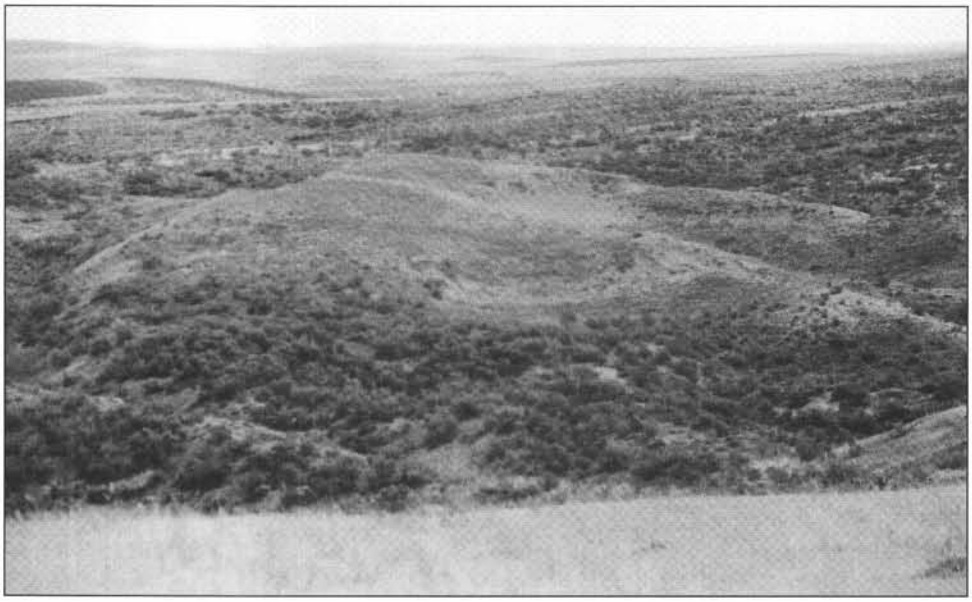

Figure 43. View downwind (northeast) of parabolic dunes at the leading edge of Juniper Dunes. One parabolic dune overlaps another. These dunes support considerable vegetation, particularly sagebrush. In the foreground is the crest of a transverse dune. In the background are the Palouse Hills of Quaternary loess.

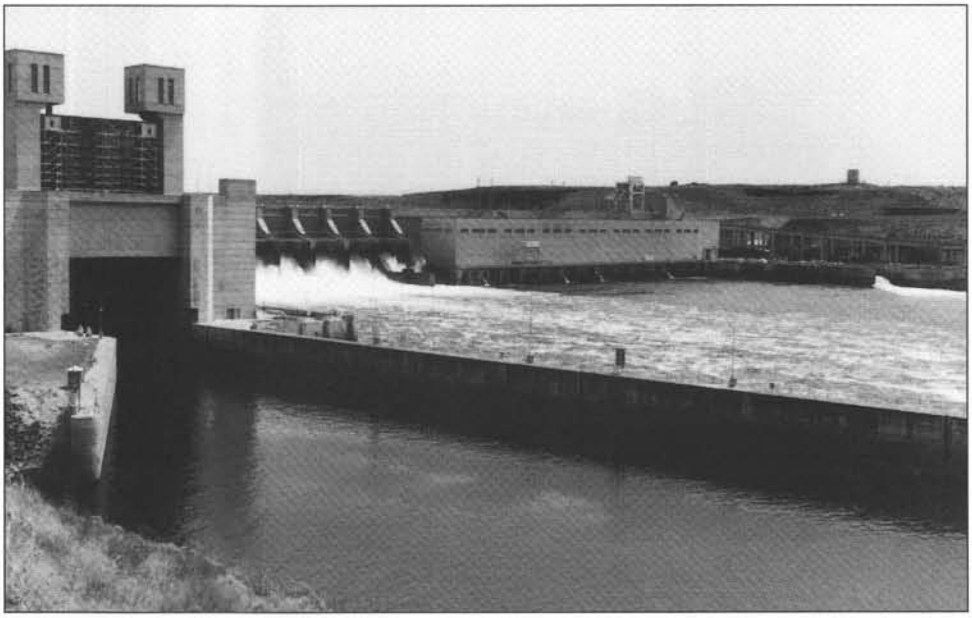

Figure 44. Ice Harbor Dam, Snake River (Stops 8 and 9). This view toward the east shows (from left to right) the lock, spillway, powerhouse, and south fish ladder.

Figure 45. View down (west) the Snake River at Ice Harbor Dam. The powerhouse, spillways, and lock are visible from left to right.

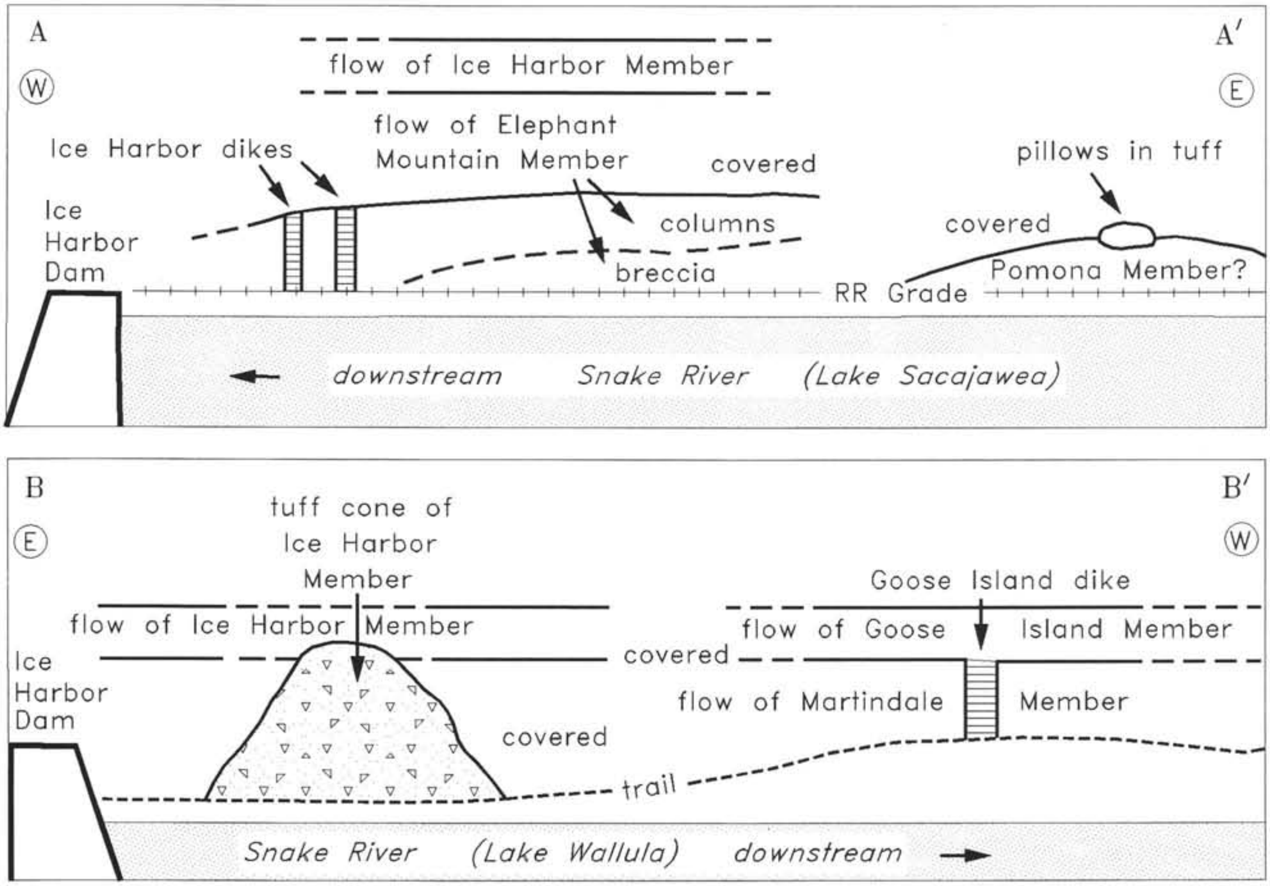

Figure 46. Diagrammatic cross sections of the basalts in the vicinity of Ice Harbor Dam. A–A′, Stop 8, upstream of the dam, north shore; B–B′, Stop 9, downstream of the dam, south shore. See text for details.

