NATURAL RESOURCES

Geologic Field Trip to the Aldercrest–Banyon Landslide and Mount St. Helens, Washington, Part I—Stevenson to Castle Rock

compiled by
Karl W. Wegmann

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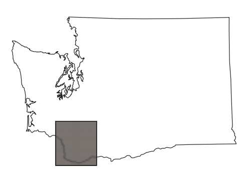

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Doug Sutherland - Commissioner of Public Lands

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Cover photos
Top: Main scarp of Aldercrest–Banyon landslide. Photo by Karl Wegmann.
Bottom: April 1983 ash and gas emission from Mount St. Helens. Photo by Pat Pringle.

Geologic Field Trip to the Aldercrest–Banyon Landslide and Mount St. Helens, Washington, Part I—Stevenson to Castle Rock

Prepared for the 96th Annual Meeting of the Association of American State Geologists, June 12–16, 2004
Field trip led by Karl W. Wegmann and Patrick T. Pringle

compiled by Karl W. Wegmann

Note: This field trip guide represents modified excerpts from Allen (1979) [miles 0 to 46 of this road guide], Deacon and others (1988) [miles 46 to 78 and 81 to 90.6 of this road guide], and Burns and others (2002) [miles 78 to 81 of this road guide]. Part II of the field trip (Castle Rock to Mount St. Helens) is described in Leg A of Pringle (2002).

WASHINGTON STATE GEOLOGY

Washington is uniquely positioned for the study of the geologic and structural setting of western North America. To the south in Oregon and Nevada, extensional features predominate as reflected by basin-and-range terrain. To the east, the Rocky Mountains influence the geology of Idaho. To the north, a massive coastal crystalline belt and remnants of the Wrangellia geologic continent characterize western British Columbia. All of these major crustal features of the adjacent regions terminate in or near Washington. The state's uniqueness is further enhanced by three major geologic conditions. First, Washington is impacted by crustal tectonics as the oceanic Juan de Fuca plate is being subducted under the North American continent (Fig. 1). Second, the Columbia Basin (Fig. 2) in Washington and adjacent Oregon was subjected to great outpourings of basalt. Third, alpine and continental glaciation and glacial floods have created spectacular landforms in the North Cascades, Puget Sound, and the Channeled Scablands.

Washington's geology is highly diverse. Rocks of Precambrian age, as well as units from every geologic period, Cambrian to Quaternary, are represented. The state has been subject to continental collisions, metamorphism, intrusion of igneous rocks, volcanism, mountain-building episodes, erosion, glaciation, and massive flooding events. This diversity has a strong influence on soil productivity, location of mineral deposits, scenic grandeur, and even the climate. *(Modified from the USGS/Cascades Volcano Observatory website at* http://vulcan.wr.usgs.gov.)

The Columbia River

The Columbia River pours more water into the Pacific Ocean than any other river in North or South America. In its 1270-mile (2045 km) course to the Pacific Ocean, the Columbia flows through four mountain ranges—the Rockies, Selkirks, Cascades, and coastal mountains—and drains 258,000 square miles (670,000 km^2). The main stem of the Columbia rises in Columbia Lake on the west slope of the Rocky Mountains in Canada. Its largest tributary, the Snake River, travels 1038 miles (1670 km) from its source in Yellowstone National Park in Wyoming before joining the Columbia.

The Columbia River Gorge is a spectacular canyon cutting through the Cascade Range. The Gorge is 80 miles (130 km) long and up to 4000 feet (1200 m) deep, with the north canyon walls in Washington State and the south canyon walls in Oregon State. The gorge is the only near sea-level passage through the Cascades.

When Lewis and Clark explored the region in the early 19th century, huge numbers of salmon returned to spawn every year. "The multitudes of this fish are almost inconceivable," Clark wrote in the autumn of 1805. At that time, the Columbia and its tributaries provided 12,935 miles (20,800 km) of pristine river habitat. (*Modified from a U.S. Army Corps of Engineers information brochure).*

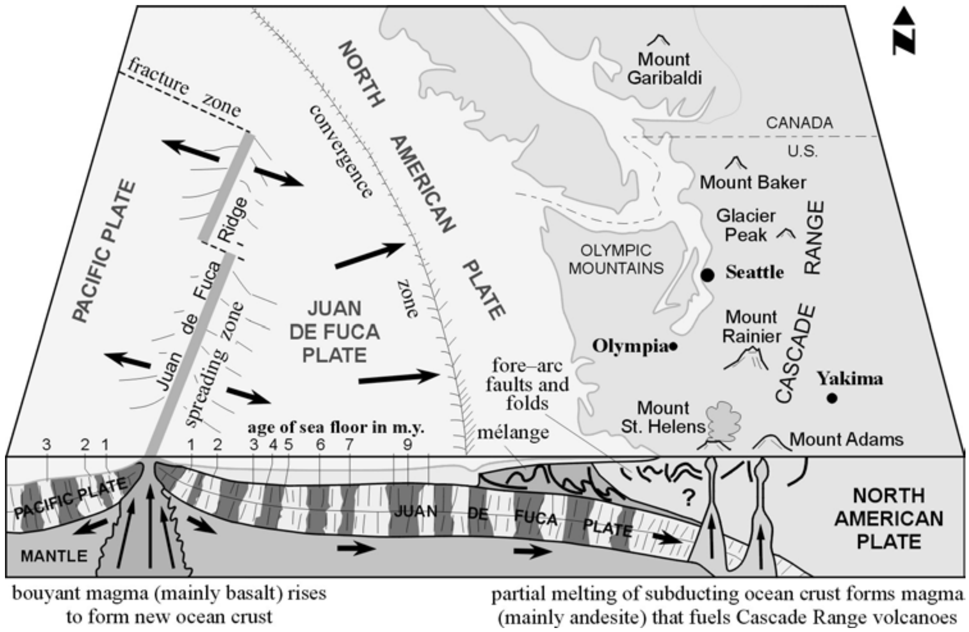

Figure 1. A diagrammatic cross section through the Juan de Fuca spreading ridge and the Cascadia subduction zone (the area from the convergence zone east to where the Juan de Fuca plate sinks beneath the North American plate), showing the magnetic orientation of the sea floor recorded at the Juan de Fuca spreading ridge. Darker stripes in the cross section of the sea floor indicate times when rock was created with a magnetic orientation of north. Notice that the age of the ocean floor is progressively older with distance from the spreading zone. The pattern of ages approximately parallels the ridge on both sides. Mélange is a jumbled mixture of continental shelf blocks and oceanic sediments that is faulted and sheared at shallow depths in the subduction zone. Fore-arc folds and faults occur in a zone of crustal deformation between the subducting sea floor and the volcanic arc. Redrawn from Foxworthy and Hill (1982), Uyeda (1978), and Pringle (2002).

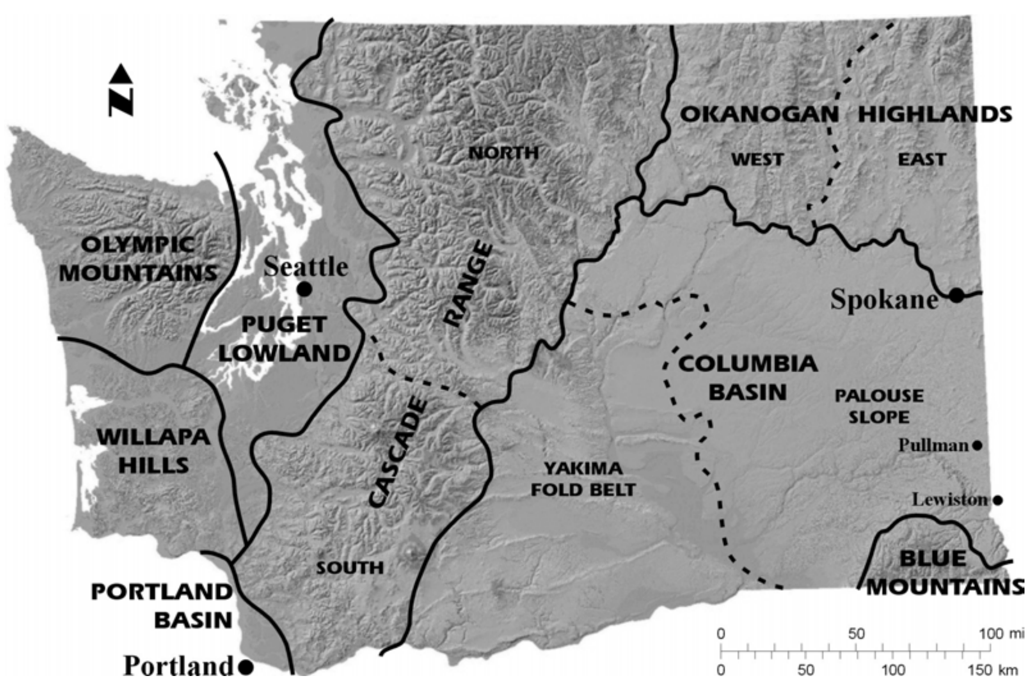

Figure 2. The physiographic provinces and subprovinces of Washington State. Subprovinces are separated by a dashed line. The Columbia River Basalt Group underlies the Columbia Basin, part of the Portland Basin, and part of the Willapa Hills, as well as adjacent areas of Oregon and Idaho.

Columbia River Basalt Group

The Columbia River Basalt Group (CRBG)(Fig. 3) is the principal rock unit in the gorge. The CRBG is a series of basalt flows (flood or fissure basalts) that were erupted between 17 million and 6 million years ago during the Miocene. The flows originated from northwest-striking feeder dikes in eastern Washington and Oregon and spread westward across the Columbia Basin (Figs. 2 and 3). Most of the lava flooded out in the first 1.5 million years—an extraordinarily short time for such an outpouring of molten rock. It is difficult to conceive of the enormity of these eruptions. Basaltic lava erupts at no less than about 1100°C. Basalt is a very fluid lava; it is likely that tongues of lava advanced at an average of 3 miles per hour (5 km/hr). Whatever topography was present prior to the CRBG eruptions was buried and smoothed over by flow upon flow of lava. More than 300 high-volume individual lava flows have been identified, along with countless smaller flows. Numerous linear vents, some over 100 miles (150 km) long, show where lava erupted near the eastern edge of the Columbia Basin, but older vents were probably buried by younger flows. *(From the USGS/Cascades Volcano Observatory website.)*

The flows now cover approximately 105,000 square miles (272,000 km^2) and total about 41,830 cubic miles (175,000 km^3) of basalt (Tolan and others, 1989). On the basis of geophysical evidence, the basalts are known to reach a maximum thickness of 16,000 feet (5000 m) in the Pasco Basin. Twenty-one of these flows poured through the Gorge, forming layers of rock up to 2000 feet (600 m) thick. The CRBG is divided into five formations, but only three, the Grande Ronde, Wanapum, and Saddle Mountains Basalts, are exposed in the tour area.

Geologists distinguish the various flows of the CRBG by examining their physical features, geochemistry, and paleomagnetism (Swanson and others, 1979a,b). Chemical composition and paleomagnetic data have proven to be the most reliable criteria for flow identification and correlation.

Glacial Floods

Quaternary deposits in the gorge are those of the cataclysmic Missoula (or Spokane) floods. The Cordilleran ice sheet from Canada advanced several times during the Pleistocene and covered parts of Washington, Idaho, and Montana. The ice formed dams on the Clark Fork River on the Idaho–Montana border and created glacial Lake Missoula (Pardee, 1910)(Fig. 3). The lake covered 3000 square miles (7800 km^2) of western Montana and held 600 cubic miles (2500 km^3) of water (Carson and Pogue, 1996).