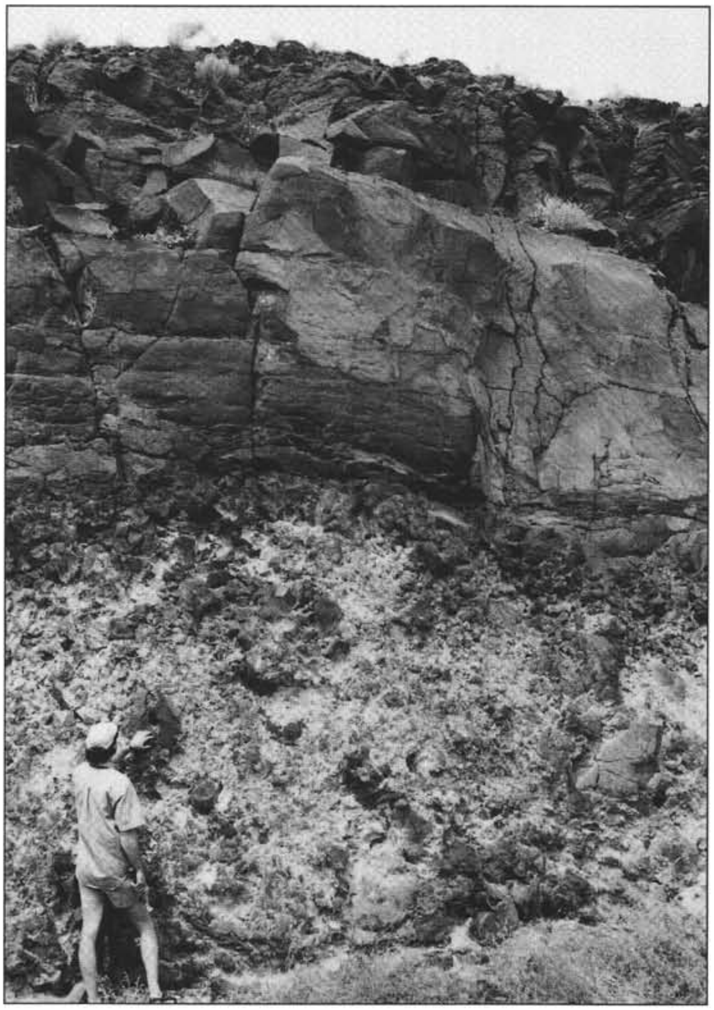

Figure 47. Saddle Mountains Basalt east of Ice Harbor Dam (Stop 8A). The large columns (top) and the thick breccia (bottom) belong to the Elephant Mountain Member.

1980). Touchet Beds are exposed in railroad cuts between the cliff and the river.

Levee Park, which has rest rooms, is 1.5 mi from the Kahlotus–Pasco highway.

126.8 Turn left (south) toward Ice Harbor Dam.

129.2 Railroad underpass.

129.5 Roadcut on the north reveals late Pleistocene Touchet Beds with clastic dikes and a thin cap of Holocene loess. From north to south across Ice Harbor Dam are the lock, a fish ladder, the spillway, the powerhouse, and another fish ladder (Figs. 44 and 45). Miklancic (1989a) summarized the engineering geology of Ice Harbor Dam.

129.6 Turn left toward boat ramp.

129.9 Continue east on the primitive dirt road from the northeast corner of the parking area for the boat ramp. (An alternative is to park here and walk 0.6 mi to the end of the dirt road.) At the two junctions on the dirt road, go either way, proceeding eastward along the north side of the Snake River.

130.5 **Stop 8:** Park here at the end of the dirt road. (The small parking/turn-around area is between an abandoned railroad grade and the Snake River.) Walk east about 300 m along the railroad grade.

Beware of rattlesnakes and ground hornets.

The geology here is described by Swanson and Wright (1976, p. 8–9; 1981, p. 22). At this stop are some of the youngest lava flows of the Columbia River Basalt Group. In railroad cuts are exposed flow contacts, dikes, and an invasive flow.

Stop 8A: Western railroad cut (Fig. 46, section A–A′). In the western railroad cut, a flow of the Elephant Mountain Member is cut by the Ice Harbor dikes. The dikes, and tuff cone at Stop 9, are part of an 80-km-long linear vent system for the Ice Harbor flows (Swanson and others, 1975). Above the railroad cut is an Ice Harbor flow.

In the railroad cut, the Elephant Mountain flow has large columns, a vesicular top, and a thick breccia at the bottom (Fig. 47). The breccia, which exhibits ropy texture in places, was described by S. P. Reidel and Karl Fecht (Westinghouse Hanford Co., unpub. data., 1987): "The base is, in part, a 'rubble' zone with chilled blocks of basalt mixed with sediment."

Stop 8B: From the east end of this railroad cut, walk approximately 250 m east along the railroad grade to the next railroad cut (Fig. 46, section A–A′). Here the Pomona flow has invaded a tuff that is exposed at the top of the northern side of the middle of the railroad cut (Fig. 48). An invasive flow occurs where the advancing, more dense lava 'submarines' through less dense sediment that is likely water saturated and of fine grain size. The basalt pillows here have glassy rims and are surrounded by white vitric tuff. The tuff is consolidated ash that contains mostly glass particles. The Pomona flow has large vesicles, some of which are called amygdules because the gas bubble cavities are filled with minerals such as calcite, quartz, and zeolites.

Walk back to the end of the primitive road and drive west toward Ice Harbor Dam.

Figure 48. Invasive flow east of Ice Harbor Dam (Stop 8B). The Pomona lava flow formed pillows (dark) where it invaded a less dense tuff (light). See text for details.

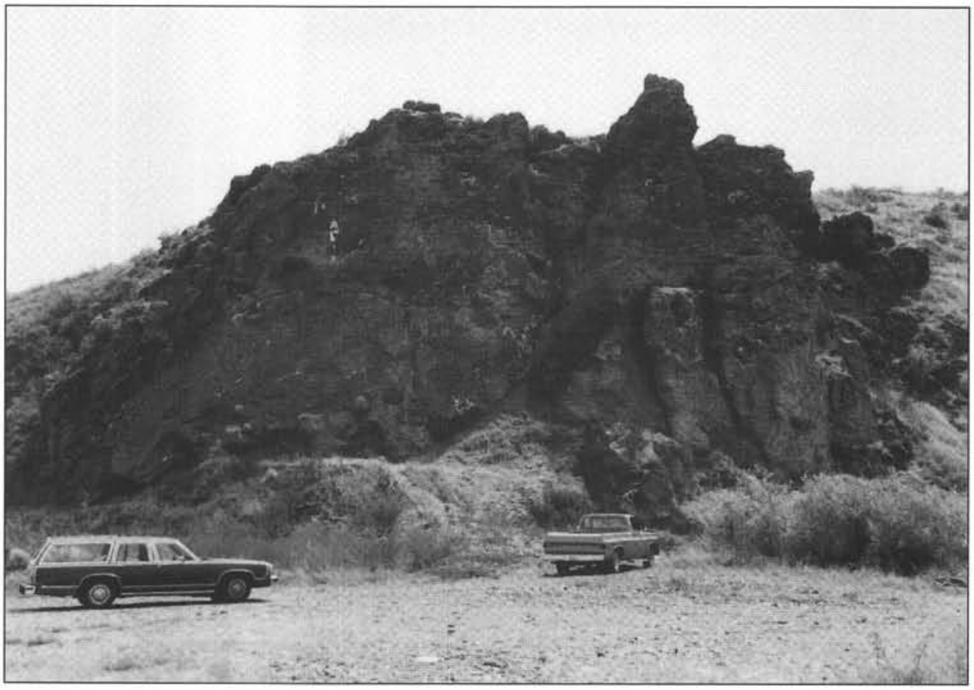

Figure 49. Tuff cone west of Ice Harbor Dam (Stop 9A). The tuff cone is part of a vent system for the Ice Harbor flows.

131.2 The dirt road becomes paved at the parking lot for the boat ramp.

131.5 Turn left toward Ice Harbor Dam.

131.6 Begin to cross the dam (daylight hours only).

132.2 Leave dam; turn right (west).

132.3 Turn right (north) toward visitor center.

132.6 Near the bottom of the hill, turn left (west) toward Stop 9. (The visitor center is to the east.) Proceed downriver on the gravel road.

133.6 End of the road, **Stop 9**. Park here and *beware of rattlesnakes and poison oak.* Swanson and Wright (1976, p. 9-10; 1981, p. 23) described the geology of the exposures of basalt.

Stop 9A (Figs. 49 and 50) is the bluff adjacent to the end of the road (Fig. 46, section B–B′). This rock is described by Swanson and others (1975, p. 893) as "crudely bedded, poorly sorted, palagonitized sideromelane breccia and tuff forming remnant of tuff cone." (In other words, the fragmental volcanic rock is composed of altered basaltic glass.) Different dips of the tuff breccia indicate minor shifting of the vent during construction of the tuff cone, which is overlain by a slightly younger Ice Harbor flow.

Walk about 700 m west along the south bank of the Snake River. Along the trail are exposures of tuff, a basalt flow, and the Pasco gravels.

Stop 9B is the cliff where the trail rises (Fig. 46, section B–B′). The lower Martindale flow is cut by a Goose Island dike, which feeds the upper flow (Fig. 51) (S. P. Reidel, Westinghouse Hanford Co. written commun., 1995). The flows and dike are part of the Ice Harbor Member of the Saddle Mountains Basalt, dated at about 8.6 Ma. The upper part of the dike is breccia interpreted by Swanson and Wright (1976, 1981) as drainback rubble.

Walk east to the tuff cone and drive toward Ice Harbor Dam.

134.6 Where the gravel road meets the paved road, continue east to the visitor center.

134.7 Ice Harbor Dam Visitor Center (open all year). Inside the visitor center are a view of the powerhouse, a window to watch migrating fish, and rest rooms.