The ice dams failed repeatedly releasing gigantic glacial floods that swept across northern Idaho, through the Spokane Valley, southwestward across eastern Washington, and down the Columbia River Gorge enroute to the Pacific Ocean (Carson and Pogue, 1996). The Missoula floods are the largest known floods on Earth in the last two million years; the flow of water was ten times the combined flow of all the rivers of the world. In eastern Washington, the floods created the Channeled Scablands, an area studied by J Harlen Bretz in the 1920s. Bretz was the first person to describe these gigantic glacial floods.

The flood crest at Wallula Gap on the Columbia River at the Washington–Oregon border was about 1200 feet (365 m) as evidenced by glacial erratics that were left stranded on the hillside. The water poured down the Columbia Gorge and widened the valley by cleaning off all the soil and talus up to 1000 feet (300 m) elevation as far as The Dalles, Oregon. By the time it reached Crown Point, the surface of the last flood had dropped to about 600 feet (180 m) elevation (Allen, 1979).

There may have been more than 40 major glacial floods (Waitt, 1980) recorded by bedded slack water deposits (rhythmites). The average interval between Missoula floods was about 30 years (Waitt and others, 1994). The last flood occurred 13,000 years ago.

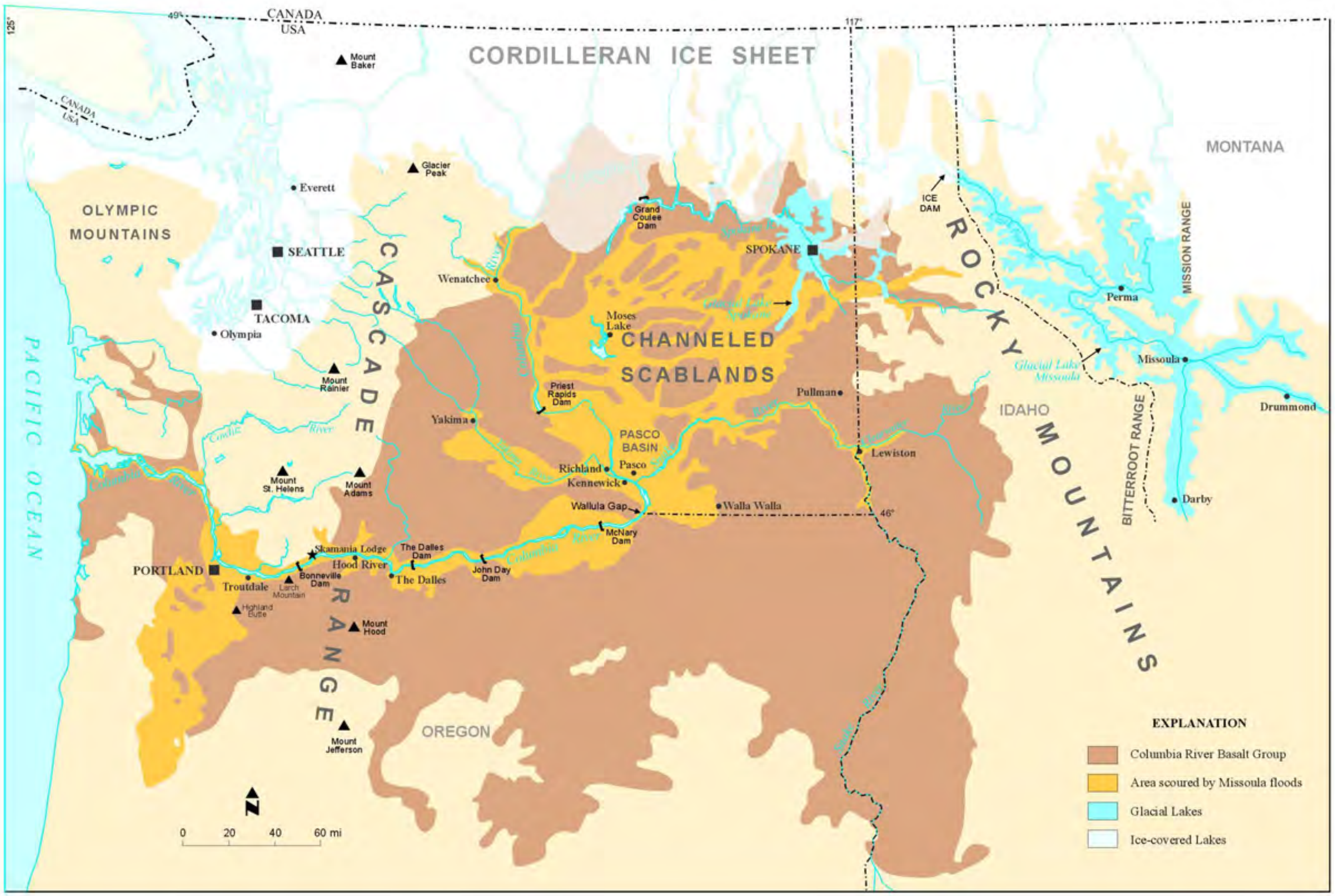

Figure 3. The probable extent of the Cordilleran ice sheet, ice-dammed glacial lakes, Missoula floods, and Columbia River Basalt Group. The failure of the ice dam of the Clark Fork River in western Montana released a 2000 ft (600 m) wall of water that rushed across eastern Washington again and again, eroding a series of intertwining canyons called coulees. This area is known as the Channeled Scablands. The various flood pathways converged in the Pasco Basin, where there was a narrow exit for the waters—Wallula Gap. The narrowness of the gap caused the floodwaters to back up and form a 1200-foot (365 m)-deep lake covering over 3500 square miles (9000 km^2). Several other temporary lakes were created by similar events near The Dalles and Portland, Ore. (Modified from Waitt, 1985, and Weis and Newman, 1989. Extent of the Columbia River Basalt Group from Reidel and others, 1994.)

ROAD GUIDE

The field trip route is shown on Figure 4. It starts at Skamania Lodge in Stevenson, Washington (45°41’12.8”N, 121°54’21.5” W). Skamania Lodge was constructed on the eastern edge of the large Cascades landslide complex (see Fig. 6), which is generally considered to be stable ground today. The lodge provides an excellent view of the river, the Columbia River Gorge, and the landslides. Turn right (south) onto Rock Creek Drive and travel approximately 0.25 miles (0.4 km).

In order to know where to look for points of interest, the “o’clock” system is used, with the front of the vehicle as 12:00, the rear as 6:00. Figure 5 illustrates the system.

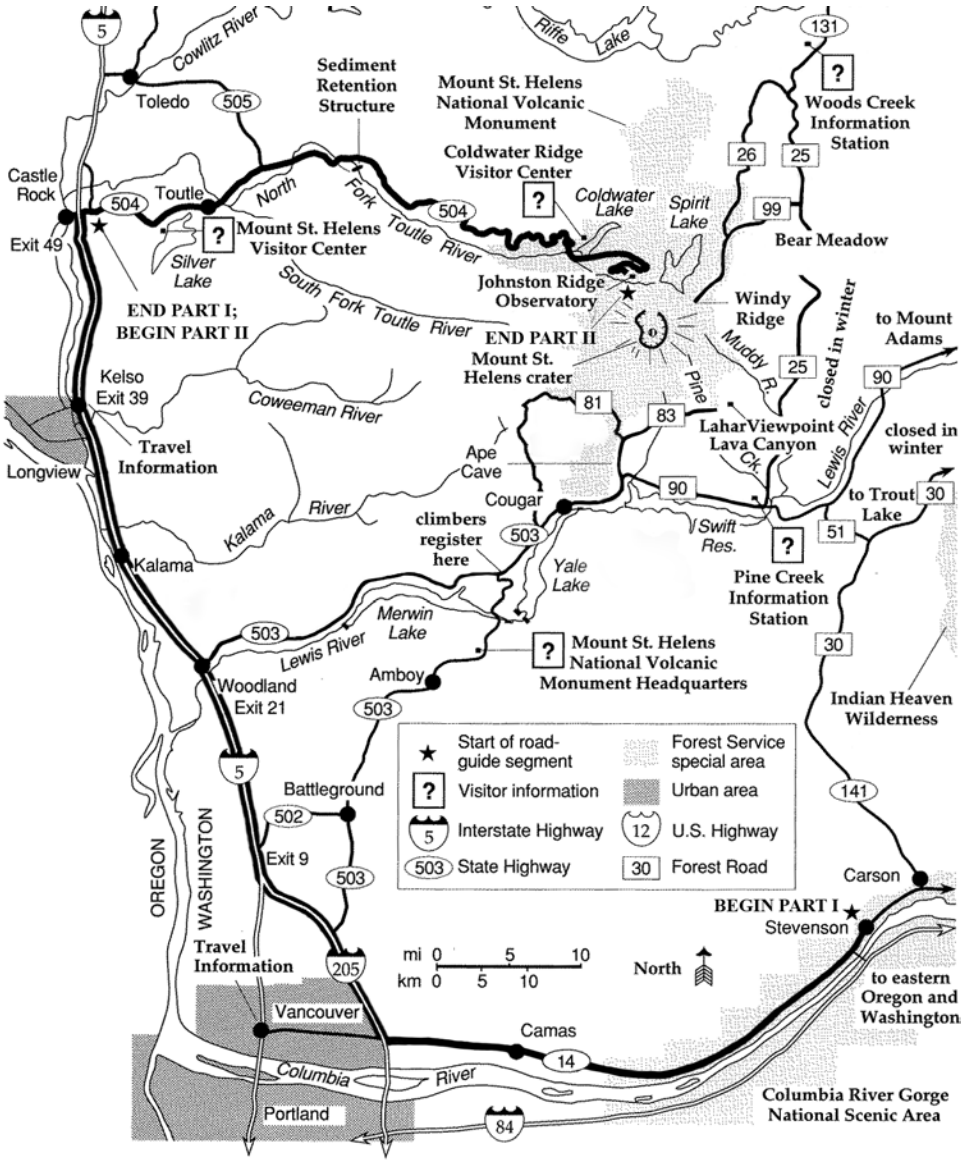

Figure 4. Location map of southwest Washington, showing the route of this road guide and of Part II of the field trip. Modified from Pringle (2002).

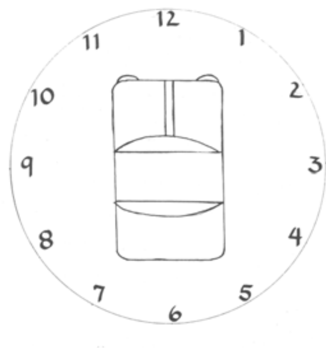

Figure 5. The "o'clock" system used to express directions in this road guide.

Mileage

0.0 **Start Trip Odometer.** Turn right at the road junction onto State Route (SR) 14 (milepost [MP] 43.09) at the western city limits of Stevenson. You are now skirting the toe of the Cascades landslide complex. Note the hummocky ground and the jumble of rocks from different formations in the slide. As you pass Ashes Lake (on your right), you have a good view of the cliffs forming the scarp at the head of the landslide.

The Cascades landslide complex is an impressive example of mass wasting created by multiple events. The source area includes portions of Table Mountain and Red Bluffs (Fig. 6). The landslide complex covers 12 to 14 square miles (30–36 km^2), with individual slide deposits of about 2 to 6 square miles (5–13 km^2). The Bonneville landslide, the youngest and largest of the four lobes of the complex, has an area of about 5.5 square miles (14 km^2). Debris from the source area of the Bonneville landslide reached as far as 3 miles (5 km) to the southeast (Figs. 6 and 7) and buried the pre-slide Columbia River channel, which was about 1.5 miles (2.5 km) north of its present location (Shannon & Wilson, 1978). The landslide substantially diverted the river channel toward the Oregon shoreline (Wang and others, 2002; Palmer, 1977).

In the late 1970s, the U.S. Army Corp of Engineers studied the Bonneville landslide for the purpose of additional construction at the Bonneville Dam site. The study found that "the mechanics of failure involved a planar movement in the rock mass and a subsequent lateral spreading at the toe of the slide. Sand liquefaction was [interpreted as] the failure mechanism for this lateral spreading. Remnant slide blocks are found surrounded by a matrix of fine mica sand" (Shannon & Wilson, 1978). It has been proposed that the high-energy deposition resulted in liquefaction and injection of sandy dikes of the debris-covered alluvium up into the landslide deposit (Wang and others, 2002; Scofield and others, 1997).

The river water impounded by the Bonneville landslide rose 275 to 300 feet (85 to 90 m), creating a lake that stretched almost 70 mi (113 km)(up to the present-day John Day Dam) (Holdredge, 1937; Jim O'Connor, U.S. Geological Survey, written commun., 2004). Within a few months, the Columbia rose high enough to wash through the southern side of the landslide creating a flood of water that was 100 feet (30 m) deep at Troutdale, Oregon (approximately 30 miles [50 km] downstream) (Scofield and others, 1997). Afterwards, things returned to normal, except that the river was displaced a mile to the south and the Cascade Rapids had formed. Evidence for the landslide dam includes submerged tree stumps observed upstream (Lawrence, 1937; Lawrence and Lawrence, 1958). Evidence for catastrophic flooding from the breach has been observed downstream near the mouth of the Sandy River and at other locations (O'Connor and others, 1996; Lunney and Taylor, 2000). The Cascade Rapids, which developed from the breaching of the landslide dam, and the submerged forests were later inundated by the reservoir of the Bonneville Dam in 1938 (Schuster and Pringle, 2002).

Although the Bonneville landslide complex has been extensively studied, the exact age of the slide remains a controversy. An 1830s account of an earlier Native American legend describes the Cascade Rapids as follows: "The Indians say those falls are not ancient, and that their fathers voyaged without obstruction in their canoes as far as The Dalles. They also assert that the river was dammed up at this place, which caused the waters to rise to a great height far above and that after cutting a passage through the impeding mass down to its present bed, those rapids first made their appearance" (Lawrence, 1937). Another legend tells of the sons of Old Coyote, Wy'east (Mount Hood) and Pahto (Mount Adams), powerful braves both in love with a maiden (Mount St. Helens). Because they crossed the "Bridge of the Gods" to fight over their love for her, Old Coyote collapsed the land bridge to keep his sons from fighting. This "Bridge of the Gods" landslide dam was formed by the Bonneville landslide. Recent radiocarbon studies indicate a calendar age of some time during the 15th century for this landslide (Pat Pringle, Wash. Div. of Geology and Earth Resources, oral commun., 2004).

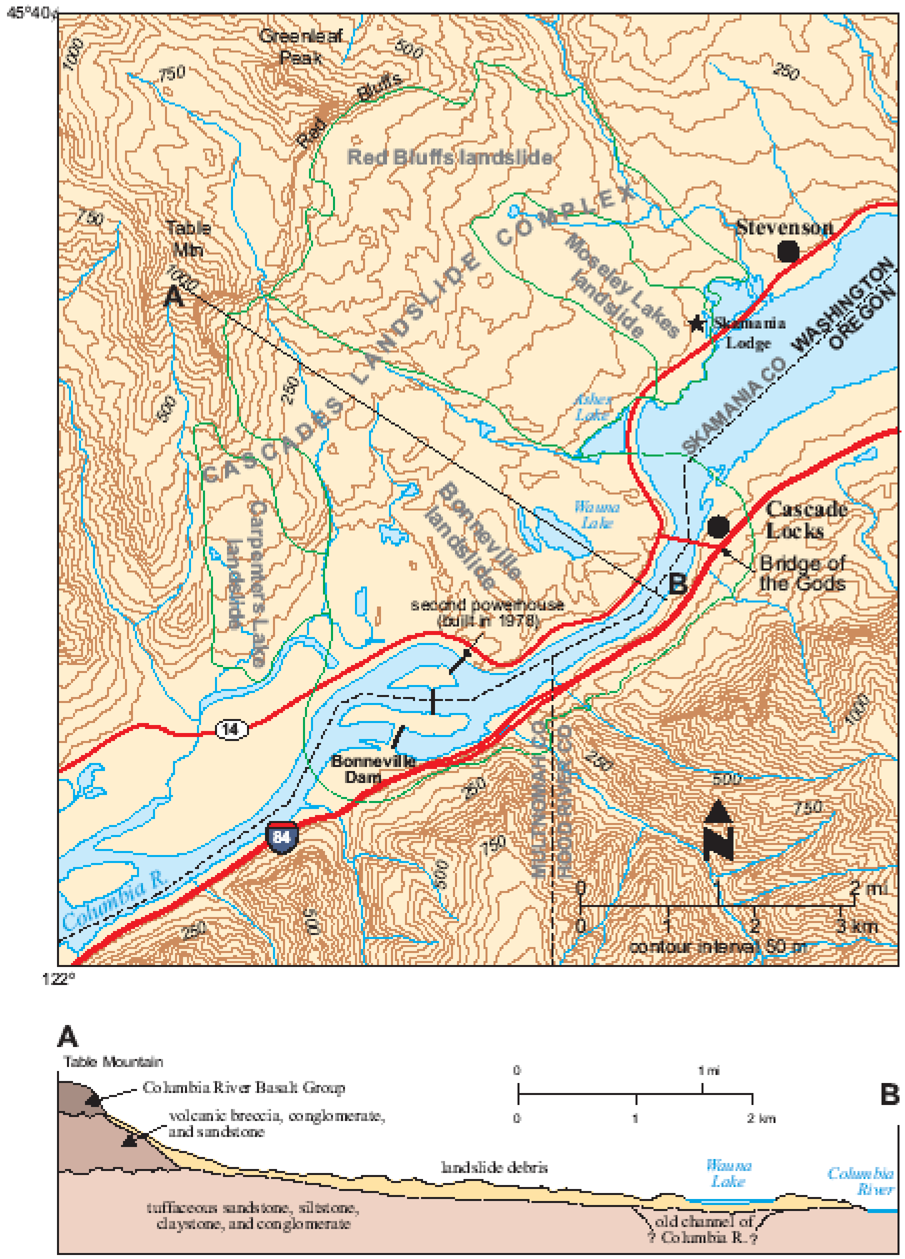

Figure 6. Approximate boundary of the Cascades landslide complex, dashed where the approximate maximum extent is inferred (after Schuster and Pringle, 2002), and a simplified cross section through the Bonneville landslide from Table Mountain to the southern shore of the Columbia River (after U.S. Army Corps of Engineers, 1976).

Figure 7. Bonneville landslide (wooded area) as seen from Cascade Locks. Table Mountain (3417 feet [1042 m]) is on the left and Greenleaf Peak (3422 feet [1043 m]) is to the right of Table Mountain, in the upper center of the photograph. Red Bluffs is the scarp area just below Greenleaf Peak. The Bridge of the Gods is partially visible in the lower right of the photograph, and Skamania Lodge is just out of camera view to the right. Photo courtesy of Derek Cornforth.

0.9 Ashes Lake on the right is a remnant of the pre-landslide main channel of the Columbia River (Fig. 6) (SR 14 MP 42.3).

1.3 Entering the east margin of the Bonneville landslide deposit (Fig. 6) (SR 14 MP 41.9). Note the small lakes upon the hummocky surface.

1.4 Junction with Ash Lake Road (SR 14 MP 41.7). A side trip up this road gives a spectacular view of the chaotic nature of a large slide.

1.55 Junction with Bridge of the Gods Road (SR 14 MP 41.55).

2.05 The lava rim of Sheridan Point on the right is a huge mass of intact lava brought downslope by landslide movement (SR 14 MP 41.04).

2.57 Cross a railroad overpass (SR 14 MP 40.52). The railroad tunnel in the landslide lies on the right. Eagle and Tanner Creeks, from 8:00 to 10:00, are major side canyons cut deeply into the south wall (Oregon side) of the Gorge, with Wauna Point between. The bare ridge of Munra Point lies west of Tanner Creek.

3.35 The second powerhouse for Bonneville Dam lies on the old town site of North Bonneville (SR 14 MP 39.74). Slide material was removed down to a bedrock knob of solid Eagle Creek Formation which once formed part of the south bank of the Columbia River. The early Miocene Eagle Creek Formation consists of coarse cobble gravels (mudflow deposits) and other, mostly andesitic, volcaniclastic rocks. The highway follows the approximate former course of the river. At 9:00 is Bonneville Dam, whose south abutment is anchored in Bonney Rock, a 250 feet (75 m) wide dike of basalt younger than the Columbia River Basalt Group.

4.55 Junction with a road to right leading to Moffetts Hot Springs (SR 14 MP 38.54). This is the western edge of the Cascade Range hot springs zone, which extends south for over a hundred miles through Austin Hot Springs on the Clackamas River, Breitenbush Hot Springs on the North Santiam River, Belknap and Foley Hot Springs on the McKenzie River, and McCredie and Kitson Hot Springs on the Willamette River (all in Oregon). On the Columbia River, the zone is about 10 miles (16 km) wide and contains five springs.

5.5 Town of North Bonneville on the left (SR 14 MP 37.59). Aldrich Butte lies above at 3:00.

5.6 Bridge over Hamilton Creek (SR 14 MP 37.48). Hamilton Mountain to the north is a fine example of "reversed topography". It is mostly composed of horizontally bedded Eagle Creek Formation, in which an ancient valley was cut by a stream, and then filled with an intracanyon flow of Grande Ronde Basalt (part of the Columbia River Basalt Group), which extends only about 2 miles (3.2 km) to the north of the summit. The softer Eagle Creek sediments have been eroded away, leaving the lava-filled former valley high on the north wall of the Gorge. The west side of the valley includes foreset-bedded palagonite tuff deposited in a lake caused by the damming of this ancient stream. The spectacular pinnacle of Beacon Rock looms ahead to the west (Fig. 8).

7.0 Cross Hardy Creek (SR 14 MP 36.09). The view to the south is of Nesmith Point, a half-eroded Quaternary basaltic volcano on the rim of the Gorge, with Yeon Mountain to the west, rimmed by lava flows from the same volcano, and St. Peters Dome, an isolated peak of Grande Ronde Basalt flows set out from the Gorge wall below the rim.

8.2 Beacon Rock State Park (SR 14 MP 34.89). Beacon Rock, named by Clark in a journal on November 2, 1805, is an olivine basaltic plug or neck that rises 840 feet (256 m) above river level (Fig. 8). It was here that the expedition first observed Pacific Ocean tidewater. The rock was once thought to be the eroded vent-filling of a Pliocene volcano (Allen, 1979); however, recent age dates by Jack Fleck of the U.S. Geological Survey (USGS) suggest an age of only 50 to 60 ka (Russ Evarts, USGS, written commun., 2004). It is the southernmost of several necks (or a great north–south dike) extending to the north for more than 2 miles (3.2 km), and is red, scoriaceous, and vesicular near the summit. Baked contacts with the Eagle Creek Formation are found to the south and southwest. The columnar structure on the east side is horizontal (east–west); on the west side, the columns are vertical (Allen, 1979). The original landowner who donated it to the state laboriously constructed a trail and stairway with 48 switchbacks. It climbs the 500 feet (150 m) to the summit, and affords a splendid view up and down the river.