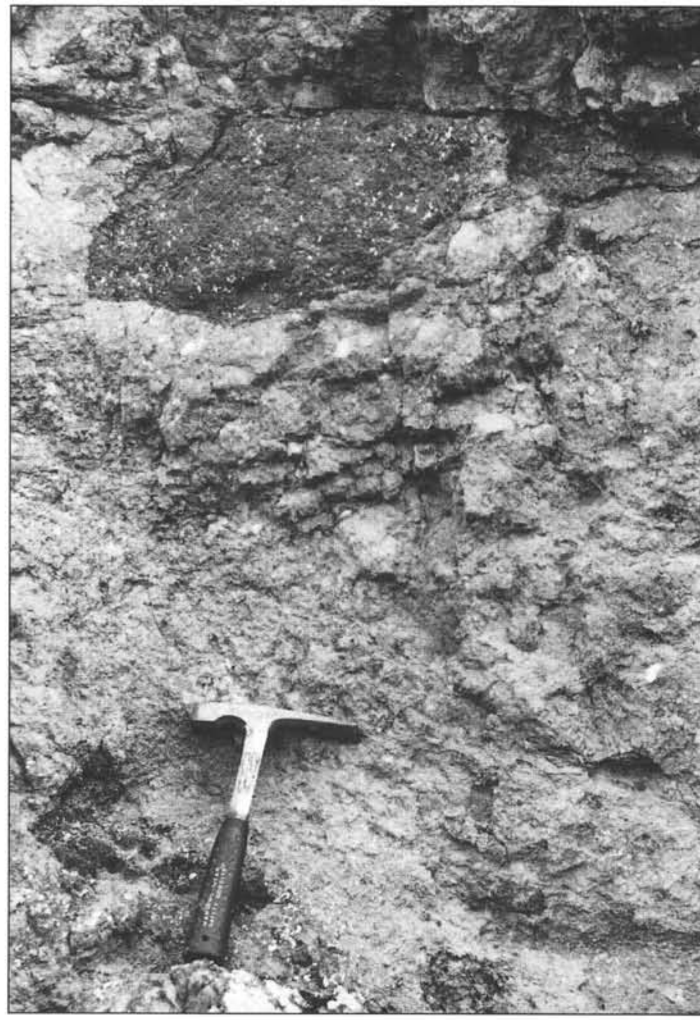

Figure 50. Tuff breccia west of Ice Harbor Dam (Stop 9A). A large clast is visible near the top of this photo. The basalt tuff breccia makes up a tuff cone that is part of the Ice Harbor Member.

Figure 51. Flows and dike west of Ice Harbor Dam (Stop 9B). The Goose Island dike (right of the person) cuts the Martindale flow (small prominent columns). The dike fed the Goose Island flow (less prominent but larger columns).

PART 4 - ICE HARBOR DAM TO WALLULA GAP

Miles

134.7 From the Ice Harbor Dam visitor center, drive southwest on the paved road toward Pasco.

137.5 Intersection with State Route 124 (elevation 530 ft). Turn west (right) toward Pasco. To the south and west there is a good view of the hills and escarpment that form the Olympic–Wallowa lineament. The anticlinal hills along the lineament include Jumpoff Joe (to the southwest), Badger Mountain (to the west), and Rattlesnake Mountain (to the west-northwest). Rattlesnake Mountain lies at the south edge of the Hanford Site managed by the U.S. Department of Energy. Formerly the emphasis of work on the site was on nuclear weapons and nuclear energy, but today work there centers on nuclear waste storage and disposal. Considerable funds are being spent for cleaning up the radioactive wastes.

141.5 Enter Burbank Heights (elevation 411 ft).

142.7 Turn left (southwest) on U.S. 12 toward Walla Walla. The mouth of the Snake River is 2 km to the southwest. Just northwest of here is Hood Park (U.S. Army Corps of Engineers). On the other side of the Snake River, where it joins the Columbia River, is Sacajawea State Park. The Lewis and Clark Expedition camped at the mouth of the Snake River in October 1805 (Majors, 1975).

143.5 McNary National Wildlife Refuge. On the northeast side of U.S. Highway 12 is the northwest end of Burbank Slough, an old meander scar that was flooded in 1953 when McNary Dam was constructed 50 km down the Columbia River.

146.7 Cross the southeast part of Burbank Slough. (You are now in the McNary State Wildlife Recreation Area.) Wallula Gap is visible 12 km to the south.

151.5 On the west side of the highway is Boise Cascade's Wallula mill. The chief products are corrugating medium and paper. Fiber sources are mainly wood chips and sawdust, but soon will include recycled paper and trees from the huge cottonwood plantation east of the highway. The genetically identical cottonwood trees, which are fertilized and irrigated, grow as much as 1 inch in diameter and 10 feet in height per year.

153.9 To the southwest, you can see the delta of the Walla Walla River (Fig. 52) extending into Lake Wallula along the Columbia River. When McNary Dam was completed, the reservoir extended up the Columbia River to Richland and several miles up the Walla Walla River. A yacht club was established in the 'harbor' along the lower Walla Walla River. The severe erosion of the Palouse loess and the Touchet Beds loads the Walla Walla River with a large amount of suspended sediment; within years the lower Walla Walla River 'silted up', and the yacht club was moved to Wallula Gap. Now the sediment carried by the Walla Walla River is deposited in a delta growing out into Lake Wallula (elevation 340 ft).

154.2 Entrance to Madame Dorion Park on the left (east). (There are rest rooms here.) Madame Dorion was an Iowa Indian who left Missouri in 1811 and arrived at Wallula in January 1812 with the Wilson Price Hunt party of the Pacific Fur Company (information from sign at park).

154.5 Cross the bridge over the mouth of the Walla Walla River. At the 'Y' turn west (right) on U.S. Highway 730 toward Umatilla. This is Wallula Junction (elevation 400 ft).

155.4 **STOP 10:** Olympic–Wallowa lineament. Park on the north (right) side of U.S. 930 and *be careful of traffic.* Raisz (1945) proposed the term Olympic–Wallowa lineament (OWL) for a northwest-striking feature stretching 600 km from Cape Flattery in northwestern Washington to the Wallowa Mountains in northeastern Oregon (Fig. 2). A segment of the OWL called the

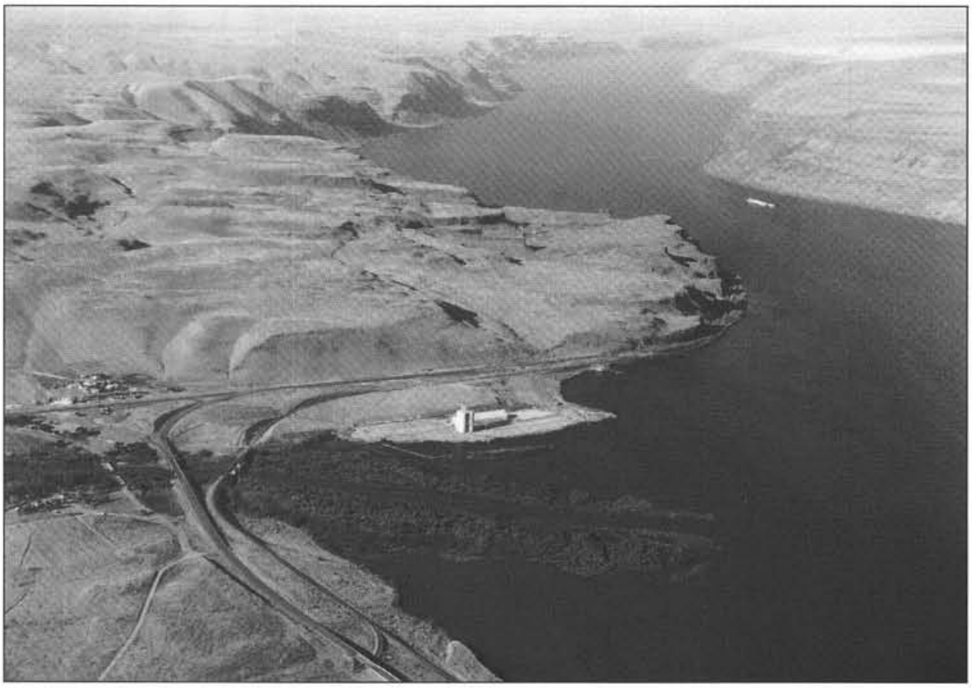

Figure 52. Wallula Gap and the delta of the Walla Walla River. The Horse Heaven Hills anticline trends from left to right across the Columbia River. The escarpment in the left center (facing the viewer) is the trace of the Olympic–Wallowa lineament. Wallula Gap is a water gap that was too small to accommodate the entire discharge of the Missoula floods as they traveled south from Washington (in the foreground) to Oregon (in the background). The construction of McNary Dam formed Lake Wallula, into which the Walla Walla River is building a tree-covered delta.

CleElum–Wallula deformed zone (CLEW) is marked by anticlines that trend N50°W. The Rattlesnake–Wallula alignment (RAW) is the part of the OWL and CLEW that forms the southwestern boundary of the Pasco Basin (Reidel and Lindsey, 1991).

The hillside to the south of this stop is the northern escarpment of the Horse Heaven Hills, a long, broad anticlinal ridge that stretches across southern Washington from the Cascades to Wallula Gap. From Wallula Gap, the ridge trends east-southeast and intersects the Blue Mountains near Milton-Freewater, Oregon (Fig. 52).

West of Wallula Gap, the OWL is expressed as northeast-facing fault scarps that extend northwestward along the flank of the Rattlesnake Hills. East of the gap, faceted spurs marking the northern boundary of the Wallula fault zone constitute the OWL (Fig. 53). The OWL is the topographic expression of a zone of high-angle faults along which Miocene basalts are in the upthrown block to the south and Quaternary sediments are in the downthrown block to the north.

In Washington, the maximum relief across the OWL occurs about 65 km to the northwest of here. On the northeast side of Rattlesnake Mountain (elevation 3,524 ft) there is about 900 m of relief, but much of that relief is due to the anticlinal fold and only in part to faulting. To the southeast of Wallula Gap, there is a fault scarp in the southeastern corner of the Zanger Junction quadrangle (1:24,000) that exceeds 100 m. Farther southeast in Oregon, the relief along the OWL along the northeast side of the Wallowa Mountains is more than 1,500 m.