For the next 10 miles (16 km) to the Cape Horn viewpoint, roadcuts are in landslide material, mostly of the Eagle Creek Formation. Boulders in the cuts are mostly of pyroxene andesite.

Figure 8. View to the east-northeast of Beacon Rock, the eroded remnants of a 50 to 60 ka volcanic plug or neck. Photo by Dave Norman.

8.8 Cross Woodward Creek (SR 14 MP 34.29). The road to the left leads to a lower campground and boat moorage.

10.05 Passing through the town of Skamania, an Indian name meaning "swift waters" (SR 14 MP 33.04).

11.4 Franz Road junction on the right (SR 14 MP 31.69). Huge landslide blocks to be seen alongside the highway are of Grande Ronde Basalt, from Archer Mountain and the long narrow Prindle Mountain on the skyline ahead. Views of the Gorge waterfalls may be seen across the river.

16.8 Canyon Creek Road (Old State Route 140) on the right, leading north to the Washougal River (SR 14 MP 26.29). For the next 2 miles (3.2 km) we will pass around the head of the Cape Horn landslide. The cliffs of Cape Horn are of Grande Ronde Basalt, overlain by Troutdale Formation (Pliocene ancestral Columbia River sediments) and by Quaternary (Boring) lavas to form an upland surface. Note the long ridge of basalt below to the left, which has dropped down and pulled away from the upper slopes to form a landslide valley.

17.8 Highway cut exposes three flows of Grande Ronde Basalt (SR 14 MP 25.29). Steel netting is necessary to prevent rocks from falling on the highway. Several pull-offs on the left provide excellent views of the Gorge.

18.05 Cape Horn viewpoint on the left (SR 14 MP 25.04). Looking east to Beacon Rock at 12:00 (Fig. 9), you can see Bobs Mountain at 10:00, one of a north–south line of Quaternary cinder cones, so recent that parts of their crater depressions are still preserved. At 11:00 other cinder cones cap the ridge to the north of Prindle Mountain, which, like Archer Mountain in the middle distance and Hamilton Mountain beyond, are all composed of Grande Ronde Basalt. The subdued topography beneath the cliffs are landslides. At 2:00 Phoca Rock (named after the harbor seal, *Phoca vitulina,* which inhabited the river in early days) is a remnant of the Cape Horn landslide, which probably post-dates the late Pleistocene Missoula floods. On the skyline above Phoca Rock is Larch Mountain, the highest (over 4000 feet [1220 m] elevation) and largest Quaternary basaltic shield volcano near the west part of the Gorge. Angels Rest and Devils Rest crest the cliffs beneath. Palmer Peak and Nesmith Point volcanoes are seen farther up the river at 1:00. Pepper Mountain can be seen at 3:00. The roadcut across the highway exposes loessal soil resting on bouldery gravels of flood origin on top of Grande Ronde Basalt. At least 3 flows of basalt occur above and 2 below the highway. Here the total thickness of flows are less than 800 feet (240 m) near the river, and they thin to 200 feet (60 m) within 2 miles (3.2 km) to the north, suggesting that they lapped against the north wall of the Miocene canyon. During the next mile (1.6 km) west, we will cross outcrops of Quaternary lava from Mount Zion volcano, which lies less than a mile (1.6 km) northwest of here.

Figure 9. View to the east from Cape Horn viewpoint. Beacon Rock is visible midway along slope on the Washington (north) side of river in the upper left portion of the photograph. The low-angle slopes visible in the foreground out to Beacon Rock are mostly landslide deposits. The high point on the Oregon (south) side of the Columbia, in the upper right portion of the photograph, is Larch Mountain, the highest and largest Quaternary basaltic shield volcano near the west part of the Gorge. Angels Rest and Devils Rest are cliffs beneath. Palmer Peak and Nesmith Point volcanoes are seen farther up the river on the Oregon (south) side.

18.8 The highway crosses the surface of Pliocene–Pleistocene basaltic lava flows (SR 14 MP 24.29). These particular flows compose the basalt of Mount Zion. Mount Zion, the eruptive center, lies approximately 1 mile (1.6 km) due north of here at 3:00. Crown Point lies at 11:00 across the river (Fig. 10).

Figure 10. Crown Point as seen from the north, across the Columbia River. Crown Point is a remnant of a thick intracanyon flow of the Priest Rapids Member of the Wanapum Basalt of the Columbia River Basalt Group (Tolan and others, 1984) that filled an early ancestral canyon of Columbia River to a total thickness of nearly 700 feet (200 m). In the face of the bluff, the lower 130 feet (40 m) of the fill is palagonite tuff, carried westward and foreset bedded by the ancestral Columbia River. Lava then advanced onto the hyaloclastic fill, piling up quickly in a series of flows to a thickness of 555 feet (170 m). The entire thickness of lava congealed as one cooling unit with an 80-foot (25 m) basal colonnade and a very thick (475 feet [145 m]) hackly entablature (Waters, 1973). Photo by Dave Norman.

19.53 Roadcut exposes a narrow vertical fissure zone of volcanic scoria, breccia, and slabby jointed olivine basalt, possible a minor vent on the south slope of Mount Zion volcano (SR 14 MP 23.56). Directly below this point the south-dipping upper surface of the Grande Ronde Basalt plunges below river level. This is almost 4 miles (6.4 km) east of the point where it goes below river level on the south side at Corbett Station, suggesting that there may be a fault beneath the river, with the south side either dropped down, moved to the west, or both.

19.64 Junction with Belle Center Road (SR 14 MP 23.45). Outcrops are of olivine basalt from Mount Pleasant, another Pliocene–Pleistocene cinder cone that lies 1 mile (1.6 km) to the northwest.

20.1 Marble Road junction (SR 14 MP 22.99).

21.32 Enter Clark County (SR 14 MP 21.77). Troutdale Formation conglomerates are exposed in roadcuts for the next 0.25 mile (0.4 km). Late Pleistocene Missoula flood gravels, deposited at 700 feet (215 m) elevation, here overlie the Troutdale Formation conglomerates.

22.2 Good exposures of Troutdale Formation, the ancient river deposits that filled the ancestral valley and basins during Pliocene time (SR 14 MP 20.89). The varied composition of the cobbles and pebbles tells us much about the geologic history of the river. Although many of the pebbles are of volcanic rocks abundant in the Cascade Range, both plutonic and metamorphic rocks also occur, rocks that must have come more than 300 miles (480 km) from the upper reaches of the river in British Columbia and the Rocky Mountains. The light-colored pebbles of quartzite (a metamorphosed sandstone) are especially characteristic of the Troutdale Formation. Note also the shingle-like arrangement of the cobbles, and the west-dipping foreset bedding, which indicate that the river also flowed from east to west more than 2 million years ago. Numerous outcrops of Troutdale Formation appear for the next mile (1.6 km).

22.18 Cross Lawton Creek (SR 14 MP 20.91). Numerous large boulders of olivine basalt were probably derived from the Mount Pleasant lava flows, undermined by the Missoula glacial outburst floodwaters and rolled down the hill. Chamberlain Hill, another Quaternary basaltic volcano, lies across the river at 10:00, capping slopes of Troutdale Formation at Broughton Bluff, east of the town of Troutdale.

24.2 Junction with Evergreen Boulevard; continue on the main highway (SR 14 MP 18.89). You are now crossing the modern floodplain of the Columbia River, with east Portland in view on the left. Prune Hill, composed of Troutdale Formation, lies at 12:00 above the town of Camas. It is capped on the south and west spurs by two small cinder cones, the westernmost volcanoes to be seen on the Washington side of the river. A thick lava flow from one of these vents has been mined for many years in Fisher Quarry for jetty rock.

27.0 Junction with 15th Street in Camas (Old State Route 140 to Washougal and the Washougal River country) (SR 14 MP 16.09). At 4:00 on the skyline, Silver Star Mountain rises to 4650 feet (1415 m) elevation. It is composed of Late Eocene through Oligocene calc-alkaline volcaniclastic sediments, intruded on the east slopes by the Silver Star stock, a deep-seated intrusion of granodiorite and quartzdiorite, whose hot juices formed a few small copper deposits. This stock is the nearest granitic intrusion to Portland. The low-lying hills immediately north of Washougal are also calc-alkaline volcaniclastic sediments (locally known as Skamania Volcanics), surrounded and overlapped by Troutdale Formation. In the Miocene they were hills lying north of the main Columbia River valley, and high enough never to have been covered by any of the floods of the Columbia River Basalt Group.

28.46 Junction with State Route 500 leading to the town of Camas at 2:00, identified both visually and olifactorially by the paper mills (SR 14 MP 14.63).

29.33 Cross Camas Slough (SR 14 MP 13.76). Prune Hill, above the paper mill, like the hills in east Portland, is composed largely of Troutdale Formation, which has been cemented by mineral waters heated by an intrusion of Pliocene to Quaternary basalt, so that it (and Mount Tabor, Kelly Butte, and others) became resistant to erosion by late Pleistocene glacial outburst floods.

30.27 Cross the bridge across lower Camas Slough (SR 14 MP 12.82). The south-dipping layers exposed north of the slough are late Eocene through Oligocene calc-alkaline volcaniclastic sediments, overlain by Troutdale Formation.

31.54 Blocky jointed flows of Quaternary lava from Prune Hill volcano overlie nearly flat lying late Eocene to Oligocene calc-alkaline tuff beds (SR 14 MP 11.54).

32.82 Brady Road on the right climbs the flank of Prune Hill volcano, which caps the west part of main Prune Hill (SR 14 MP 10.27).

33.3 Roadcuts on the right expose Quaternary lava flow (SR 14 MP 9.79)

33.64 Fisher Quarry on the right (SR14 MP 9.45). Quaternary lava from Prune Hill volcano has been mined for many years to supply giant blocks for the jetties at the mouth of the Columbia. They are trucked beneath the highway overpass to the loading facilities at 3:00, and barged down river.

36.48 Exit State Route 14 onto Interstate 205 North (towards Seattle) (SR 14 MP 6.61).

36.8 Merge onto Interstate Highway 205 (I-205) North (I-205 MP 27.54). I-205 was constructed across late Pleistocene glacial outburst flood bar deposits (Missoula floods) of primarily gravels and sands. The entire 10-mile (16 km) distance we will travel on I-205 until the I-5 interchange is built upon glacial flood bar deposits.

45.26 Cross Salmon Creek (I-205 MP 36.00). The valley of Salmon Creek is cut into late Pleistocene glacial outburst flood (Missoula flood) sediments.

46.45 Exit I-205 onto I-5 North (I-205 MP 37.16).

46.75 Merge onto I-5 North (I-5 MP 7.68)

54.52 Weigh station on the right (I-5 MP 15.45). Possible views of Mount St. Helens at 2:00, weather permitting.

57.28 Cross the East Fork Lewis River bridge (I-5 MP 18.21). For the next 34 miles (55 km), the field trip route passes through good exposures of Tertiary volcanic rocks. There are three major groups of volcanic rocks in southwestern Washington: oceanic basalts, Cascade arc andesites, and flows of the Columbia River Basalt Group (Fig. 11).