Examine the subparallel faults (part of the much wider Wallula fault zone) in the basalt in the roadcut on the south side of U.S. Highway 12 (Fig. 54). The lava is the Two Sisters unit of the Frenchman Springs Member of the Wanapum Basalt (Gardner and others, 1981). The Two Sisters unit is equivalent to the Sand Hollow unit of south-central Washington (S. P. Reidel, Westinghouse Hanford Co., written commun., 1995). Note the fault breccia and yellowish fault gouge along each of the near-vertical faults. Along the western fault are subhorizontal slickensides that indicate that the last movement was strike-slip (Fig. 55). About 8 km to the east, a fault on the southwest side of Vansycle Canyon appears to deflect intermittent streams as much as 250 m; the offset drainage suggests right-lateral strike-slip movement (Gardner and others, 1981). However, nearby drainages and ridges are not as deflected, so the apparent offset drainage may be due to local erosion along the fault plane (Reidel and Tolan, 1994, p. 1638).

Figure 53. The Wallula fault zone east of Wallula Gap. Movement along the fault zone has created the escarpment that forms part of the Olympic–Wallowa lineament. Here on the north flank of the Horse Heaven Hills anticline, the Wallula fault zone is marked by a line of triangular faceted spurs with exposures of basalt. In the foreground the floor of the lower Walla Walla River valley is underlain by Touchet Beds.

Figure 54. Fault at Wallula (Stop 10). This high-angle fault is part of the Wallula fault zone. This is one of a group of subparallel faults marked by subhorizontal slickensides, lineations, breccia, gouge, and accelerated weathering.

The age of the most recent movement along the faults that form the OWL is not known with certainty. Carson and others (1989) found evidence for deformation along the OWL on the northeast side of the Wallowa Mountains; the Enterprise Gravels (about 2 Ma) have been tilted. Mann and Meyer (1993) argue that there has been some right-oblique slip displacement along the OWL in the Holocene. Their assessment is based in part on what they interpret as a 5-m offset of a Mount St. Helens ash (dated at 10.7 ka) between here and Milton-Freewater, Oregon. Also near Milton-Freewater there was an earthquake of approximately magnitude 6 in 1936 (Brown, 1937), but that earthquake may have been associated with the Hite fault (Fig. 2) rather than the OWL (Reidel and Tolan, 1994, p. 1636).

The delta of the Walla Walla River, visible less than a kilometer to the northeast, is advancing into Lake Wallula.

On the floor of Lake Wallula is the April 1806 campsite of Lewis and Clark. They described the "Wallah wallah River" as "a handsom stream about 4½ feet deep and 50 yards wide." When members of the Lewis and Clark expedition danced to a fiddle, the "chimnahpoms" (Yakima Indians) and "wollahwollahs" sang and joined the dance (Majors, 1975).

A bit farther north, and also now submerged, Fort Nez Perce (also known as Fort Walla Walla) was established in 1818. The log fort burned in 1841 and was replaced by an adobe fort that washed away during the Columbia River flood of 1894 (Majors, 1975). That flood had a recorded discharge of 34,000 m^3/sec (1,200,000 ft^3/s). The mean discharge of the Columbia River (at Bonneville) is 5,266 m^3/sec (185,900 ft^3/sec). Of this discharge, 1,446 m^3/sec (51,060 ft^3/sec) is contributed by the Snake River (Bonneville Power Administration, 1993).

Contrast the 1894 floodflow with Baker's (1973b) estimate for a typical Missoula flood of 21,000,000 m^3/sec (740,000,000 ft^3/s). (This is about 18 mi^3 of water per hour!) These floods poured into the Pasco Basin from the northeast, north, and northwest, but the only outlet was Wallula Gap. At less than 2 km wide, Wallula Gap could accommodate only about half of the peak discharge of a Missoula flood. Therefore, the water level in the Pasco Basin rose rapidly to 1,200 ft. This formed Lake Lewis, which lasted about a week during each Missoula flood (Allen and others, 1986). Lake Lewis backed east and west up the Walla Walla

Figure 55. Close view of the fault in Figure 54 (Stop 10). The fault trace is from upper left through the hammer to lower right. The lower left side of the fault is somewhat brecciated basalt. Above the hammer are faint slickensides (parallel to the hammer head) indicating that the last fault movement was subhorizontal.

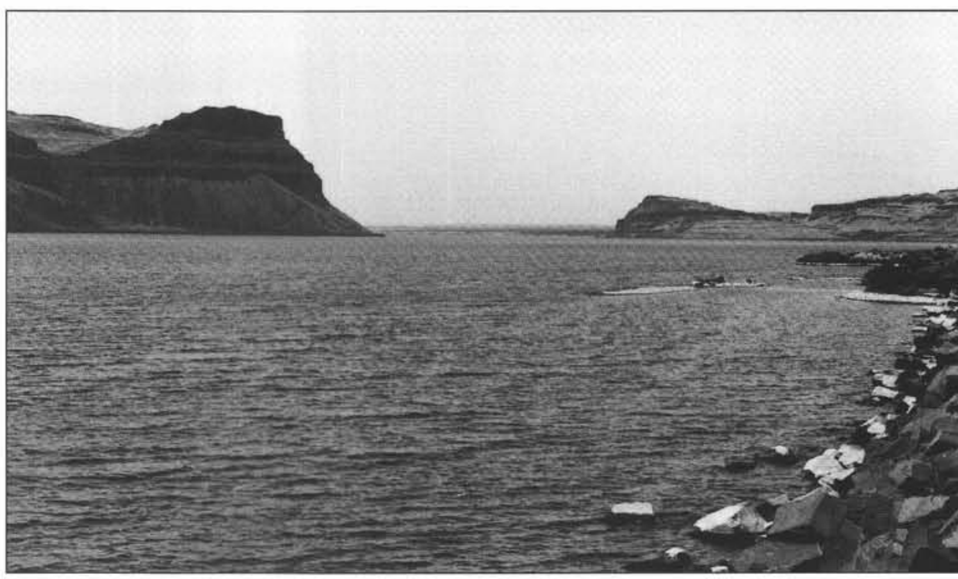

Figure 56. Wallula Gap on the Columbia River (view north). Parts of the Grande Ronde, Wanapum, and Saddle Mountains Basalts are exposed at Wallula Gap. The elevation of Lake Wallula is 340 ft. In the far distance is the Pasco Basin. The distant cliffs on the east side of the river rise to 783 ft; they were overtopped by the Missoula floods, which cut channels farther to the right (east). The cliffs on the west side of the river reach 1,147 ft; even this elevation is below the 1,200 ft estimated as the upper limit of the floods.

and Yakima Valleys, respectively; in these arms of the lake accumulated thick slackwater sediments, or the Touchet Beds. The bottom of the Columbia River has an elevation here of about 300 ft. Imagine 275 m (900 ft) of water rushing through Wallula Gap at velocities of as much as 80 km/hr (50 mph) (Allen and others, 1986).

Continue southwest on U.S. Highway 730 through Wallula Gap (Fig. 56).

156.6 The Two Sisters stand above the east side of U.S. Highway 730 (Figs. 57 and 58). These buttes are scabs or erosional remnants of basalt (Frenchman Springs Member) left after passage of the Missoula floods. Each butte is part of the entablature of a basalt flow whose colonnade is at the base of the buttes.

The uppermost limit of flood scour at Wallula Gap is about 1,200 ft (Waitt and others, 1994). The largest flood channel adjacent to Wallula Gap is east of the Two Sisters (Fig. 57). Huge volumes of water rushed south there, creating an area of 'channeled scabland' with a floor at 500 ft. At the south end of that channel, from the Two Sisters to the Columbia River and on both sides of U.S. Highway 730, is a small dune field most of which is inactive because it has been stabilized by vegetation.

157.4 The basalt exposure on the east (left) side of U.S. Highway 730 is followed by a roadcut that exposes a lens of Mazama ash about 1 m thick. This lava flow is near the bottom of the Frenchman Springs Member of the Wanapum Basalt. To the southwest, between the road and the river, is the uppermost flow of Grande Ronde Basalt (Gardner and others, 1981).

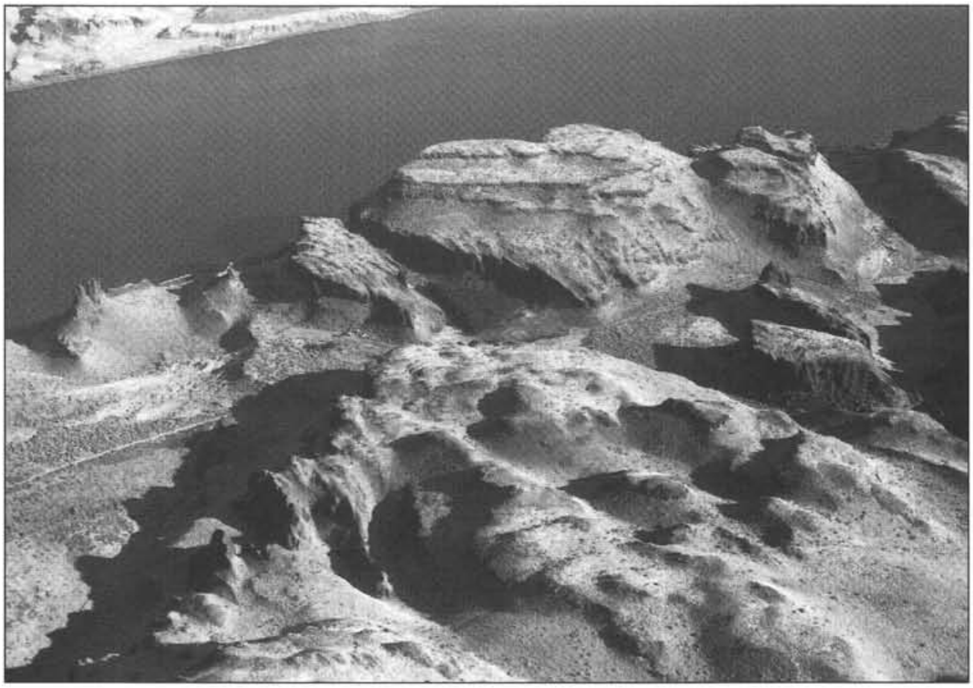

Figure 57. View westerly across the Columbia River at Two Sisters. The Missoula floods traveling down the Columbia River (from right to left) cut this part of the Channeled Scabland. The Two Sisters are the two buttes (erosional remnants) by the river in the left center. See text for details. A small dune field is visible as light patches on this side of the Two Sisters.