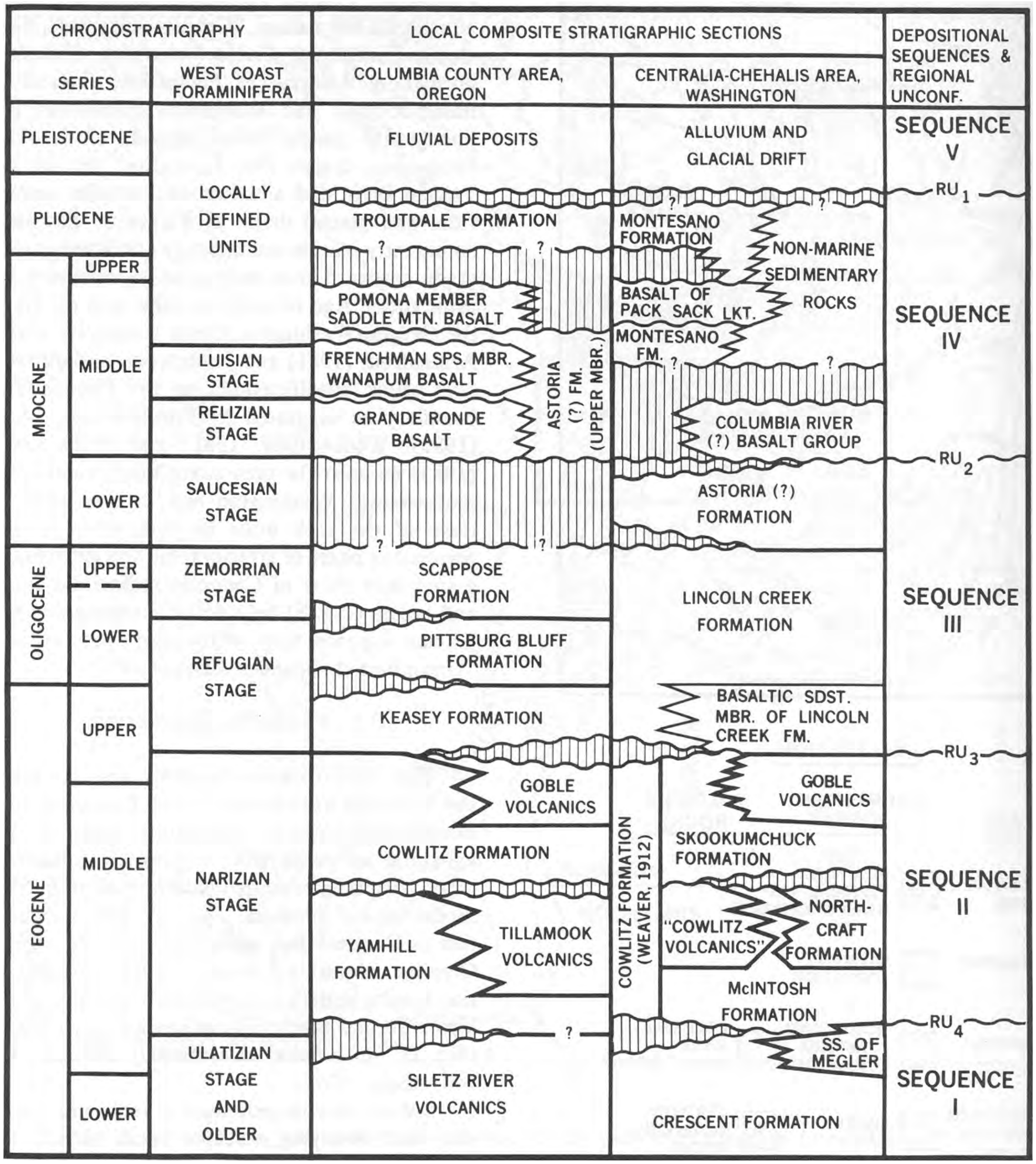

Figure 11. Composite stratigraphic correlation chart for northwest Oregon and southwest Washington (Armentrout, 1987).

The oceanic basalts are represented by the Crescent Formation and the “Cowlitz volcanics”, also known as the Grays River volcanics. The Crescent forms “basement” in southwest Washington and ranges in age from about 55 to 48 Ma (lower to middle Eocene). The volcanic rocks of Grays River are younger than the Crescent, about 45 to about 38 Ma (middle to upper Eocene). Grays River flows are typically high in TiO_2 and are interbedded with the arkosic sandstone and coal of the Cowlitz Formation. The Cowlitz Formation rocks were deposited in shallow-marine and nearshore deltaic depositional environments prior to the onset of subduction-related volcanism in what is now known as the Cascade Range. The inferred source area for arkosic sandstones in the Cowlitz Formation is from pre-Tertiary plutonic and metamorphic terranes in Idaho and northern Washington. Geochemically, the Crescent and Grays River units share similarities with present-day mid-ocean ridge basalts or intraplate oceanic island basalts.

Cascade-derived lavas and pyroclastic rocks are contained within the Goble Volcanics and Toutle Formation. These units record the inception of volcanism along the Cascade arc trend beginning about 38 Ma (late Eocene) and continuing until at least 34 Ma (early Oligocene). The Goble is dominated by lava flows of andesite to basaltic andesite composition, while the Toutle contains abundant andesitic to dacitic pyroclastic flows and associated laharic deposits in addition to nearshore marine deposits.

Columbia River Basalt Group flows that reached western Washington were erupted about 16.5 to 12 Ma (Miocene). These lavas were extruded from fissure vents in southeast Washington and adjacent Oregon and Idaho and flowed to the Pacific Ocean, forming piles of pillow basalts. In some cases, the lavas invaded unconsolidated sediments, creating intrusive structures.

58.96 Cross the Lewis River bridge (I-5 MP 19.86). I-5 is now traveling across Quaternary alluvium at the confluence of the Lewis River and Columbia River.

59.9 Pass through Woodland, Washington. This was the site of extensive flooding and landslide activity in February of 1996 (I-5 MP 20.83).

61.6 Terraced bluffs on the east (I-5 MP 22.53). These bluffs consist of Pliocene to Quaternary continental deposits of Sandy River Mudstone (Trimble, 1963) and Troutdale Formation sediments capped by distal glacial outwash deposits of the Lewis River; the base of the bluffs consists of basaltic andesite breccia of the Goble Volcanics, whose late Eocene age is demonstrated by a $^{40}Ar/^{39}Ar$ age of 37.3 ±0.3 Ma (Evarts, 2002). The continental deposits are micaceous sand and conglomerate. Clasts in the conglomerate consist of Columbia River basalt, Pliocene to Quaternary lavas from the eastern margin of the Portland Basin (Boring Lava), Cascade-derived lavas, and small amounts of granite or quartzite. The sediments of the Troutdale represent deposits of the ancient Columbia River; granite and quartzite clasts are probably from northeast Washington. The Troutdale Formation has yielded fossil leaves assigned to the Pliocene.

62.09 I-5 milepost 23 (I-5 MP 23.02). Directly below the Troutdale are Eocene and lower Oligocene basaltic andesite and andesite lava flows and pyroclastic rocks assigned to the Goble Volcanics. The same rocks are visible to the west across the Columbia River in Oregon where they form the foundation for the Trojan Nuclear Plant. The plant is visible at 9:00 to the west.

63.89 Landslide located on the east side of the interstate (I-5 MP 24.00). On the right (northeast) side is the site of a major landslide that reactivated in February 1996 (Fig. 12). This landslide had one of the largest economic impacts of any individual landslide in Washington resulting from the 1996 winter storm events.

The landslide failure, with an approximate volume of 32,000 cubic yards (25,000 m^3), blocked I-5 and the Burlington Northern–Santa Fe railroad tracks 3 miles (4.8 km) north of Woodland. The initial landslide of about 12,000 cubic yards (9,000 m^3) occurred shortly after 2:00 p.m., February 8. Its initial movement blocked only the northbound lanes of the interstate. On Friday, February 9, Washington State Department of Transportation (WSDOT) was planning to open the northbound lanes at 6:30 p.m., when, shortly after 6:00 p.m., a larger landslide mass of 20,000 cubic yards (15,000 m^3) failed from the same source area and covered all lanes of I-5 as well as the adjacent rail lines. Even after reopening part of the interstate on February 10, northbound traffic was commonly delayed for several hours because only one lane was open in that direction. This situation persisted until February 19 (Harp and others, 1998).

The landslide began as a rotational slump in Pliocene fluvial sediments and remained relatively undeformed until descending a bench about 60 ft above the roadcut of I-5, which was originally about 120 ft high (Blodgett *in* Harp and others, 1998). At this point, the toe portion of the landslide became extremely disrupted and behaved much as a flow as it overran I-5 and the rail lines.

Figure 12. Slump north of Woodland, Washington that covered I-5 and the Burlington Northern–Santa Fe rail line (USGS photo).

The lower bedrock slopes exposed in the roadcut are grayish weathering Goble Volcanics. The Goble Volcanics consist of basaltic andesite and andesite lava flows that are interbedded with nonmarine calc-alkaline volcaniclastic sediments for a stratigraphic package approximately 5000 feet (152 m) thick at the type section between Woodland and Kelso. From Kelso (15 miles [24 km] to the north) to this point, the Goble Volcanics dip generally south.

68.56 Pass Exit 30 to Kalama (I-5 MP 29.58). Note the undulatory, reddish basal contacts of subaerial Goble lava flows and interbedded pyroclastic rocks. Goble quarries near Kalama and across the Columbia River near Goble, Oregon have yielded excellent specimens of some 13 zeolites and 8 associated minerals. The area is famous among mineralogists for fine specimens of chabazite (Fig. 13), mordenite, and levyne. The zeolite *cowlesite* was first described at Goble, Oregon in 1971.

Figure 13. Chabazite, a zeolite common to volcanic vugs found within the Goble Volcanics.

70.82 Crossing the Kalama River with excellent exposures of Goble Volcanics in roadcuts (I-5 MP 31.81). A K-Ar age of 37.4 ±0.7 Ma (late Eocene) for these rocks was reported in Armentrout and others (1980). The isolated hill on the west side of the freeway is called Drays Mound (Fig. 14). Drays Mound is a cross section through a Goble volcanic vent, probably a shield volcano. Note the lenses of massive andesite surrounded by oxidized flow breccia and cinders. Several narrow vertical dikes also cut the structure.

Figure 14. Drays Mound, a cross section through a Goble volcanic vent, is visible on the west (left) side of I-5 just north of the Kalama River. Photo by Washington State Dept. of Transportation.

72.37 Excellent exposure of Goble basaltic andesite and andesite lava flows along Carrolls Bluff (I-5 MP 33.27). Note the irregular geometry of Goble flows. Unlike the laterally extensive sheet flows of the Columbia River Basalt Group, Goble flows have not been correlated over significant distances. The lack of distinctive marker horizons within the Goble flow complex has made mapping of structures such as folds or faults very difficult.

75.59 Intersection of SR 432 and I-5 (locally known as the "Kelso Y") (I-5 MP 36.5). A faulted anticline is exposed on the east side of the highway (Fig. 15). The light-colored strata in the core of the structure are arkosic sandstones of the Cowlitz Formation. Dark-colored strata consist of massive to thickly bedded basaltic tuff of the Grays River volcanics (Fig. 11).

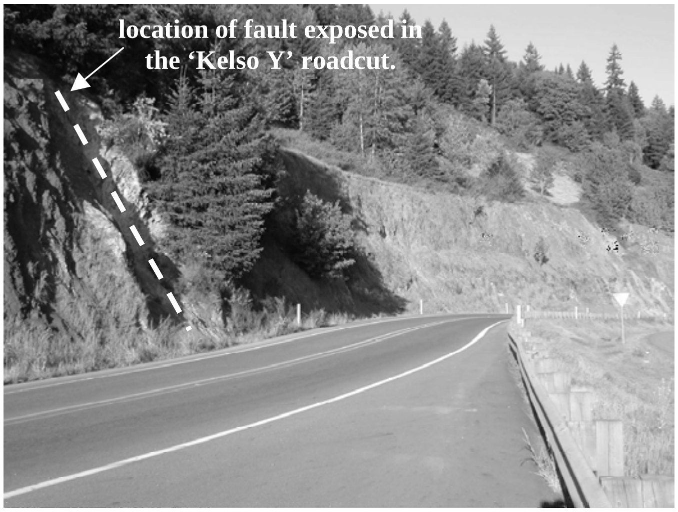

Figure 15. View to the east of faulted anticline exposed on east side of I-5 at the Kelso Y. Coincidentally, the fault trends south directly towards the Trojan Nuclear Plant in Oregon. Photo by Dave Norman.

For the next 23 miles (37 km), from Longview to north of Castle Rock (beyond the end of this road guide), generally east- to southeast-dipping Cascade-derived Goble Volcanics and Toutle Formation form highlands on the east side of I-5. To the west and along the interstate, slightly older oceanic-type basalts (Grays River volcanics, referred to as the "Cowlitz volcanics" in Fig. 11) are interbedded with nearshore marine and nonmarine sediments of the Cowlitz Formation (Fig. 11).

Several flows of Miocene Grande Ronde Basalt of the Columbia River Basalt Group are also present and lie unconformably on the Eocene section (Fig. 11).

77.43 Cross the Coweeman River bridge (I-5 MP 38.34). The skyline to the east is Davis Terrace, which is capped by Pliocene fluvial sediments of the Troutdale Formation. The top of Davis Terrace is approximately 500 feet (150 m) above the Columbia River floodplain. About 2 miles (3.2 km) of the west-facing side of Davis Terrace is a very large deep-seated landslide complex, portions of which are presently active. In the 1960s the WSDOT re-routed I-5 to the west side of the Coweeman River due to continual slow landslide disturbance of the interstate by the Davis Terrace landslide complex (Shannon & Wilson, 1965).

78.0 Exit I-5 at the North Kelso Exit 39 and proceed east (I-5 MP 39.59). Turn right onto Allen Street and go 1 block to the east. Turn right onto Kelso Drive and go south, re-crossing the Coweeman River.

78.55 Turn left onto Russell Street (first left after crossing the Coweeman River), go 1 block, turn right, and proceed uphill. The road becomes Alma Drive.

78.70 Turn left onto Grim Road (appropriately named!) and travel uphill until the road ends in a T intersection (Fig. 16).

Figure 16. Grim Road—Banyon Road intersection.

79.35 Turn right (the road still keeps the name Grim Road).

79.5 **STOP 1: Aldercrest–Banyon landslide, Kelso, Washington. This is the second largest landslide disaster in U.S. history involving homes.** Turn left onto Aldercrest Drive (first left after T intersection). Park vehicles and get out. *Note:* Aldercrest Drive is gated by the city of Kelso. Permission to enter beyond the gate is required by the City of Kelso (Fig. 17). Please contact the City of Kelso, Public Works Department at 360-423-6590 or 906 Croy Street, Kelso, WA 98626-0078 for access.

Figure 17. "Danger, Slide Area!" sign posted at the top of Aldercrest Drive.

Infrastructure damage from landslide activity has been a recognized problem for southwestern Washington and the greater Longview–Kelso urban area for quite some time (Shannon & Wilson, 1965; Thorsen, 1989; Harp and others, 1998). Periodic increases in the activity state of landslides in southwest Washington generally coincide with increases in the amount and duration of regional precipitation. Significantly higher than normal annual precipitation was recorded for most of western Washington, including Cowlitz County and the Longview–Kelso urban area, beginning in the 1995 water year (October 1994 to September 1995) and lasting through the 1999 water year (Fig. 18). Furthermore, the 1996 water year, as recorded in Longview, was the wettest year on record for the past 70 years. The five-year increase in annual precipitation resulted in elevated ground-water levels that, in turn, triggered reactivation of numerous dormant deep-seated landslides throughout southwestern Washington (Burns and others, 1999).

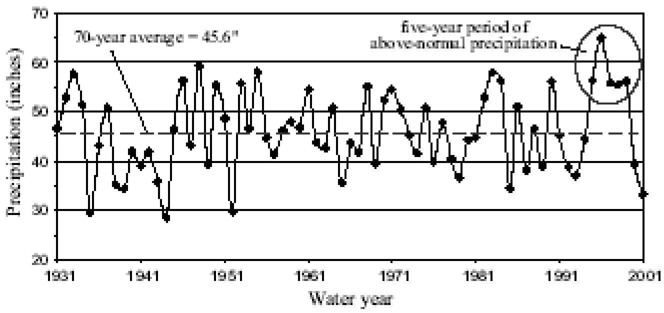

Figure 18. Seventy-year precipitation record for Longview, Washington (Desert Research Institute Western Regional Climate Center, 2002). Note that the five-year increase in precipitation at the end of the 1990s correlates to a period of increased landslide activity and damage along the Cowlitz County urban corridor.

Specifically, in February of 1998, a deep-seated earth slide–earth flow reactivated in the Aldercrest neighborhood of Kelso (Aldercrest–Banyon landslide) (Fig. 19). The housing development was built in the early 1970s on a hill to the southeast of downtown Kelso. In October of 1998, President Clinton issued a federal disaster declaration for the 138 homes affected by the landslide (Burns, 1999; Buss and others, 2000) (Fig. 20). The reactivation of the landslide complex destroyed 60 homes and endangered another 78 on the surrounding slopes.

Figure 19. *(next page)* Aldercrest–Banyon landslide, Kelso. Landslide motion initiated on this deep-seated earth slide-earth flow in February of 1998 and by October of the same year had affected 138 homes, causing President Clinton to declare it a federal disaster area. Damage to public facilities and private property is estimated in excess of $30 million (Buss and others, 2000). The landslide is about 3000 feet (915 m) wide by 1500 feet (457 m) in length, and the main scarp is over 100 feet high in places. **A**. Stereophoto pair of the landslide from 1999 Washington Dept. of Natural Resources aerial photographs. For a three-dimensional view, focus your eyes on the far distance and bring the photo pair up in front of your face at your normal reading distance, or use either a pocket or mirror stereoscope. The slide is interior to a larger landslide feature, as defined by the pre-existing dormant scarp. The straight line is the approximate location of the geologic cross section shown in Figure 21. **B**. Inventory map of the landslide area, generated from the ArcView shapefiles (Wegmann, 2003a). Active landslides are shown in yellow, dormant landslides in red, and non-field-checked landslides in blue; active landslides within larger dormant landslides appear orange. The three-digit numbers are unique identification numbers for each landslide polygon. The black arrows indicate approximate landslide movement directions. Landslide scarps are shown as hachured lines, the colors of which correspond to the color of the associated landslide polygon. The map shows where a portion of a dormant landslide (ID 271) reactivated in 1998, resulting in the Aldercrest–Banyon landslide (ID 272). The slight apparent difference in mapped landslide and scarp size and location between this map and the stereophoto pair in A is due to distortion created by the use of unrectified aerial photographs. The true size and location of the reactivated Aldercrest–Banyon landslide is shown in this inventory map. **C**. View northwest along the main scarp of the landslide as it appeared in August 2000. Note the destroyed houses and tilting trees at the base of the scarp. Prior to the landslide, these houses were slightly above the elevation of the top of the scarp. This photo was taken in the former basement (light gray area on the left) of a house now at the bottom of the hill outside the photo area. The scarp exposes Pliocene fluvial gravels and sands of the Troutdale Formation. **D**. View to the southeast across the middle section of the landslide as photographed in June 2000. The houses in this view are uninhabitable. Note the internal rotation within the landslide body as evidenced by the back tilting of the distant house.

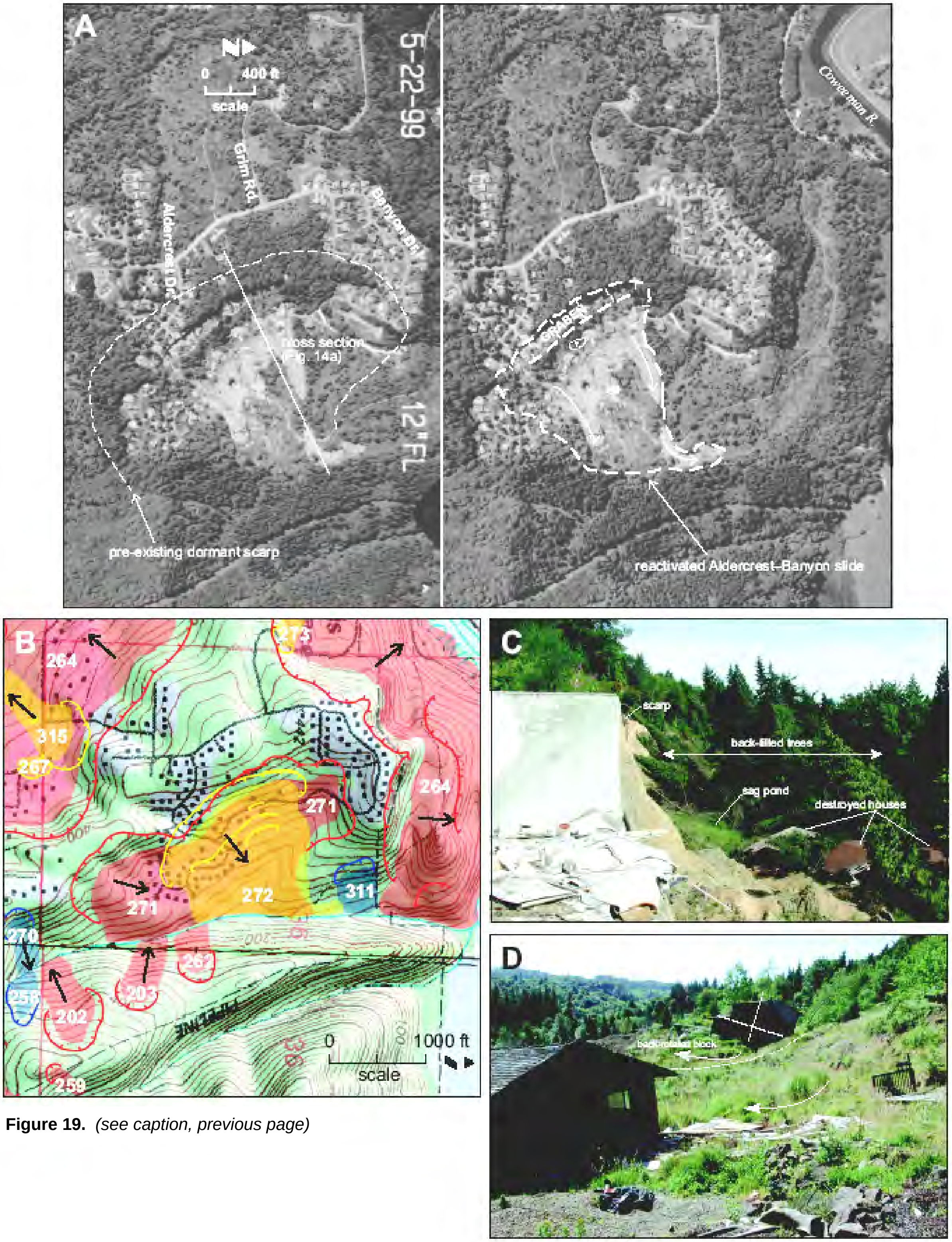

Figure 19. *(see caption, previous page)*

Figure 20. House damaged by movement of the Aldercrest–Banyon landslide.