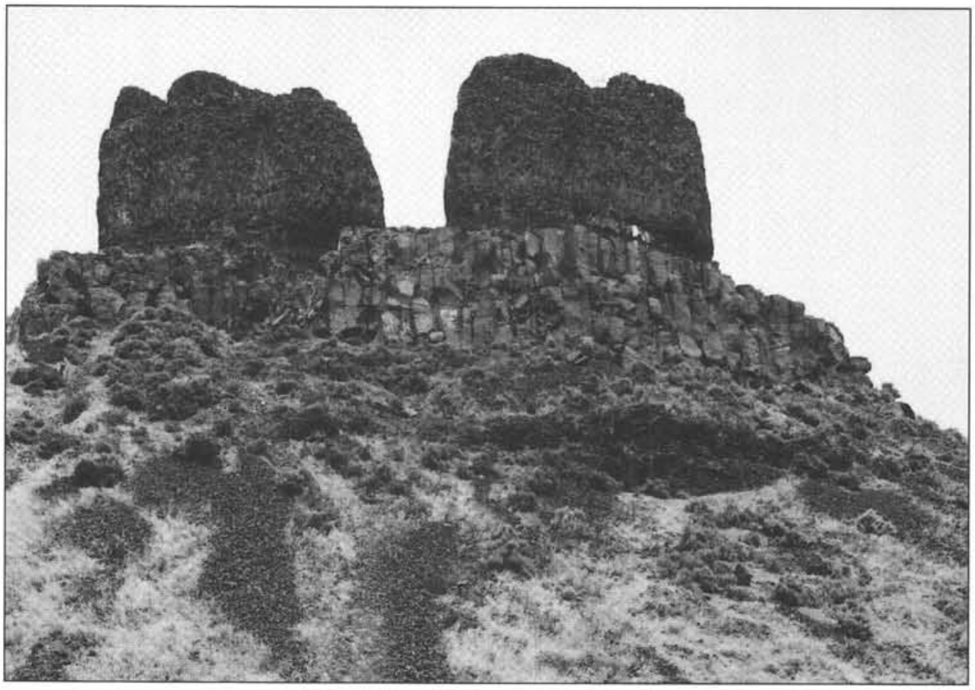

Figure 58. Two Sisters, Wallula Gap. These are erosional remnants of basalt left by the Missoula floods. These scabs are cut from the Frenchman Springs Member of the Wanapum Basalt. The two buttes are part of the entablature of a lava flow. The colonnade, about 5 m high, is popular for rock climbing.

Notice the huge talus slopes on both sides of the Columbia River. It is likely that the high-discharge, high-velocity Missoula floods removed all unconsolidated debris from Wallula Gap, so all this talus has accumulated in the last 12,700 years.

160.6 Washington–Oregon state line. Continue southwest on U.S. Highway 730.

161.4 **STOP 11:** View of Wallula Gap (Fig. 56). Park on the left (southeast) side of U.S. 730. *Be careful of traffic!*

Parts of the Grande Ronde, Wanapum, and Saddle Mountains Basalts are exposed at Wallula Gap (Swanson and others, 1980). A thick section of the Frenchman Springs Member of the Wanapum Basalt is overlain by the Umatilla Member of Saddle Mountains Basalt. A Martindale flow of the Ice Harbor Member (about 8.5 m.y. old) of the Saddle Mountains Basalt caps the highest point visible on the northwest side of the Columbia River. This does not mean that there is a complete section of the Columbia River Basalt Group exposed here. The cliffs at Wallula Gap are a maximum of 300 m high, but the total thickness of the Columbia River basalts is thousands of meters. More than 300 individual flows are known (Tolan and others, 1989), but only about 20 flows have been recognized in the vicinity of Wallula Gap (Gardner and others, 1981, p. 6).

The Martindale flow overlies gravel compositionally similar to that at Stop 7. Therefore, we can conclude that the Clearwater–Salmon River was cutting across the Horse Heaven Hills here by 8.5 m.y. ago (Swanson and Wright, 1981). At that time the course of the Columbia River was about 80 km (50 mi) northwest of Wallula Gap. There has been considerable debate about why the Columbia River shifted east to Wallula Gap.

Fecht and others (1987, p. 238) "...believe that continued subsidence of the central Columbia Plateau centered in the Pasco Basin and uplift of the Yakima folds, specifically the Horse Heaven Hills, were important factors in the diversion of the Columbia River" and its capture by the Clearwater–Salmon River. Fecht and others (1987) described the paleodrainage of the Columbia River system and summarized the history of the theories about why the Columbia River shifted eastward from the central Pasco Basin to Wallula Gap.

At road level are lava flows of the Frenchman Springs Member (about 15.5 Ma) of the Wanapum Basalt. Note the following: the flow contact with flow-top breccia and ropy texture, which is called pahoehoe; the difference between polygonal contraction columns in the entablature and the basal colonnade; and the presence of phenocrysts, vesicles, and amygdules. The pahoehoe flows of the Columbia River basalt were very fluid; rapid cooling of the flow surface produced a smooth or ropy texture. As the molten interior continued to move, the surface was cracked and broken, and solid fragments became incorporated in the molten part of the flow. The upper part of a flow that consists of these fragments is called a flow-top breccia. The top of the flow and (or) some fragments may be arranged so that they resemble ropes laid side by side or mixed together. The geological contact where a younger flow overrides the older flow-top breccia may be a reddish zone, due to oxidation. Phenocrysts are large crystals (commonly the mineral plagioclase) that crystallized in the lava before it erupted. Vesicles are cavities that formed by bubbles of volcanic gases; amygdules are vesicles that were filled by minerals such as calcite, quartz (or opal), or zeolites.

Return to the Oregon–Washington state line by driving northeast on U.S. Highway 730. We now start the last leg of the field trip.

PART 5 - WALLULA GAP TO WALLA WALLA

Miles

162.2 **STOP 12:** Mazama ash at Oregon–Washington state line (Fig. 59). Park on the right (southeast) side of U.S. 730. *Be alert for traffic and rattlesnakes.*

Between the basalt cliffs and the Columbia River are talus slopes and alluvial fans that have formed since the passage of the last Missoula flood about 12,700 years ago. This alluvial fan was partly covered by a debris flow about a decade ago; notice the boulders, particularly near the head of the fan. The channel on the alluvial fan, partly created by the Washington highway department, reveals about 3 m of Mazama ash and fan sediments. Mount Mazama underwent a catastrophic eruption and caldera collapse 6,845 years ago that resulted in Crater Lake (more than 400 km away in Oregon's southern Cascades) (Bacon, 1983). A thin blanket of tephra fell on the Horse Heaven Hills and as far northeast as Alberta (Wilcox, 1965). The ash washed off the Horse Heaven Hills, down gullies, and onto alluvial fans where it was buried and preserved.

Across the river at the base of the cliffs are more alluvial fans (Fig. 60). From here the light-colored lenses of Mazama ash are visible in railroad cuts through the alluvial fans. Gravel bars (Fig. 60) were deposited by the Missoula floods high in canyons tributary to the Columbia River here at Wallula Gap.

After passing through Wallula Gap the Missoula floods poured into the Umatilla Basin and then rushed down the Columbia River Gorge and inundated the Willamette Valley before draining into the Pacific Ocean at Astoria (Fig. 5).

Between U.S. Highway 730 and the railroad tracks is a railroad rockfall warning device designed to alert train engineers if large rocks fall from the cliffs or down the talus slopes. The wire fence here has a mesh size such that small rocks may pass through and land between the tracks. Any rocks large enough to obstruct passage of a train would hit the fence and send an electrical alert signal to trip a semaphore to stop the train.

Continue northeast on U.S. Highway 730, returning to Wallula Junction.

168.1 Wallula Junction. End of U.S. Highway 730. Proceed east on U.S. Highway 12 toward Walla Walla. On the right (south) side of U.S. 12 is a row of about a half dozen faceted spurs along the Olympic–Wallowa lineament (Figs. 53 and 61). The faceted spurs are truncated ends of ridges between the gullies that were cut by the intermittent streams that flow north off the Horse Heaven Hills: each truncated spur is a triangle about 100 m high.

171.1 Across the road from the Wallula Habitat Management Unit sign, a 1-cm-thick bed of Mount St. Helens set S tephra is exposed in Touchet Beds; this tephra is about 13,000 years old (Mullineaux and others, 1978). Mount St. Helens ash did not fall this far south on May 18, 1980; distribution of ash is controlled by the prevailing winds at the time of the eruption.

172.5 The Walla Walla River is meandering across its flood plain in the lower Walla Walla Valley. On the north side of the valley are exposed lava flows of the Frenchman Springs Member (15.5 m.y. old) of the Wanapum Basalt and the Umatilla Member (about 14 m.y. old) and Ice Harbor Member (Martindale flow)(about 8.5 m.y. old) of the Saddle Mountains Basalt (Swanson and Wright, 1981). (See Fig. 62.) The ancestral Clearwater–Salmon river system cut a valley in the Umatilla basalt and partly filled that valley with basaltic, metamorphic, and plutonic clasts. At about 8.5 m.y. ago, the Martindale flow of the Ice Harbor Member capped the sequence (Fecht and others, 1987).

The drainage system of the Walla Walla River was established by the late Miocene to middle Pliocene (Fecht and others, 1987, p. 240). The oldest unconsolidated deposits in the Walla Walla Valley are termed the "old gravel and clay" (Newcomb, 1965, p. 20-22). In

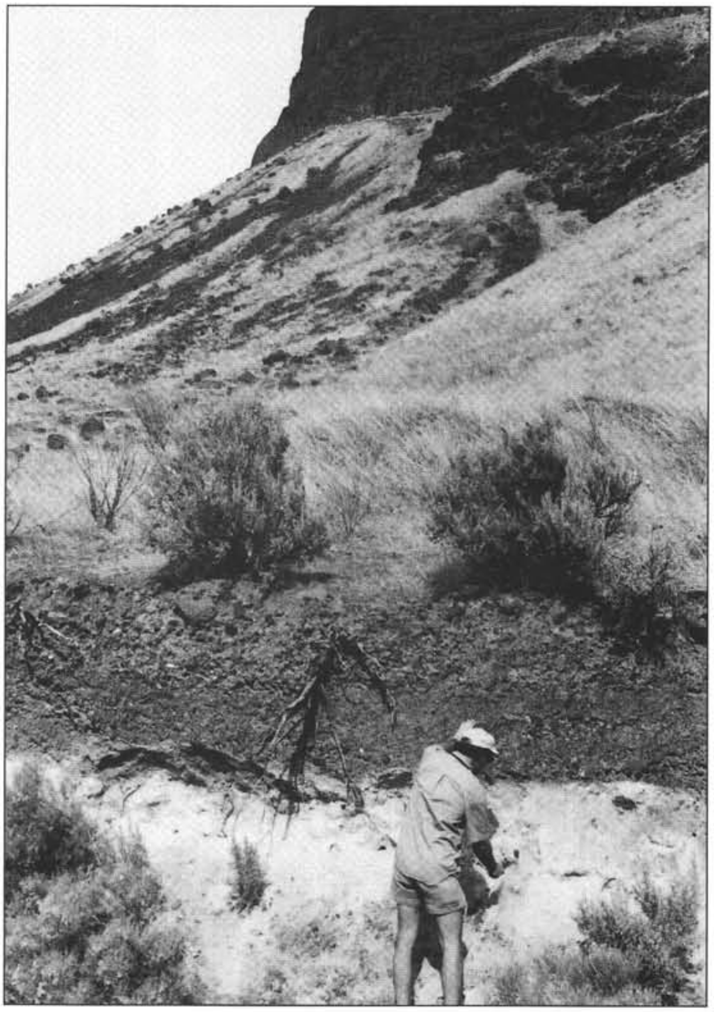

Figure 59. Alluvial fan and talus at the Washington–Oregon state line. The cliffs are basalt flows of the Frenchman Springs Member. Below the cliff is talus covered with grass. In the foreground is a channel in an alluvial fan. At the bottom of the channel is Mazama ash (white) from the eruption at Crater Lake about 6,845 years ago. Overlying the ash is alluvial gravel at the surface of the fan.

the late Pleistocene, the Missoula floods partially filled the Walla Walla Valley with Touchet Beds. In the Holocene, the river has partially excavated these beds, forming a flood plain and locally cutting down to the basalt bedrock.

174.6 Bridge over the Walla Walla River at Reese (elevation 389 ft). Roadcuts from here to the top of the hill are in the Frenchman Springs Member of the Wanapum Basalt (Swanson and Wright, 1981).

There is an area of channeled scabland near the hill just southeast of here (elevation 716 ft) and the hill at Divide. There are small buttes, or scabs, of basalt and shallow coulees with southeasterly orientations. The erosion that shaped this area occurred as the Missoula floods overtopped the hills as they poured from the Pasco Basin into the main Walla Walla Valley. With flood levels at 1,200 ft, there was 150 m (500 ft) of water flowing over these hills.

Figure 60. West side of Wallula Gap near the Washington–Oregon border. To the right and left are ledges of Columbia River basalts. In the center is a giant eddy bar deposited by the Missoula floods. The vertical distance from the bottom of Lake Wallula to the top of the eddy bar (170 m) is the minimum water depth of the Missoula floods; some of the floods were about 275 m deep. A large gully in the eddy bar leads down an alluvial fan in the lower right. The light patches in the fan are Mazama ash from Crater Lake, Oregon.

176.0 **STOP 13:** Unconformities at Divide (Figs. 63 and 64). Park at the east end of the roadcut and walk back down the hill. Be alert for traffic.

This is the crest of a north-trending anticline at the west edge of the main Walla Walla Valley (Swanson and Wright, 1981). The Frenchman Springs Member of the Wanapum Basalt is overlain by poorly sorted and crudely stratified caliche-rich strata. Almost all the clasts are basalt, but at least two weathered erratics (one granite and one gneiss) have been discovered near the base of the sediments.

Vrooman and Spencer (1990) interpret these sediments as the remains of two debris flows that were covered by colluvium (talus), loess, and, finally, a soil. According to their scenario, there would have been a hill of basalt just to the east of these sediments. An ancient jökulhlaup left one or more icebergs that were transporting the erratics on the hill. Mass wasting of the western hill slope brought the erratics downslope into the diamictons. The geomorphology, the presence of weathered erratics, and the degree of development of the caliche all suggest great age, perhaps several hundred thousand years, for these Pleistocene diamictons.

Overlying the diamictons and the basalt are about a dozen thin Touchet Beds deposited by the late Pleistocene Missoula floods (Fig. 63). Holocene eolian sediments (mostly loess, but some sand) cap the section.

To the north of the highway are iceberg-transported cobbles and boulders. Walk a short distance (50–100 m) north from the west end of the roadcut to see a variety of iceberg-transported erratics (granite, gneiss, quartzite, sandstone, and siltstone). Bartlett and Carson

Figure 61. Olympic–Wallowa lineament (or OWL) east of Wallula Gap. Truncated spurs along the lineament are visible in this view toward the east-southeast. This Horse Heaven Hills anticline is on the upthrown (right) side of the OWL. In the lower left is part of the delta of the Walla Walla River.

(1995) reported on a bergmound located 10 km southeast of here. They estimated that the pile of large boulders had been deposited by an iceberg with a volume of 6,000–12,000 m^3 (200,000–400,000 ft^3).

Here at Divide is evidence for glacial flooding not only in the late Pleistocene but also much earlier in the Pleistocene. The evidence for late Pleistocene jökulhlaups from glacial Lake Missoula is twofold: (1) Touchet Beds near the top of the exposure and (2) erratics at the surface. The evidence for jökulhlaups earlier in the Pleistocene consists of the erratics near the base of the diamictons.

Vrooman and Spencer (1990) interpret the diamictons as follows:

"The lowermost unit consists of a fining-upward diamicton. Large clasts are basaltic except for a few clasts of exotic lithology. Textural parameters suggest deposition by a mudflow, or colluviation concurrent with deposition of loess. A truncated clastic dike in this unit indicates a period of erosion before deposition of the overlying units, which are coarser-grained and caliche-rich. Texturally, these upper units, in which exotic lithologies are lacking, suggest colluvium deposited as a nearby basaltic high weathered and mass-wasted. The upper, caliche-bearing portion of these units is fine-grained, suggesting a period of loess deposition. The presence of caliche indicates that colluviation was followed by long periods of soil development; based on the apparent stage of development, each caliche horizon may represent a minimum of 5–10 Ka, and perhaps considerably more."

The evidence for two distinct ages of flooding is an example of the principle of uniformitarianism, which geologists sometimes state as "the present is the key to the past." On this hill today are basalt outcrops, loess, and erratics from the latest glacial Lake Missoula

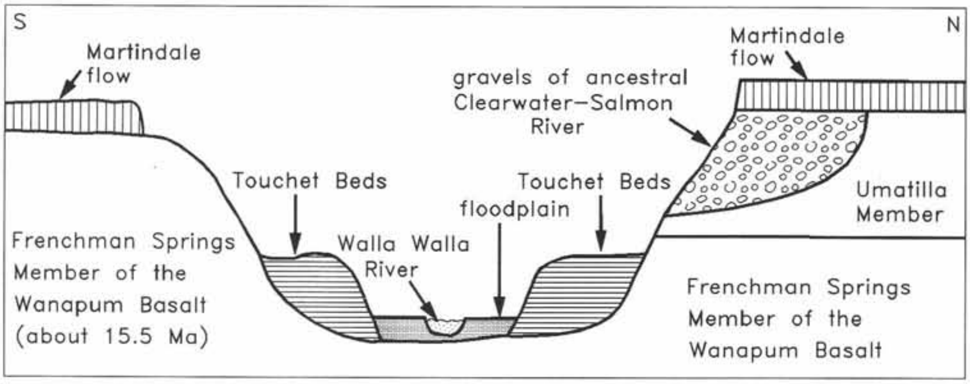

Figure 62. Cross section of the lower Walla Walla River valley. The Umatilla Member (between 14.5 and 13 m.y. old) and the Martindale flow of the Ice Harbor Member (8.5 m.y. old) belong to the Saddle Mountains Basalt.