The landslide occurred in the Troutdale Formation, and it moved over a paleosol on the Eocene-aged Cowlitz Formation (GeoEngineers, 1998; Wegmann and Walsh, 2001) (Fig. 21). The original landslide may have occurred during the Missoula floods (15,300–12,700 years ago). Its width is approximately 3000 feet (1000 meters) and length about 1500 feet (500 m). The scarp is about 115 feet (35 m) high, and the depth to the surface of failure ranges from 10 feet (3 m) to about 40 feet (12 m) (Figs. 19C, 21B, and 22). The maximum slide movement in 1998 was about 6 to 12 inches (15 to 30 cm) per day. Damage to private property is estimated to be about $25.7 million, and damage to public infrastructure about $6.2 million (GeoEngineers, 1998). The motion is mainly translational, but some investigators have also classified it as a large earthflow. Internal rotation of landslide blocks is evidenced by deformation of rigid structures, such as houses (Fig. 19D). Extraordinary precipitation for the previous three winters contributed to the reactivation of the landslide (GeoEngineers, 1998). Also a road excavation in February 1998 across the lower part of the slide may have been a trigger to cause the initial reactivated movement, which then caused storm drains to break and storm water to be fed back into the slide. Logging operations at the toe of the landslide may also have contributed to the reactivation.

The costs of repairing damage from this landslide were prohibitive. There is essentially no home insurance for landslides, so homeowners were at risk of losing the entire value of their homes. The people living above the scarp wondered if their houses might also go. The Federal Emergency Management Agency offered to purchase the homes and property from the homeowners for $0.35 on the dollar value. All but eleven homeowners took the offer; those eleven still remain in their homes and are taking their chances of the upper area not reactivating. The federal government has removed all of the purchased homes.

This disaster has raised public awareness of landslides in the Pacific Northwest. If we are heading into a 20-year wet cycle, as is believed by some, more of these now-dormant landslides may reactivate (Taylor and Hannan, 1999). Communities do not want to have another “Kelso Landslide” happen in their area.

In response to the Aldercrest–Banyon and other recent damaging landslides in Cowlitz County, the Washington Division of Geology and Earth Resources began a field- and geographic information systems (GIS) -based landslide inventory and slope stability mapping project in 2000. In total, 260 square miles (680 km^2) of urbanizing lands in Cowlitz County between the Toutle River and the Lewis and Wahkiakum County lines have been mapped for all landslides, regardless of age (for example, Wegmann and Walsh, 2001; Wegmann, 2002, 2003a,b). Slides were identified from 1951, 1974, 1984, 1993, 1996, and 1999 aerial photographs. Nearly 600 deep-seated and 260 shallow landslides have been identified, 80 percent of which were previously unmapped. In total, 23 square miles (59.5 km^2) or 11 percent of the sloping lands within the study area are identified as landslide terrain. Of the deep-seated slides identified from aerial photos, 70 percent were field checked, and of these, 20 percent exhibit evidence of movement within the past 10 years. Deep-seated slides range in size from 0.00003 to 0.65 square miles (0.001 to 1.65 km^2). Deep-seated slide movement occurs on slopes with gradients as low as 10 percent (6°).

The Cowlitz County landslide study area, characterized by moderate to steep slopes that tend to fail via slow to moderate, rotational to translational rock and (or) earth slides, is underlain by high-plasticity clay-rich soils and deeply weathered Tertiary bedrock (saprolites). Irrespective of age, slides occur within all rock units, but have the highest occurrence on steep to moderate slopes underlain by deeply weathered Paleogene volcanic tuffs and volcaniclastic sedimentary rocks, the Cowlitz Formation the Toutle Formation, and the Neogene Sandy River Mudstone and Troutdale Formation (Fig. 11). The majority of slides appear to have moved in response to natural causes, such as above-average annual precipitation. Some of the now-dormant deep-seated slides may have been seismically triggered, and others (below 230 feet [70 m]) may have initiated in response to rapid drawdown of late Pleistocene glacial outburst floodwaters along the Columbia River and tributaries (Wegmann and Walsh, 2001). Human actions, such as the alteration of slope hydrology through development and forestry practices, surface mining operations, and improper placement and design of fill material on slopes, have contributed to the initiation of new, and reactivation of dormant deep-seated slides.

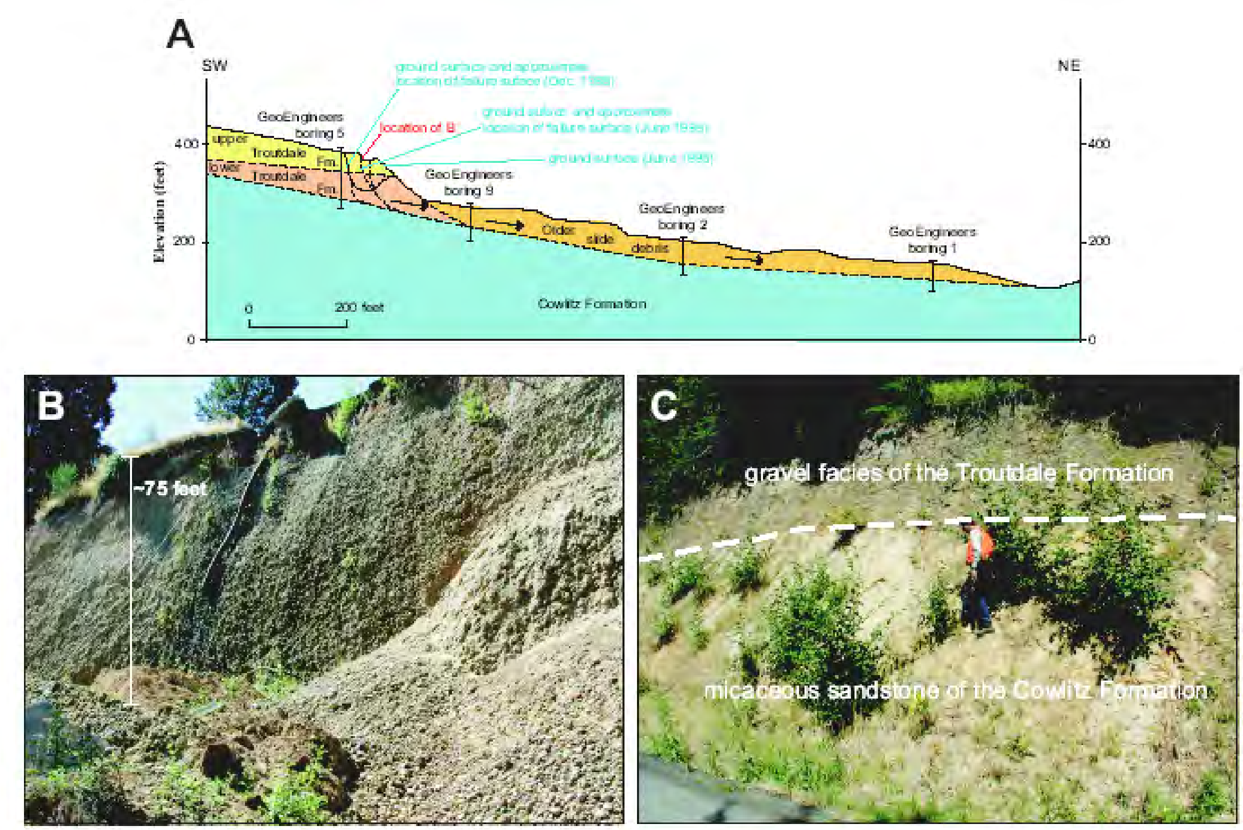

Figure 21. Geologic cross section and photographs illustrating the geologic controls on the Aldercrest–Banyon landslide. **A**. Generalized geologic cross section through the Aldercrest–Banyon landslide (modified from GeoEngineers, 1998; see Fig. 19 for location). Interpretation of the geology of the landslide indicates that the recent landslide is a reactivation of an older landslide, and exploratory geotechnical drilling has revealed that the landslide failure plane is at or near the contact of Neogene fluvial sediments of the Troutdale Formation and (or) older slide debris with Paleogene sedimentary rocks of the Cowlitz Formation (GeoEngineers, 1998). **B**. View to the south from the base of the approximately 75-foot-high main scarp of the Aldercrest-Banyon landslide. The scarp exposes Neogene fluvial gravels and sands of the Troutdale Formation. **C**. Road cut exposure off of Carroll Road (SW¼SE¼ sec. 1, T7N R2W) that exposes the contact between Neogene fluvial gravels of the Troutdale Formation and underlying deeply weathered (saprolitic) sandstones of the Paleogene Cowlitz Formation. It is believed that the Aldercrest–Banyon and other landslides in the study area are failing at the contact between these two formations.

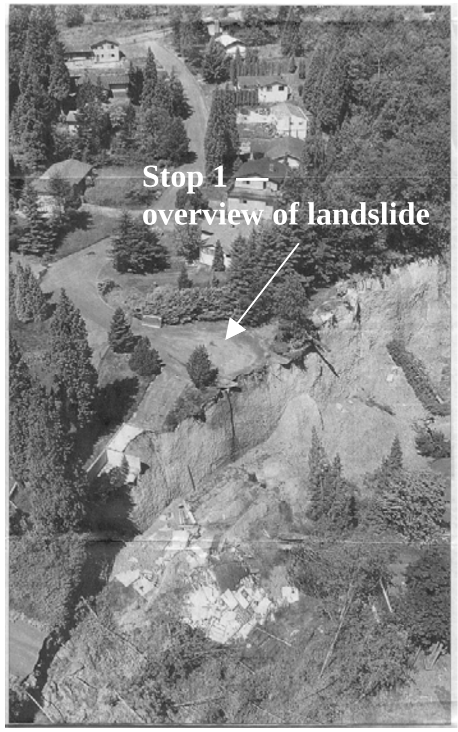

Figure 22. Aerial view to west of the Aldercrest–Banyon landslide head scarp as it appeared in 2000 (Photo from *The Oregonian*, June 11, 2000).

Turn around and retrace 1.5-mile route back to I-5.

81.0 Enter I-5 Northbound (right turn) off of Allen Street.

82.9 Rocky Point (I-5 MP 41.8). On the west side of the highway are dull black, massive, spheroidally weathering hyaloclastite of the Eocene Grays River volcanics. The hyaloclastite consists of altered basalt glass, basalt clasts, and secondary zeolites and calcite formed when lava contacted water. The unit grades into a massive lava flow on the west; on the east side of the freeway are basaltic sandstone and conglomerate.

88.3 Castle Rock area (I-5 MP 47.20). Dredge spoils of Mount St. Helens 1980 laharic deposits are on the west. The Cowlitz and Toutle Rivers are dredged to reduce flooding hazard to communities of Kelso and Longview. The flood plain of the lower Cowlitz River (on the left) has been inundated by catastrophic laharic deposits from Mount St. Helens area many times in the past 2,000 to 36,000 years.

90.6 Turn off I-5 for Castle Rock (Exit 49) (I-5 MP 49.5). Make a right turn onto Mount St. Helens Way (SR 504). This ends Part I of the field trip (Skamania to Castle Rock) and begins Part II (Castle Rock to Mount St. Helens, Leg A in Pringle, 2002).

REFERENCES CITED

Allen, J. E., 1979, The magnificent gateway—A layman's guide to the geology of the Columbia River gorge: Timber Press [Forest Grove, Ore.] Scenic Trips to the Northwest's Geologic Past 1, 144 p.

Armentrout, J. M., 1987, Cenozoic stratigraphy, unconformity-bounded sequences, and tectonic history of southwestern Washington. *In* Schuster, J. E., editor, Selected papers on the geology of Washington: Washington Division of Geology and Earth Resources Bulletin 77, p. 291-320.

Armentrout, J. M.; McDougall, K. A.; Jefferis, P. T.; Nesbitt, Elizabeth A., 1980, Geologic field trip guide for the Cenozoic stratigraphy and late Eocene paleoecology of southwestern Washington. *In* Oles, K. F.; Johnson, J. G.; and others, editors, Geologic field trips in western Oregon and southwestern Washington: Oregon Department of Geology and Mineral Industries Bulletin 101, p. 79-92.

Burns, S. F., 1999, Aldercrest landslide, Kelso, Washington, engulfs subdivision [abstract]: Geological Society of America Abstracts with Programs, v. 31, no. 6, p. A-41.

Burns, S. F.; Burns, W. J.; James, D. H.; Hinkle, J. C., 1999, Reactivation of ancient landslides in northwest Oregon and southwest Washington [abstract]: Association of Engineering Geologists, 42nd Annual Meeting, Program with Abstracts, p. 61.

Burns, S. F.; Kuper, H. T.; Lawes, J. L., 2002, Landslides at Kelso, Washington, and Portland, Oregon. *In* Moore, G. W., editor, Field guide to geologic processes in Cascadia: Oregon Department of Geology and Mineral Industries Special Paper 36, p. 257-272.

Buss, K. G.; Benson, B. E.; Koloski, J. W., 2000, Aldercrest–Banyon landslide—Technical and social considerations [abstract]: AEG News, v. 43, no. 4, p. 78.

Carson, R. J.; Pogue, K. R., 1996, Flood basalts and glacier floods—Roadside geology of parts of Walla Walla, Franklin, and Columbia Counties, Washington: Washington Division of Geology and Earth Resources Information Circular 90, 47 p.

Deacon, R. J.; Hales, P. O.; Phillips, W. M.; Walsh, T. J., 1988, Geologic road log from Portland to Ocean Shores: Northwest Petroleum Association, 14 p.

Desert Research Institute Western Regional Climate Center, 2002, Longview, Washington (454769); Period of record monthly climate summary; Period of record—1/1/1931 to 12/31/2001: Desert Research Institute Western Regional Climate Center [accessed Dec. 31, 2002 at http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?walvie].

Evarts, R. C., 2002, Geologic map of the Deer Island quadrangle, Columbia County, Oregon and Cowlitz County, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF-2392, 45 p., 1 plate, scale 1:24,000.

Foxworthy, B. L.; Hill, Mary, 1982, Volcanic eruptions of 1980 at Mount St. Helens—The first 100 days: U.S. Geological Survey Professional Paper 1249, 125 p.

GeoEngineers, Inc., 1998, Report—Geotechnical engineering services, slope failure evaluation, Aldercrest–Banyon Landslide, Kelso, Washington: GeoEngineers, Inc. [under contract to] City of Kelso, 1 v.

Harp, E. L.; Chleborad, A. F.; Schuster, R. L.; Cannon, S. H.; Reid, M. E.; Wilson, R. C., 1998, Landslides and landslide hazards in Washington State due to February 5-9, 1996 storm: U.S. Geological Survey Administrative Report, 1 v.

Holdredge, C. P., 1937, Final geological report on the Bonneville Project: U.S. Army Engineer District [Portland, Ore.], 1 v.

Lawrence, D. B., 1937, Drowned forests of the Columbia River gorge: Geological Society of the Oregon Country Geological News Letter, v. 3, no. 8, p. 78-83.

Lawrence, D. B.; Lawrence, E. G., 1958, Bridge of the Gods legend—Its origin, history, and dating: Mazama, v. 40, no. 13, p. 33-41.

Lunney, Meghan; Taylor, J. M., 2000, Analysis of probable Bridge of the Gods landslide dam outburst sediments in the lower Columbia River basin [abstract]: Geological Society of America Abstracts with Programs, v. 32, no. 6, p. A-26.

O'Connor, J. E.; Pierson, T. C.; Turner, Daniel; Atwater, B. F.; Pringle, P. T., 1996, An exceptionally large Columbia River flood between 500 and 600 years ago—Breaching of the Bridge-of-the-Gods landslide? [abstract]: Geological Society of America Abstracts with Programs, v. 28, no. 5, p. 97.

Palmer, L. A., 1977, Large landslides of the Columbia River gorge, Oregon and Washington. *In* Coates, D. R., editor, Landslides: Geological Society of America Reviews in Engineering Geology, v. III, p. 69-83.

Pardee, J. T., 1910, The glacial Lake Missoula: Journal of Geology, v. 18, p. 376-386.

Pringle, P. T., 2002, Roadside geology of Mount St. Helens National Volcanic Monument and vicinity; rev. ed.: Washington Division of Geology and Earth Resources Information Circular 88, rev. ed., 122 p.

Reidel, S. P.; Tolan, T. L.; Beeson, M. H., 1994, Factors that influenced the eruptive and emplacement histories of flood basalt flows—A field guide to selected vents and flows of the Columbia River Basalt Group. *In* Swanson, D. A.; Haugerud, R. A., editors, Geologic field trips in the Pacific Northwest: University of Washington Department of Geological Sciences, v. 1, p. 1B 1 - 1B 18.

Schuster, R. L.; Pringle, P. T., 2002, Engineering history and impacts of the Bonneville landslides, Columbia River gorge, Washington–Oregon, USA. *In* Rybar, Jan; Stemberk, Joseph; Wagner, Peter, editors, Landslides—Proceedings of the First European Conference on Landslides: A. A. Balkema, p. 689-699.

Scofield, D. H.; Harvey, A. F., Burns, S. F., 1997, Engineering geology of the Columbia River gorge—Association of Engineering Geologists 40th Annual Meeting field trip: Association of Engineering Geologists, 27 p.

Shannon & Wilson, Inc., 1965, Preliminary engineering studies of landslide areas along proposed Interstate Highway 5, south Kelso, Washington: Shannon & Wilson, Inc. [under contract to] Washington State Highway Commission, 1 v.

Shannon & Wilson, Inc., 1978, Columbia River gorge slide studies, Oregon and Washington—Report prepared for Portland General Electric Company; investigators R. C. Newcomb, R. J. Pope, and W. L. Wright: Shannon & Wilson, Inc. unpublished report, Job no. O-1203, 23 p.

Swanson, D. A.; Anderson, J. L.; Bentley, R. D.; Byerly, G. R.; Camp, V. E.; Gardner, J. N.; Wright, T. L., 1979a, Reconnaissance geologic map of the Columbia River Basalt Group in eastern Washington and northern Idaho: U.S. Geological Survey Open-File Report 79-1363, 26 p., 12 plates.

Swanson, D. A.; Wright, T. L.; Hooper, P. R.; Bentley, R. D., 1979b, Revisions in stratigraphic nomenclature of the Columbia River Basalt Group: U.S. Geological Survey Bulletin 1457-G, 59 p., 1 plate.

Taylor, G. H.; Hannan, Chris, 1999, The climate of Oregon—From rain forest to desert: Oregon State University Press, 211 p.

Thorsen, G. W., 1989, Landslide provinces in Washington. *In* Galster, R. W., chairman, Engineering geology in Washington: Washington Division of Geology and Earth Resources Bulletin 78, v. I, p. 71-89.

Tolan, T. L.; Beeson, M. W.; Vogt, B. F., 1984, Exploring the Neogene history of the Columbia River—Discussion and geologic field trip guide to the Columbia River gorge; Part II, Road log and comments: Oregon Geology, v. 46, no. 9, p. 103-112.

Tolan, T. L.; Reidel, S. P.; Beeson, M. H.; Anderson, James Lee; Fecht, K. R.; Swanson, D. A., 1989, Revisions to the estimates of the areal extent and volume of the Columbia River Basalt Group. *In* Reidel, S. P.; Hooper, P. R., editors, Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America Special Paper 239, p. 1-20.

Trimble, D. E., 1963, Geology of Portland, Oregon, and adjacent areas: U.S. Geological Survey Bulletin 1119, 119 p., 1 plate.

U.S. Army Corps of Engineers, 1976, Columbia River basin, Oregon-Washington, Bonneville lock and dam; 2nd powerhouse railroad tunnel, design memorandum no. 7, supplement no. 4: U.S. Army Corps of Engineers, 1 v.

Uyeda, Seiya, 1978, The new view of the Earth—Moving continents and moving oceans: W. H. Freeman and Company, 217 p.

Waitt, R. B., Jr., 1980, About forty last-glacial Lake Missoula jokulhlaups through southern Washington: Journal of Geology, v. 88, no. 6, p. 653-679.

Waitt, R. B., Jr., 1985, Case for periodic, colossal jokulhlaups from Pleistocene glacial Lake Missoula: Geological Society of America Bulletin, v. 96, no. 10, p. 1271-1286.

Waitt, R. B.; O'Connor, J. E.; Benito, Gerardo, 1994, Scores of gigantic, successively smaller Lake Missoula floods through Channeled Scabland and Columbia valley. *In* Swanson, D. A.; Haugerud, R. A., editors, Geologic field trips in the Pacific Northwest: University of Washington Department of Geological Sciences, v. 1, p. 1K 1 - 1K 88.

Wang, Yumei; Hofmeister, R. J.; McConnell, Vicki; Burns, S. F.; Pringle, P. T., 2002, Columbia River gorge landslides—Field trip guidebook for the National Academies: [Privately published by the authors], 22 p.

Waters, A. C., 1973, The Columbia River gorge—Basalt stratigraphy, ancient lava dams, and landslide dams. *In* Beaulieu, J. D., Geologic field trips in northern Oregon and southern Washington: Oregon Department of Geology and Mineral Industries Bulletin 77, p. 133-162.

Wegmann, K. W., 2002, Landslide inventory mapping between Kelso and Woodland, Cowlitz County, Washington State [abstract]: Geological Society of America Abstracts with Programs, v. 34, no. 5, p. A-106.

Wegmann, K. W., 2003a, Digital landslide inventory for the Cowlitz County urban —Kelso to Woodland (Coweeman River to Lewis River), Cowlitz County, Washington: Washington Division of Geology and Earth Resources Report of Investigations 34, 1 CD-ROM disk.

Wegmann, K. W., 2003b, Landslide inventory and slope stability mapping of the urban growth areas within Cowlitz County, Washington State [abstract]: Geological Society of America Abstracts with Programs, v. 35, no. 6, p. 331.

Wegmann, K. W.; Walsh, T. J., 2001, Landslide hazard mapping in Cowlitz County—A progress report: Washington Geology, v. 29, no. 1/2, p. 30-33.

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.