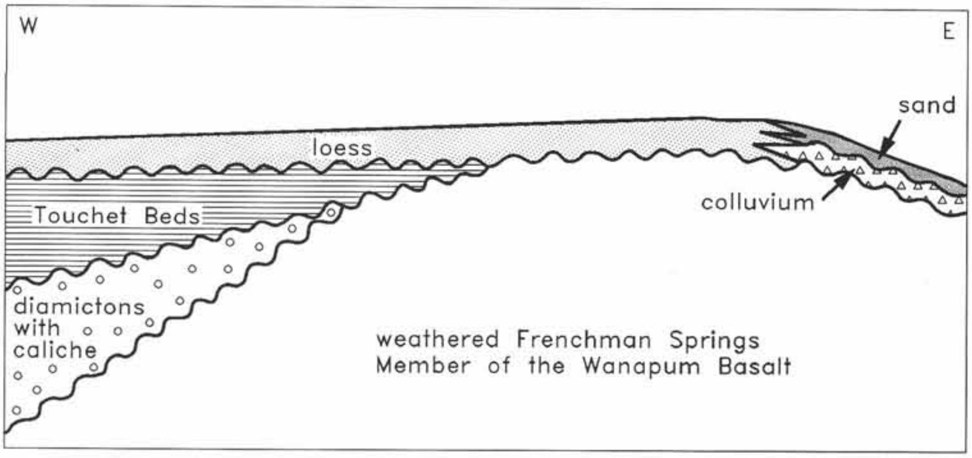

Figure 63. North roadcut at Divide. In the lower portion of the caliche-rich diamictons are rare granitic and metamorphic erratics.

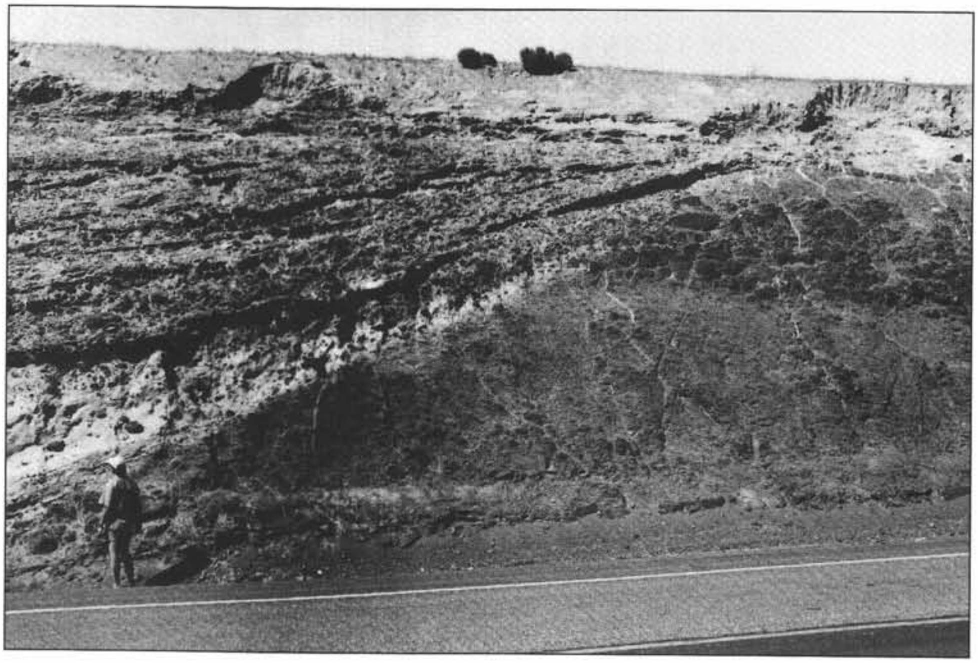

Figure 64. Unconformities at Divide (Stop 13). To the man's right is weathered basalt of the Frenchman Springs Member. Above the unconformable contact (at the level of the man's head) are crudely stratified diamictons dipping to the west. The diamictons are rich in caliche and have sparse erratics near the base. Unconformably overlying both the basalt and the diamictons are a few thin Touchet Beds deposited by late Pleistocene Missoula floods. The sequence is covered with about 1 m of Holocene loess.

floods. With time, these materials will creep (a type of slow mass wasting) down the hill, and a soil containing caliche will form. Evidently, this is what happened earlier in the Pleistocene, with the result that the erratics were buried, preserving the evidence for the ancient floods.

Return to your vehicle and continue east on U.S. Highway 12. To the south are the Horse Heaven Hills anticline and fault scarps of the Wallula fault zone. To the east is the much larger Blue Mountains anticline; this northeast-trending anticline is composed mostly of the Columbia River Basalt Group. However, erosion at the crest and in some deep canyons has resulted in limited exposures of Mesozoic granitic rocks and of parts of accreted terranes of mostly Mesozoic metamorphic rocks (Fig. 15).

Figure 65. Mount St. Helens ash (approximately 13,000 years old) in Touchet Beds north of Touchet. The layer of white Mount St. Helens set S tephra, about 1 cm thick, lies near the top of a Touchet bed. On the left is a clastic dike.

179.9 Cross the Touchet River (near its confluence with the Walla Walla River), then enter Touchet (elevation 443 ft). To the south, on the left bank of the Walla Walla River, is the type locality for the Touchet Beds (Flint, 1938). (There are still better exposures at Stop 14.)

180.6 Near the east end of Touchet, turn left (north) on Touchet Road (or Touchet River North Road).

183.1 At the south end of the roadcut in Touchet Beds is exposed Mount St. Helens set S tephra (Fig. 65). In places there are two closely spaced thin ash layers, suggesting that the eruption pattern of 13,000 years ago was somewhat like that of 1980—multiple eruptions over a period of time. In 1980, winds distributed ash from Mount St. Helens eruptions as follows: May 18, east-northeast; May 25, northwest; June 12, southwest; July 22, northeast; August 7, north-northeast; October 16–18, southwest (and southeast) (Sarna-Wojcicki and others, 1981). The result was partial geographic overlap of multiple ash falls. Between the thin set S ash layers is a few centimeters of eolian silt, or possibly sheet wash sediment (Waitt, 1980, p. 664-667; 1985, p. 1273).

183.5 **STOP 14:** Touchet Beds and clastic dikes. Park on west side of road. *Beware of black widow spiders at this stop.*

Although the Touchet Beds were originally believed to represent only two major floods (see review in Carson and others, 1978), most geologists now believe (see, for example, Waitt, 1980, 1985) that each Touchet bed represents one jökulhlaup or glacier outburst flood. Waitt (1980, 1985) has found considerable evidence that the Touchet Beds were deposited by dozens of Missoula floods. Between some flood-deposited rhythmites are slope wash sediments in channels, loess, volcanic ash, rip-up clasts (material pried loose from underlying sediments), and clayey lacustrine beds. Further evidence for a significant amount of time between successive floods includes rodent burrows and reworked shells and vertebrate remains—proof that animals were living in and on the Touchet Beds between these floods (Waitt, 1980, p. 668).

According to Waitt (1987, p. 345), "floodwater backed up dead-end valleys off the main Scabland floodways to form transient ponds in which suspended load settled. Because the side valleys were protected from violent currents, flood-laid strata were not eroded by later floods but became buried and preserved."

Spencer (1989) compared the sedimentology and paleontology at this stop and at the 'Little Grand Canyon' near Lowden (see mile 190.4). The Little Grand Canyon is in the middle of the Walla Walla Valley, but here the Touchet valley is narrower and has a higher elevation and a steeper gradient. Compared with those in the Little Grand Canyon, the graded rhythmites at this stop are poorly developed. More rapid drainage at this site resulted in more vigorous post-flood erosion and removal of the finer upper part of the rhythmites here. At this site Spencer (1989) found rodent fossils (including ground squirrel, vole, and kangaroo rat) and burrows indicating colonization by small animals between flood episodes.

The clastic dikes range in thickness from millimeters to meters and have various strikes and dips—most large ones are nearly vertical. Many consist of alternating vertical laminae of silt and sand (Fig. 66). There are many proposed origins (summarized from Carson and others, 1978): earthquake fissures, cracks that formed as buried ice melted, fissures due to erosion by under-ground streams, landslide fissures, permafrost-related crevices, desiccation fractures, ground-water injection, and extensional fractures accompanying slumping of unstable rapidly deposited turbidites.

Black (1979) studied the clastic dikes in the Touchet Beds and other geologic material in the Pasco Basin. Most dikes there "are megascopically similar in texture, fabric, and relation to their host." They "display the pronounced vertical layers of sand and silt, and have thick clay and silt coatings separating them and lining the walls of the host. The bulk of the material came down from above aperiodically as openings were enlarged underwater" (Black, 1979, p. 55).

Figure 66. Clastic dikes in Touchet Beds north of Touchet (Stop 14). Although there are many small dikes and faults at this exposure, here are two subvertical clastic dikes offset about 0.5 m by a subhorizontal fault. The clastic dikes have vertical laminae of alternating sand and silt.

Black (1979) concluded that the clastic dikes do not all have the same origin. However, for most of the dikes, he "hypothesized that hydraulically dammed Pleistocene floodwater that repeatedly covered the Pasco Basin is primarily responsible for the initial fracturing, for the aperiodic widening, and for the primary source of sediments that filled the fractures" (Black, 1979, p. 61).

While most of the dikes were filled from above, some small dikes were produced when liquefied layers of sediment were injected into overlying layers. Sudden loading by a Missoula flood or earthquake vibrations may have caused the unconsolidated sediment below the water table to liquefy. The weight of the overlying sediments forced the liquefied sediments to intrude upward to form the dikes.

Turn around. Drive south down the Touchet valley.

186.4 In Touchet, turn left (east) on U.S. Highway 12. All roadcuts between here and Walla Walla expose Touchet Beds.

The Battle of Walla Walla was fought in December 1855; the Oregon Militia and the Walla Walla Indians had a 4-day skirmish from here up the Walla Walla River to Mill Creek (Majors, 1975).

190.4 Cross Dry Creek and enter Lowden (elevation 489 ft). To the south is a hill of Touchet Beds, an erosional remnant left as the Walla Walla River cut its flood plain.

Three kilometers to the south is the Little Grand Canyon. The canyon is on private property and entry without permission is forbidden. Because of the potential danger at the Little Grand Canyon, if you plan to visit the site *you must have liability insurance specific to this site and a notarized hold-harmless agreement.* For information, contact Stuart Durfee, Secretary/Manager, Gardena Farms District No. 13, Box 137, Touchet, WA 99360 (509-394-2331).

The Little Grand Canyon (Figs. 67 and 68) cuts the south side of the ridge visible to the south. The ridge is part of an extensive but dissected surface that slopes gently down the Walla Walla Valley. The surface is at 800 ft just west of College Place, 625 ft here, and 500 ft southwest of Touchet. This surface is the top of the Touchet Beds, with about a meter of loess added. In other words, the surface is the bottom of the intermittent lake that aggraded during each Missoula flood. The surface has been dissected by the Walla Walla River and its tributaries.

Along the crest of the ridge runs the Burlingame irrigation ditch. This ditch is fed by a diversion structure near Mile 36 of the Walla Walla River (southwest of College Place).

The history of the formation of the Little Grand Canyon is summarized from *Soil Conservation* magazine (December 1935, p. 14-15). In 1904, a diversion canal was built from Burlingame irrigation ditch south to Pine Creek; the purpose was to control discharge in Burlingame ditch, especially when spring winds pile enough tumbleweeds into the ditch to choke the water flow. Until March 1926, the diversion canal was a gully about 10 ft deep and 6 or 8 ft wide. Then for 6 days steady winds caused enough tumbleweeds to accumulate to force the entire 80 ft^3/s (2 m^3/sec) flow of Burlingame ditch into the diversion canal. The water soon eroded 4,725,000 ft^3 (134,000 m^3) of Touchet Beds.

In 1927, an overshot flume was constructed to prevent further headward erosion. The flume collapsed into the canyon and another was built. Within a decade the canyon was 100 ft (30 m) wide and as much as 120 ft (36 m) deep. The Soil Conservation Service calculated that 9,588,000 ft^3 (271,000 m^3) of earth had been removed, and engineers recommended that a wooden flume be constructed around the gully.

The Touchet Beds exposed in the walls of the Little Grand Canyon (Fig. 48) have been studied many times. (See Carson and others, 1978, for review; Bjornstad, 1980; Waitt, 1980, 1985, 1987; Spencer, 1989; O'Connor and Waitt, 1994.) For a comparison of the Touchet Beds in the Little Grand Canyon and those exposed in the lower Touchet valley, see the description for Stop 14.

190.9 Leave Lowden. The Blue Mountains anticline rises above the Walla Walla Valley to the east.

196.1 The road to the Whitman Mission National Historical Site enters from the right (south). You can see a monument about a kilometer to the southeast on the west end of a ridge forming the drainage divide between Mill Creek and the Walla Walla River. The ridge is composed of Touchet Beds. The Whitmans settled on the flood plain between the creek and the river. A nearby highway sign reads:

"A short distance to the south near the Walla Walla River is Waiilatpu, the place of the people of the rye grass, a mission founded among the Cayuse Indians of the Walla Walla Valley in 1836 by Dr. Marcus Whitman and his wife Narcissa. As increasing numbers of immigrants moved into the Oregon country during the 1840s, Whitman Mission became an important station on the Oregon Trail. Cultural differences climaxed by a measles epidemic that killed many Cayuse ended the missionary effort. A few suspicious Cayuse took the lives of Marcus and Narcissa Whitman and eleven others on November 29, 1847."

Figure 67. 'Little Grand Canyon' south of Lowden. Approximately 40 rhythmites of the Touchet Beds are cut by clastic dikes (closeup, top photo). Much of the canyon was eroded in a few days in 1926. (See text for details.)

198.1 The road to College Place enters from the right (southeast). When the highway department improved this intersection in the summer of 1994, new vertical cuts were made in the Touchet Beds and loess on the left (north) side of U.S. Highway 12. Notice all the holes in the roadcuts; within days after the new cuts were made, they became homes for thousands of bank swallows.

201.7 Enter Walla Walla; continue east on U.S. Highway 12. Walla Walla lies on the flood plain of Mill Creek. Before the Army Corps of Engineers made a three-pronged attack on Mill Creek there was occasional severe flooding in Walla Walla, particularly in 1906 and 1931.

That attack includes construction of Bennington Lake, channelization of Mill Creek through Walla Walla, and small dams to divert water from Mill

Creek into Garrison and Yellowhawk Creeks that run south of the city. From Bennington Lake, potentially one of the largest off-stream flood storage projects in the state (Mills, 1989), water can drain into Russell Creek or back into Mill Creek. The earth–rock dam for Mill Creek Reservoir has never been able to hold much water without leaking. Much of the way through Walla Walla, Mill Creek's channel has concrete sides and bottom. The creek runs beneath many downtown buildings. Garrison, Yellowhawk, and Russell Creeks flow into the Walla Walla River. Floodwaters diverted into these creeks would not re-enter Mill Creek.

Figure 68. View northwest of the Little Grand Canyon south of Lowden. Serious erosion of the Touchet Beds began in 1926; today the canyon is 36 m deep. See text for details. The predominant land use here is alfalfa seed production.

202.9 Take Rees Avenue exit from U.S. Highway 12 and proceed southeasterly.

203.0 Veer southerly on Park Street.

203.4 The Whitman College parking lot is to the left (east). This marks the end of field trip.

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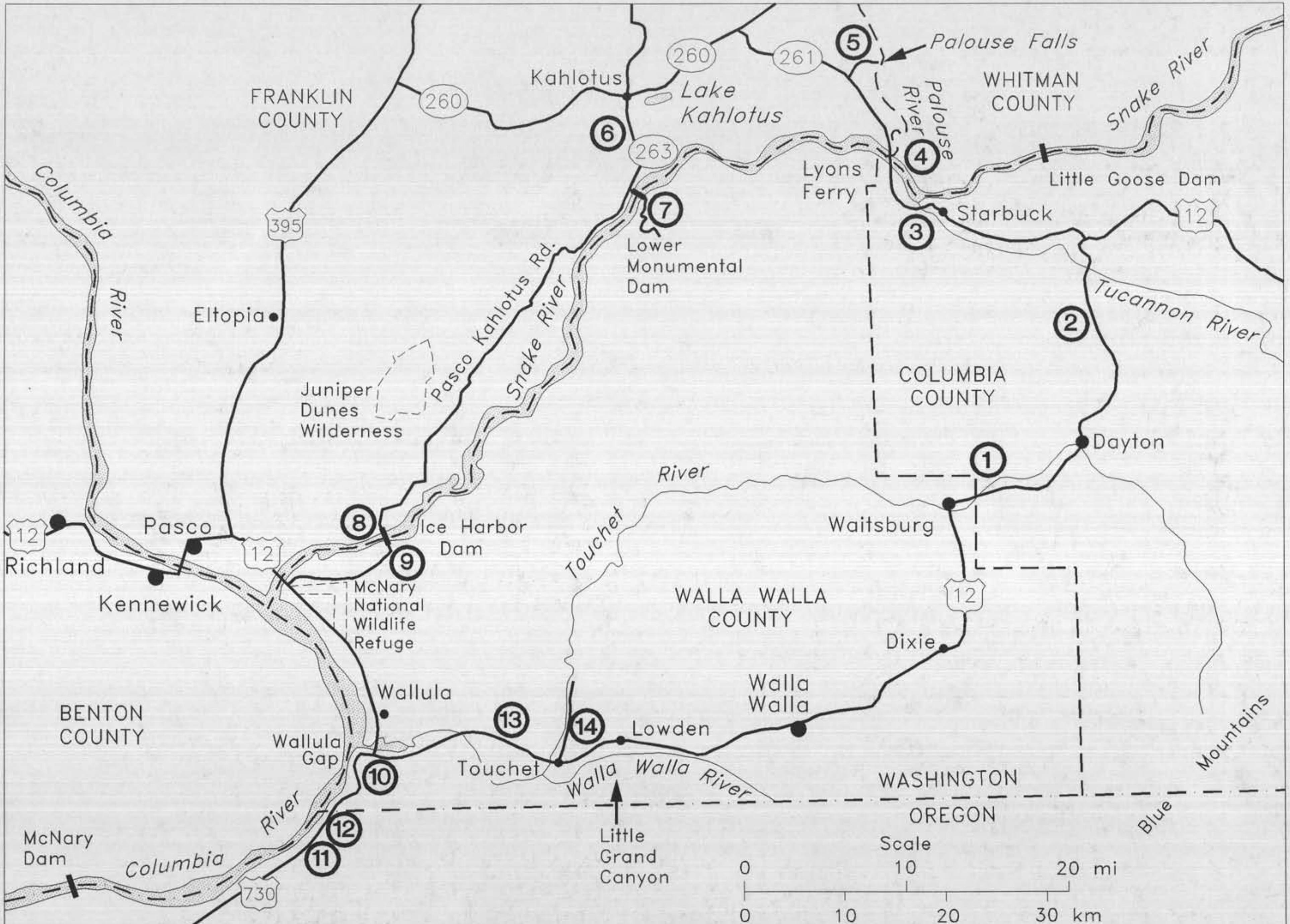

Route of the field trip. Stop locations are indicated by the circled numbers.